



Determinants of electricity consumption in South Africa: Insights from linear and nonlinear modeling approaches

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Article history:

Received: October 03,
2024

1st Revision: April 10,
2025

Accepted: May 16, 2025

JEL classification:

Q41

Q43

C22

C32

O55

DOI:

[10.14254/jems.2025.10-1.1](https://doi.org/10.14254/jems.2025.10-1.1)

Abstract: *Purpose:* This study investigates the determinants of electricity consumption in South Africa, focusing on economic, demographic, and energy-related factors from 1980 to 2023.

Methodology: The study employs linear models (Dynamic Ordinary Least Squares and Canonical Cointegrating Regression) and a nonlinear Threshold Autoregressive (TAR) model to analyze the relationships between electricity consumption and its determinants.

Results: Economic growth, electricity prices, and income per capita are found to be positive determinants of electricity consumption, while population growth and inflation exhibit negative relationships. The TAR model reveals asymmetric effects of these determinants across different income regimes.

Theoretical contribution: This study extends the literature on electricity consumption determinants in developing countries by incorporating both linear and nonlinear modeling approaches, providing a more comprehensive understanding of the complex relationships involved.

Practical implications: The findings inform policymakers and energy stakeholders in South Africa on effective strategies for managing electricity demand, promoting energy efficiency, and addressing the ongoing challenges in the electricity sector.

Keywords: electricity consumption, South Africa, dynamic ordinary least squares, canonical cointegrating regression, threshold autoregressive model



**Sustainable Development Goals (SDGs): SDG 7:
Affordable and Clean Energy; SDG 9: Industry,
Innovation and Infrastructure**

1. Introduction

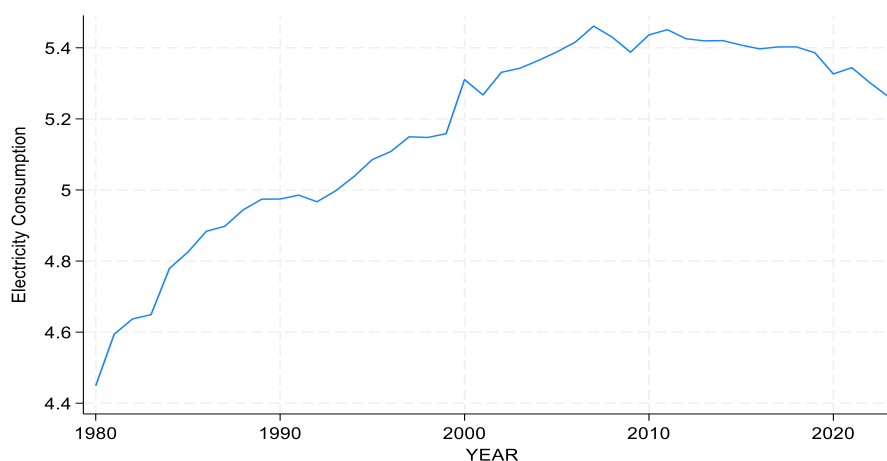
South Africa is one of the countries facing a challenge in balancing electricity demand and supply, as witnessed by constant load shedding and power reductions rolled out by Eskom since 2007. The primary reason for this crisis is Eskom's inadequate generation capacity, which is a state-owned power company. Despite alerts from Eskom and experts, the government seems to have neglected to tackle the problem, resulting in a lack of electricity. Roy-Aikins (2016) highlights that "Load growth, as a result of economic growth and a national electrification program, caused an erosion of the electricity reserve margin, which was quite massive in the early nineties." This indicates that the growth in electricity demand negatively affects the amount of electricity available in the reserves to consume, mainly driven by rising economic growth. The main objective of this study is to investigate the determinants of electricity consumption in South Africa using time series data from 1980 to 2023.

The studies of Erero (2023), Walsh *et al.* (2021), du Venage (2020), Gehringer *et al.* (2018), Naidoo (2023), Lenoke (2017), Wiese *et al.* (2024), Marope and Phiri (2024) have investigated the impact of load shedding on the South African economy, health facilities, consumers, and housing markets and found that the shortage of electricity supply is detrimental to these sectors. It is, therefore, crucial to have a stable electricity supply for the growth of the economy and the booming of the business since electricity is the backbone of every economy in the era of technology.

Researchers such as Hlongwane and Daw (2022) have investigated the challenges and opportunities of electricity generation in South Africa and found that the circumstances have been worsened by multiple elements, such as several of Eskom's power stations being nearly 50 years old and approaching the end of their life span. The absence of maintenance and disregard for Eskom's power facilities over the last 12 years has led to an erratic and untrustworthy system. Roy-Aikins (2016) argues that "executing planned plant maintenance will improve plant health and, hence, plant availability, which can bring about a turnaround in the short-term power supply situation as Eskom awaits new capacity from the New Build Programme." These studies show that for any electricity generation plant to be able to sustain electricity supply, proper maintenance is needed.

Gregory (2020), Bowman (2020), and Kapstein (2023) investigated the impact of corruption and the scope of governance on electricity generation infrastructures in South Africa, and the reports indicated that sabotage and corruption at Eskom have played a role in the issues with power supply. Specifically, Bowman (2020) argues that "Eskom's extreme dysfunctionality results from long-running, and as yet unresolved, contestation of the parastatal and electricity policy more broadly by various interest groups, in a context of an increasingly fragmented political and business elite." This shows the influence various interest groups have on Eskom resulting in the parastatal being dysfunctional and unable to meet electricity demand in the country. The study presents the status quo of South Africa's electricity consumption trends from 1980 to 2023, as presented in Figure 1 below.

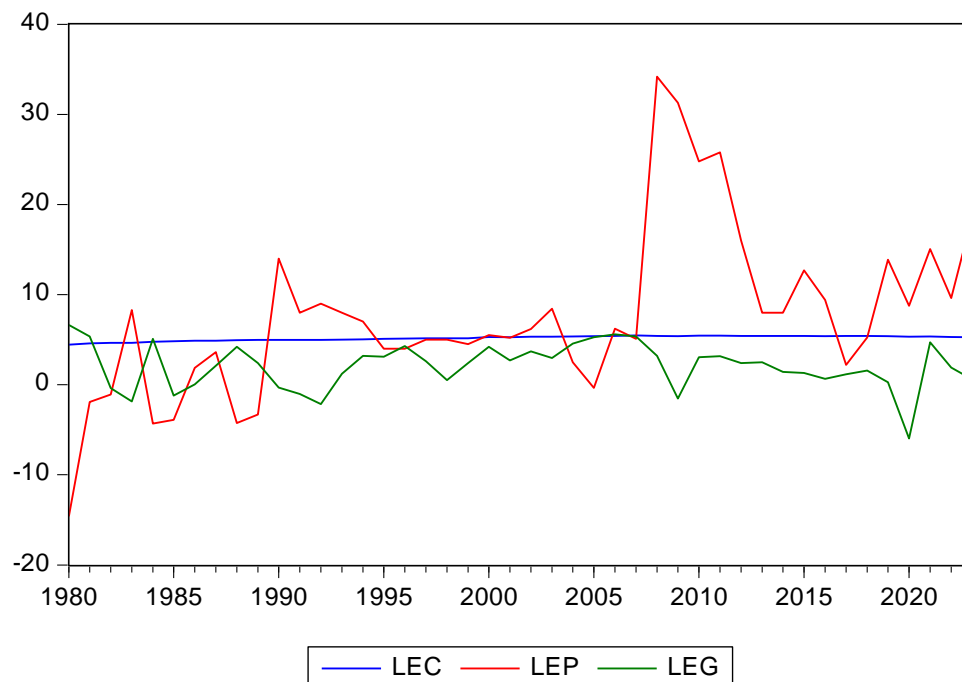
Figure 1: Electricity Consumption in South Africa from 1980 to 2023



Source: Author's computation using data from Global Economy

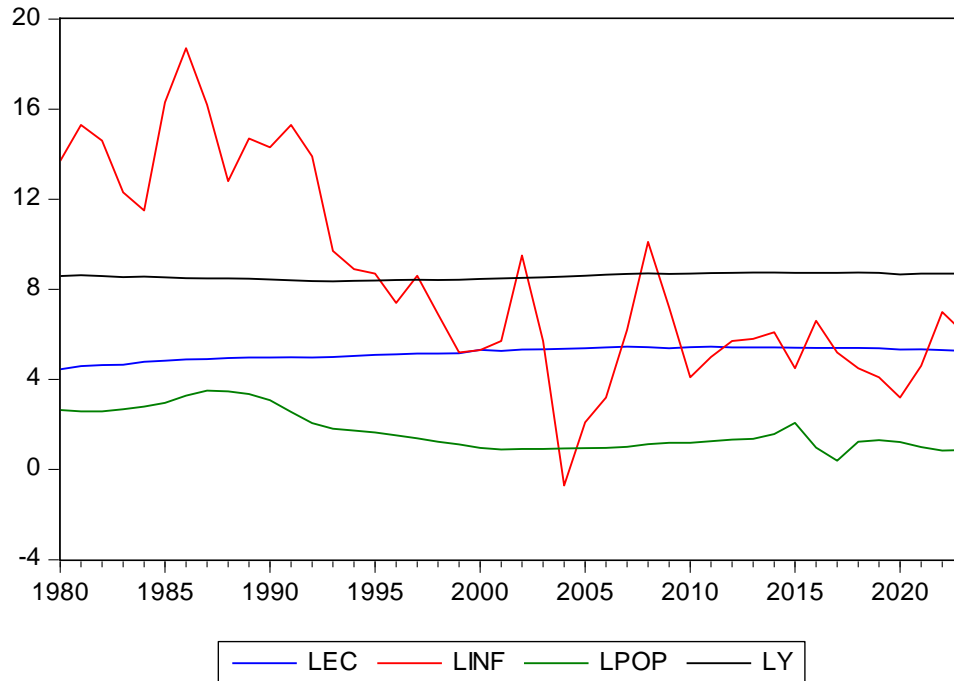
Figure 1 above presents the trend in South Africa's electricity consumption from 1980 to 2023, which was computed using data from the Global Economy. The data shows an upward trend from 1980 to 2000, and thereafter, it starts fluctuating above 2000 levels until a downward trend in post-2020. Regarding electricity consumption, Hlongwane and Daw (2022) note that South Africa's energy mix continues to depend significantly on coal-fired power stations, which contribute approximately 95% to the nation's electricity production. Nonetheless, initiatives are in progress to transition to renewable energy sources like wind and solar energy, as witnessed in the studies of Baker and Phillips (2019), Wright *et al.* (2019), and Todd and McCauley (2021). In general, South Africa's electricity dilemma is a complicated matter that needs a diverse strategy to address it. Addressing the root cause of the crisis and ensuring a reliable and sustainable electricity supply for the country will probably require time, investment, and a joint effort from the government, Eskom, the private sector, Independent Power Producers, and other parties involved. Figure 2 below visualizes the trends in electricity consumption, electricity prices, and economic growth in South Africa from 1980 to 2023.

Figure 2: Electricity consumption, electricity prices, and economic growth in South Africa



Source: Author's computation using data from Eskom and Global Economy

Figure 2 above shows the trends in electricity consumption, electricity prices, and economic growth in South Africa from 1980 to 2023, computed using data from Eskom and Global Economy. Electricity consumption has a stable trend, whereas electricity prices have been fluctuating above electricity consumption while economic growth has remained below electricity consumption since 1982. Several studies, such as Ezesele (2017), Khobai *et al.* (2017), and Gasealahwe (2020), have investigated the relationship between electricity prices, electricity consumption, and economic growth in South Africa and discovered different findings. These trends help explain the poor economic growth experienced in South Africa since its electricity supply challenges. Figure 3 below shows the trends in electricity consumption, population growth, income, and inflation in South Africa from 1980 to 2023.

Figure 3: Electricity consumption, inflation, population growth, and income in South Africa

Source: Author's computation using data from Eskom and Global Economy

Figure 3 above shows the trend between electricity consumption, inflation, population growth, and income in South Africa from 1980 to 2023, presented as a percentage using data from the Global Economy. The trends show that against electricity consumption, income has remained above while population growth has remained below electricity consumption. It is important to note that population growth has not been exceeding electricity consumption in South Africa; however, national income has remained electricity consumption. These relationships point out that income and inflation are likely to affect electricity consumption in South Africa for the period under; however, this will be ascertained by the models selected for the study.

Problem Statement: South Africa faces significant energy challenges, including growing demand for electricity, inadequate supply, and increasing energy costs. The growing electricity consumption in South Africa is visualized in Figure 1 above, using data from the Global Economy, which shows that electricity consumption has increased drastically since the 1980s. Electricity prices, as shown in Figure 2, show a drastically upward trend from the 1980s to 2023, indicating that the increased cost of electricity is likely to be detrimental to the consumption of electricity. The studies of Erero (2023), Walsh *et al.* (2021), du Venage (2020), Gehringer *et al.* (2018), Naidoo (2023), Lenoke (2017), Wiese *et al.* (2024), Marope and Phiri (2024) has shown that load shedding hurts load shedding that translates to detriment the economy, businesses, and other sectors. Understanding the determinants of electricity consumption is crucial for policymakers to develop effective energy policies and ensure a sustainable energy future.

Research Gaps:

1. There are limited studies on South African data concentrating on the determinants of electricity consumption. Most studies on electricity consumption have focused on developed countries, with limited studies focusing on South Africa. Specifically, the studies of Ye *et al.* (2018) and Bohlmann and Inglesi-Lotz (2021) have concentrated on the determinants of household electricity consumption, neglecting the overall determinants of electricity consumption in South Africa. Sehlapelo and Inglesi-Lotz (2022) conducted a panel data analysis of the determinants of electricity consumption in South Africa; however, they only covered the period from 1990 to 2019, which makes the current study robust.
2. There is an inadequate analysis of demographic factors that determine the determinants of electricity consumption. Previous studies have not fully explored the impact of demographic characteristics, such as income, education, and population growth, on electricity consumption in South Africa.
3. There is a lack of consideration of energy efficiency factors in South Africa. Studies have not adequately examined the impact of energy efficiency measures, such as energy-efficient appliances and building insulation, on electricity consumption.

4. There is an insufficient investigation of the economic factors that determine the determinants of electricity consumption in South Africa. The relationship between economic factors, such as GDP growth, inflation, energy prices, and electricity consumption, has not been fully explored. Studies such as those of Ezesele (2017), Khobai *et al.* (2017), and Gasealahwe (2020) check on the impact of electricity consumption and electricity prices on economic growth, makes this current study robust since it utilizes electricity consumption as a dependent variable.

Research Questions:

1. What are the key determinants of electricity consumption in South Africa?
2. How do demographic factors such as income, education, and population growth influence electricity consumption?
3. What is the impact of energy efficiency measures on electricity consumption?
4. How do economic factors such as GDP growth, inflation, and energy prices affect electricity consumption?
5. Are there any nonlinear relationships between electricity consumption and its determinants?

Significance of the study:

1. The significance of this study rests in informing energy policy. This study will provide policymakers with valuable insights into the determinants of electricity consumption in South Africa, enabling them to develop effective energy policies.
2. This study makes a significant difference by promoting energy efficiency. By identifying the impact of energy efficiency measures on electricity consumption, this study will contribute to the development of strategies to promote energy efficiency.
3. The significance of this study also lies in enhancing energy security. Understanding the determinants of electricity consumption will help ensure a sustainable energy future and enhance energy security.

Contribution of the study:

1. This study contributes to empirical evidence by providing quantitative estimates of the determinants of electricity consumption in South Africa.
2. This study contributes to electricity consumption policy recommendations by informing policymakers on developing effective energy policies.
3. This study contributes to energy efficiency strategies by developing strategies to promote energy efficiency and reduce electricity consumption.
4. This study contributes to energy security enhancement by broadening our understanding of the development of electricity consumption. This study will enhance energy security and ensure a sustainable energy future.

The rest of the study is structured as follows: Section 2 discusses the literature review between electricity consumption and its determinants. Section 3 presents the methodology and data analysis of the study, followed by results, interpretations, and discussions of the study in Section 4. Section 5 presents the summary, policy recommendations, and conclusion of the study.

2. Literature review

2.1. International experiences

Al-Bajjali and Shamayleh (2018) employed a VECM model to analyze the determinants of electricity consumption in Jordan on data spanning from 1986 to 2015. The study's findings indicated that economic growth, urbanization, population, structure of the economy, and aggregate water consumption are significant positive determinants of electricity consumption. In contrast, electricity prices are negatively related to electricity consumption in Jordan. The authors recommend investing more in green energy projects and banning the importation of low-efficiency electrical appliances. On an international level, Dokas *et al.* (2022) used error correction, FMOLS, DOLS, and GMM models from 2010 to 2018 as the determinants of energy and electricity consumption in developed and developing countries. The findings suggest a consistent model with strong interpretative capability, showing that the primary factors influencing energy consumption in developing nations are trade openness, corruption, and innovation. In contrast, for developed nations, the key factors are economic growth, investment, population growth, and winter temperatures. The authors recommend the formulation and implementation of environmentally friendly policies. Kwakwa (2018) analyzed the determinants of electricity consumption in Benin from 1971 to 2014 using FMOLS and CCR models. The findings revealed that population, education, urbanization, and

industrialization positively influence electricity consumption, whereas income negatively affects it. The author recommends the use of environmentally friendly energy practices and energy efficiency.

The determinants of electricity consumption in Nigeria were examined by Onisanwa and Adaji (2020) from 1981 to 2017 using the ARDL model. The study's findings revealed that the determinants are per capita income, population, and number of electricity customers. Using a NARDL and VECM approach, the macroeconomic determinants of electricity consumption in India were investigated by Sharma and Kautish (2019) from 1980 to 2015. The study's findings reveal that GDP and FDI are India's positive determinants of electricity consumption. Consequently, the research suggests that if the nation continues to experience notable growth in the future, the government must provide consistent electricity, achievable by establishing additional power plants in the area. Using a PRISMA framework, the determinants of residential electricity consumption in South, East, and Southeast Asia were explored by Najeeb *et al.* (2024). The study's findings indicate that household expenditure, household income, social category, and price of electricity are significant socioeconomic variables of renewable energy consumption.

Using a questionnaire of 310 households in Botswana, a cluster analysis of the determinants of household electricity consumption was conducted by Ofetotse *et al.* (2021). The findings of the study revealed that dwelling type, tenure, the number of rooms, the number of bedrooms, annualized electricity consumption, and the number of appliances are the determinants of electricity consumption. On a quantile approach, the determinants of household electricity consumption in Taiwan were analyzed by Huang (2015) from 1981 to 2011. The results of the study revealed that socioeconomic, demographic, and household-dwelling characteristics are different across quantiles for each year. The results further show that higher income, larger household size, and more elderly households consume more electricity. The author recommends that policymakers should not only encourage the use of energy-efficient appliances but also promote behavioral change in household electricity consumption.

Using a survey of 1245 households across California, Chen *et al.* (2018) investigate the role of household-level electricity data in improving estimates of the impacts of climate on building electricity use using a segmented linear regression approach. The findings of the study indicate that temperature has the most substantial impact on electricity consumption and highlight that it should be noted that the use of daily average maximum temperatures depends on the research questions, and there are cases where it might not be a variable of choice. Though using daily temperature data is imperative for capturing its impact on electricity consumption, the study did not consider other determinants, such as household income and household size, which could have given a more accurate picture of the determinants of household electricity consumption. The determinants of household electricity consumption in Malaysia using a survey of 620 urban households in Seremban were examined by Ali *et al.* (2021) using a multiple linear regression model. The findings of the study indicated that monthly household income, room sizes, and married couples result in more electricity consumption. Consequently, the authors recommend that it is crucial to advance low-carbon initiatives aimed at energy conservation and technological enhancements, along with enforcing policies in the domestic sector to realize the maximum possible reduction in energy consumption in urban areas.

Using a Censored Tobit model, Wassie and Ahlgren (2023) examine the factors influencing Ethiopian rural households and small businesses' electricity consumption on a survey of 218 electrified customers in Omorate and Tum towns. The empirical findings of the study indicated that household electricity consumption is determined by household income, household size, dwelling type, number of rooms, cooling fans, cooking with electricity, and loadshedding. Further results show that electricity consumption for businesses is strongly correlated with income, electricity price, number of rooms, number of cooling fans, refrigerators, number of other appliances, and loadshedding. The authors recommend that the development of mini-grid policies and sizing in rural East Africa should consider the varying electricity needs and influencing factors among different customer groups and areas. On a multiple linear regression, Sena *et al.* (2021) analyzed the determinants of Malaysian electricity consumption from November 2017 to January 2018 among 214 university students. The findings of the study indicate that air conditioners, fluorescent lamps, and flat-screen TVs are the most significant determinants of electricity consumption.

In ASEAN countries, Ismail *et al.* (2017) investigated the determinants of electricity consumption using VAR and VECM models from 1980 to 2015. The findings of the Granger causality model revealed bidirectional causality running from electricity consumption to GDP, exports, and CO₂ emissions. The authors recommend that ASEAN ought to consider various factors when formulating their electricity policy, as electricity influences and is simultaneously influenced by other elements and must seek to manage CO₂ emissions through electricity consumption. In the context of Greece, the determinants of household electricity consumption were examined by Kotsila and Polychronidou (2021) among 1801 dwellings using Two-stage OLS and log-linear regression models.

The findings of the study revealed that the most significant determinants of electricity consumption are the number of occupants, the size of the dwelling, the heating type, the heating and cooling hours, and weather conditions. The authors recommend that the government and utilities improve and encourage the use of modern technology and electrical devices, like smart appliances and those with A++ energy labels, which consume less electricity.

The relationship between electricity consumption and its significant determinants in Pakistan was examined by Zaman *et al.* (2015) using a multivariate VECM Granger causality model from 1972 to 2012. The study's findings indicated that economic growth and the number of electricity customers are positively linked to electricity consumption, while electricity prices and electricity shortages are negatively related to electricity consumption. The authors recommend that it is essential to reassess the electricity pricing policy and explore alternative renewable sources for producing low-cost electricity, in addition to improving energy management skills to handle the crisis effectively. Moreover, in Pakistan, the determinants and forecasting of electricity consumption were examined by Wahid *et al.* (2021) using OLS and ARIMA models from 1970 to 2018. The study's findings revealed that GDP and population growth are positive determinants of electricity consumption, while electricity prices are negative determinants of electricity consumption. The authors recommend that a detailed initiative for both short- and long-term projects must be launched to produce electricity from solar and wind sources involving the private sector.

The macroeconomic factors that determine electricity consumption in Greece were identified by Azam *et al.* (2016) using a VECM model from 1975 to 2013. The findings of the study indicate that infrastructure, trade, income, population growth, foreign direct investment, and urbanization are the main determinants of electricity consumption in Greece. The authors conclude that the findings of the study indicate that to meet the country's energy requirements, policymakers must develop energy strategies that prioritize increasing the supply of energy, particularly renewable energy, to promote economic growth and development. Among Ghanaian households, appliance ownership and electricity consumption determinants were investigated by Sakar *et al.* (2019) using multiple linear regression in Tema City. The study's findings indicate that energy efficiency, income levels, household size, floor area, air conditioners, freezers, fans, refrigerators, and televisions are the determinants of electricity consumption. This study lays a strong groundwork for creating more customized energy-saving policy measures focused on households.

Using quantile regression, Kostakis (2020) provides empirical evidence of Greece's regional, socioeconomic, and demographic determinants of electricity consumption. The study's findings indicate that disposable income, educational level, age, and the number of employed members are positive determinants of electricity consumption. The author highlights that it is crucial to establish policies to enhance efficient electricity usage and safeguard the environment while ensuring society's welfare is not compromised. By employing a Tobit model, Zou and Luo (2019) analyzed the determinants of Chinese rural energy consumption based on a survey of 1472 rural households. Findings indicate that rural families led by healthy and elderly heads decrease their coal usage, while household members with off-farm employment, higher education, and larger family sizes tend to increase their utilization of LPG and electricity. The favorable economic status of rural families aids in decreasing biomass usage. Based on the outcomes, the government ought to focus on alleviating poverty, providing subsidies for the purchase of modern equipment, implementing policies for effective renewable energy technologies, and investing in education in rural regions, which could facilitate a favorable shift in energy consumption for rural households. Monyei *et al.* (2019) argue that governments and policymakers in the global south should adopt a quantitative-based policy framework for electrification schemes indicating the inability of the qualitative-based policy framework when it comes to issues of sustainable electricity. This indicates the importance of policies backed by having tangible benchmarks that are nationally agreed to be crucial when it comes to sufficient electricity access and mobility.

2.2. South African context

In South Africa, the determinants of household electricity consumption were investigated by Ye *et al.* (2018) using two-part and OLS models on data from September 2010 to August 2011. The study's findings indicated that household income and electricity prices are the significant determinants of consumption in South Africa. Further results showed that increased electricity prices reduce electricity consumption while increased household income leads to increased electricity consumption. The authors recommend that further research is needed to uncover the impact of rolling out the national electricity grid on household electricity use and other forms of energy. The determinants of electricity demand by South African households per income level were investigated by Bohlmann and Inglesi-Lotz (2021) using an ARDL model on data from 1975 to 2016. The findings of the study revealed that disposable income increases electricity consumption while

electricity prices reduce electricity consumption in South Africa. The authors recommend that a price mechanism be used to reduce electricity consumption in South Africa, yielding to the efforts to reduce greenhouse gas emissions since South Africa relies much on non-renewable electricity.

Using a Logistic regression, Ismail and Khembo (2015) investigated the determinants of energy poverty in South Africa. The study results indicated that household expenditure, race, education level, household size, location of household, and access to electricity are the key determinants of electricity consumption in South Africa. The authors recommend that more accurate results can be obtained by incorporating the pricing of electricity and the quantity of different energy sources in future research. Using a panel data approach, Sehlapelo and Inglesi-Lotz (2022) examined the determinants of electricity consumption in nine South Africans using fixed effects and PMG from 1995 to 2019. The study's findings revealed that CPI is a positive determinant while the population is a negative determinant of electricity consumption in South Africa. The authors highlight that electricity generation switches to renewable energies with higher flexibility in location and size. The distribution network will tend to each region's electricity needs more appropriately.

Ateba et al. (2019) investigate the significance of electricity supply sustainability to industrial growth in South Africa mainly focusing on Gauteng and North West provinces. The study's findings indicated that unsustainable electricity supply has a negative impact on industrial growth and recommended that the public sector should apply a good governance framework to ensure policies that prioritize sustainable electricity supply. From the literature above, the study has also identified gaps in terms of nonlinear studies in South Africa focusing on the determinants of electricity consumption. As a result, this study will employ the Threshold Autoregressive (TAR) model to capture nonlinear relationships.

3 Methodology and data collection

3.1. Data collection, variable description and sources

The study relies on a quantitative research approach. The main objective of this study is to investigate the determinants of electricity consumption in South Africa using data collected from reputable secondary online statistical sources such as Eskom and Global Economy, spanning from 1980 to 2023. The study will estimate both linear and nonlinear relationships, and variables that are not in percentages will be transformed into logarithms to avoid spurious regressions. The study will make use of EViews 10 and Stata 18 econometric estimation software.

Table 1: Data collection and sources

Variables	Description	Unit	Source
EC	Electricity consumption	Billion kilowatt-hours	Global Economy
EG	Economic growth	Rate of change in real GDP	Global Economy
INF	Inflation	Percentage change in CPI	Global Economy
POP	Population growth	Percentage	Global Economy
EP	Electricity Price	Real price increase percentage	Eskom
Y	Income	GDP per capita constant dollars	Global Economy

Source: Author's compilation

3.2. Theoretical framework and model specification

The main objective of the study is to investigate the determinants of electricity consumption in South Africa from 1980 to 2023 using time series data. The study relies on the energy demand theory, which states that energy demand is influenced by factors such as income, prices, and technology. Medlock (2009) advocated for the energy demand theory, and Hasanov and Mikayilov (2020) later modified the theory to suit specific research objectives. The theoretical foundation for deriving the functional specifications of energy demand requirements for companies that manufacture goods and services is linked to the Cobb-Douglas production function developed by Cobb and Douglas (1928). Linking output to the factors of production is expressed as follows for this study:

$$Q = AK^{\alpha}L^{\beta}E^{\gamma}M^{\delta} \quad (1)$$

Where Q, K, L, E, and M are output, capital, labor, energy consumption, and materials, respectively; α, β, γ and δ are positive constants. Based on this Cobb-Douglas specification as per Hasanov and Mikayilov (2020), this study reduced and modified the energy demand equation to fit the objective of the study, and the variables chosen can be specified as follows transformed into logarithms:

$$LEC = \alpha_1 + \alpha_2 LEP + \alpha_3 LY + \alpha_4 LPOP + \alpha_5 LEG + \alpha_6 LINF + \varepsilon_t \quad (2)$$

Where LEC refers to logged energy consumption, LEP is the electricity price, LY is the income, LPOP is population growth, LEG is economic growth, LINF is inflation, and ε_t is the error term.

3.3. Estimation techniques

3.3.1. Unit Root Test

The study performs the time series KPSS unit root test of Kwiatkowski *et al.* (1992) and the ADF unit root of Dickey and Fuller (1981). These unit root tests assist in identifying whether a time series is stationary or non-stationary. A unit root test signifies that a series is non-stationary, requiring differentiation to achieve stationarity. The null hypothesis of the ADF test is that the series has a unit root. Said and Dickey (1984) augmented the DF unit root, which is specified as follows:

$$\Delta y_t = \beta' \mathcal{D}_t + \pi y_{t-1} + \sum_{j=1}^p \psi_j \Delta y_{t-j} + \varepsilon_t \quad (3)$$

Where $\pi = \phi - 1$. The null hypothesis of the KPSS stationarity test is that an observable time series is stationary around a deterministic trend against the alternative of a unit root. The KPSS unit root test is specified as follows:

$$KPSS = (T^{-2} \sum_{t=1}^T \hat{S}_t^2) / \hat{\sigma}^2 \quad (4)$$

Where $\hat{S}_t = \sum_{j=1}^t \hat{u}_j$. The study continues to estimate nonlinear relationships as specified below in Section 3.3.2.

3.3.2. Nonlinearity test

One of the study's research questions is to check for the possibility of nonlinearity between electricity consumption and its determinants. To answer this question, the study will estimate the BDS nonlinearity test proposed by Brock, Dechert, and Scheinkman (1987). The null hypothesis of the BDS test is that the data in a time series is independently and identically distributed (iid). The BDS test can be specified as follows:

$$BDS_{\varepsilon, m} = \frac{\sqrt{N} [C_{\varepsilon, m} - (C_{\varepsilon, 1})^m]}{\sqrt{V_{\varepsilon, m}}} \quad (5)$$

We should reject the null hypothesis if the BDS test statistic is greater than or less than the critical values, that is, $\alpha = 0.05$ and the critical value = ± 1.96 .

3.3.4. Cointegration test

The study will perform the Johansen cointegration test to answer the question of whether there are long-run relationships between electricity consumption and its determinants in South Africa. The Johansen cointegration test was developed by Johansen (1988, 1991, 1995, 2002, 2009) and checks for the possibility of long-run relationships using Trace and Maximum Eigenvalue tests. The model specified by Johansen (2002) is adopted from Engle and Granger (1987) and is specified as follows:

$$\mathcal{M}_1: \Delta X_t = \Pi X_{t-1} + \Upsilon t^{n_d} + \sum_{i=1}^{k-1} \Gamma_i \Delta X_{t-i} + \sum_{i=0}^{n_d-1} \Phi_i t^i + \varepsilon_t \quad (t = 1, \dots, T) \quad (6)$$

If X_t is $I(1)$ and $\Pi = \alpha\beta'$, then $\beta'X_t - E[\beta'X_t]$ is stationary, and X_t is considered to cointegrate with a cointegrating vector β . Johansen (2002) further alludes that "Under the assumption of Gaussian errors, the derivation of the likelihood ratio (LR) test for the hypothesis $\Pi = \alpha\beta'$ and $Y = \alpha\beta'$, the so-called trace test and the estimation of the parameters are performed by the technique of reduced regression."

3.3.5. Dynamic-OLS and Canonical Cointegrating Regression Models

The study will employ the Dynamic Ordinary Least Squares (DOLS) formulated by Stock and Watson (1993) to estimate short-run relationships between electricity consumption and its determinants. The DOLS models are specified as follows:

$$C_t = B'X_t + \sum_{j=-J}^{j=J} \eta_j \Delta P_{t-j} + \sum_{j=-K}^{j=K} \lambda_j \Delta Y_{t-j} + \xi_t \quad (7)$$

Where $B = [c, \alpha, \beta]'$ and $X = [1, P_t, Y_t]$. According to Masih *et al.* (1996), "the DOLS procedure involves regressing and I(1) on other I(1) variables, and I(0) variables, and leads and lags of the first differences of any I(1) variables."

This model can estimate the effect of independent variables on a dependent variable when the variables are non-stationary but cointegrated. The DOLS is better than other estimators in small samples, it accommodates higher orders of integration and accounts for the possibility of simultaneity within regressors. Furthermore, the study will estimate the Canonical Cointegrating Regression specified by Park (1992) and later modified by Choi *et al.* (1997) to estimate long-run relationships among electricity consumption and its determinants in South Africa. The feasible CCR estimate of the coefficient vector $\beta = (\gamma', \alpha')$ is obtained by running the transformed OLS regressions on:

$$\bar{y}_t = \beta' \bar{q}_t + \bar{u}_t \quad (8)$$

Where $\bar{q}_t = (f'_t, \bar{x}'_t)'$ and \bar{y}_t and \bar{x}_t denote the transformed time series. The study will perform a robustness check using the Threshold Autoregressive model as presented in Section 3.4 below.

3.4. Robustness check

The study will estimate the nonlinear relationships between electricity consumption and its determinants using a Threshold Autoregressive (TAR) model developed by Tong and Lim (1980). By estimating the TAR model, the study will answer the question of checking asymmetrical relationships between electricity consumption and its determinants in South Africa, as well as robustness checks. The TAR model is chosen due to its ability to check the impact of certain variables above a threshold impact of variables such as income. The general form of TAR models is specified as follows:

$$Y_t = \begin{cases} \phi_1 + \phi_{11}Y_{t-1} + \phi_{12}Y_{t-2} + \dots + \epsilon_t, & \text{if } Z_{t-d} \leq \gamma \\ \phi_2 + \phi_{21}Y_{t-1} + \phi_{22}Y_{t-2} + \dots + \epsilon_t, & \text{if } Z_{t-d} > \gamma \end{cases} \quad (9)$$

Where Y_t is the dependent variable, Z_{t-d} is the threshold variable, γ is the threshold value, ϕ_1 and ϕ_2 are the intercept terms of each regime, $\phi_{11}, \phi_{12}, \phi_{21}, \phi_{22}$ are the autoregressive coefficients for each regime, and ϵ_t is the error term.

A TAR model is a nonlinear approach that employs regimes divided by thresholds representing behaviors that linear time series models are unable to capture. TAR model has the following characteristics: It facilitates asymmetric behavior that a single ARMA model cannot account for, the system is defined by a specific variable about a threshold value, it can be estimated through methods like conditional least squares or minimum AIC, finally analyzing residuals can be utilized for model diagnostics.

4. Results, interpretations, and discussions

4.1. Descriptive analysis

From the data presented in Table 2 above, electricity consumption, economic growth, and income are negatively skewed, while electricity prices, inflation, and population growth are positively skewed. The kurtosis indicates that electricity consumption, inflation, population growth, and income are platykurtic, while economic growth and electricity prices are leptokurtic. The Jarque-Bera statistic indicates that electricity prices may not have a normal distribution at a 5% significance level; however, this does not pose a threat to the current study since it assumes the normality of the residuals from the estimated model. The study conducted correlation analysis as presented in Section 4.2 below.

Table 2: Descriptive statistical analysis

Variable	LEC	LEG	LEP	LINF	LPOP	LY
Mean	5.166485	2.066136	7.529091	8.450000	1.692045	8.576585
Median	5.284176	2.400000	6.210000	6.950000	1.315000	8.580941
Maximum	5.461031	6.620000	34.20000	18.70000	3.500000	8.742431
Minimum	4.448750	-5.960000	-14.60000	-0.700000	0.390000	8.359299
Std. Dev.	0.273209	2.511806	9.272800	4.575186	0.863418	0.129414
Skewness	-0.875423	-0.698194	0.801710	0.465718	0.783603	-0.147280
Kurtosis	2.757158	3.805658	4.453025	2.262839	2.288316	1.565205
JB-Stat	5.728124	4.764798	8.584099	2.586793	5.431483	3.933238
Prob	0.057037	0.092329	0.013677	0.274337	0.066156	0.139929
Observation	44	44	44	44	44	44

Source: Author's computation

4.2. Correlation analysis

The study conducted a correlation analysis between electricity consumption and its determinants, as shown in Table 3 above. The findings indicate that inflation and population growth are negatively correlated with electricity consumption, while economic growth, electricity prices, and income are positively correlated with electricity consumption. The coefficients of correlation are less than 0.9, indicating that there are weaker linear relationships between electricity consumption and its determinants. The study conducts unit root tests, as presented in Section 4.3 below, to determine the order of integration of the variables.

Table 3: Correlation analysis

Variable	LEC	LEG	LEP	LINF	LPOP	LY
LEC	1.000000					
LEG	0.052235	1.000000				
LEP	0.593123	-0.255425	1.000000			
LINF	-0.813991	-0.192619	-0.339934	1.000000		
LPOP	-0.789326	-0.140274	-0.423283	0.854663	1.000000	
LY	0.513815	0.039539	0.381611	-0.453663	-0.387644	1.000000

Source: Author's computation

4.3. Unit root test

Table 4: Unit root analysis

Variables	Augmented Dickey-Fuller				Kwiatkowski-Phillips-Schmidt-Shin			
	Without Trend		Trend		Without Trend		Trend	
	Level	Δ	Level	Δ	Level	Δ	Level	Δ
LEC	-4.4478 ***	-6.4346 ***	0.0588	-8.9256 ***	0.7339 **	0.7861 ***	0.2126 **	0.0723
LEG	-5.3002 ***	-8.9483 ***	-5.2243 ***	-8.8505 ***	0.1528	0.2282	0.1427 *	0.1779 **
LEP	-3.3977 **	-7.7704 ***	-3.8471 **	-7.6378 ***	0.5588 ***	0.1107	0.0737	0.0796
LINF	-0.9390	-5.7799 ***	-0.9521	-5.7436 ***	0.6574 **	0.3683 *	0.1769 **	0.3334 ***
LPOP	-1.0424	-5.6445 ***	-1.4349	-5.5755 ***	0.5859 **	0.0884	0.1397 *	0.0830
LY	-0.7811	-4.4328 ***	-2.5784	-4.6483 ***	0.5175 **	0.2687	0.1475 **	0.1740 **

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

The study has conducted the ADF and KPSS unit root tests as presented in Table 4 above to avoid spurious regressions and help identify the order of integration of the variables for the selected models. The results of both tests indicate that the variables are stationary at first difference except for electricity consumption, economic growth, and electricity prices which are significant at the level form $I(0)$. The results do not affect the selected models such as DOLS, CCR, and TAR as they can deal with variables that are integrated into different orders. The study conducted the nonlinearity tests as presented in Section 4.4 below to check for the possibility of nonlinearity between electricity consumption and its determinants in South Africa.

4.4. BDS Nonlinearity test

Table 5: Brock, Dechert, and Scheinkman (1987) Nonlinearity results

Variables	Dimensions	BDS Statistics
LEC	2	0.198004***
	3	0.341188***
	4	0.438927***
	5	0.502932***
	6	0.542149***
LEG	2	0.040165***
	3	0.066686***
	4	0.064083***
	5	0.029076
	6	0.035704*
LEP	2	0.086368***
	3	0.155894***
	4	0.191057***
	5	0.218529***
	6	0.224170***
LINF	2	0.132525***
	3	0.232906***
	4	0.303523***
	5	0.345689***
	6	0.367729***
LPOP	2	0.171053***
	3	0.286043***
	4	0.360195***
	5	0.411909***
	6	0.441787***
LY	2	0.165516***
	3	0.273888***
	4	0.341668***
	5	0.380111***
	6	0.386230***

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

The study conducted the BDS nonlinearity test of Brock, Dechert, and Scheinkman (1987) to check for the possibility of nonlinear relationships among the variables presented in Table 5 above as part of answering one of the research questions. The results of the BDS reveal that there are nonlinear relationships among the selected determinants of electricity consumption in the model since we fail to accept the null hypothesis that there are linear relationships among the variables. We, therefore, conclude that the study will also test for nonlinear relationships using a Threshold Auto Regressive (TAR) model since electricity consumption can exhibit nonlinear relationships with its determinants, such as income and electricity prices. The study uses the optimal lag selection criterion presented in Section 4.5 below.

4.5. Optimal Lags Selection

Table 6: Optimal Lag Selection

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-301.4769	NA	0.131555	14.99887	15.24964	15.09019
1	61.77063	602.4594*	1.570008*	-0.964421	0.790945*	-0.325213*
2	93.48930	43.32306	2.170008	-0.755575	2.504391	0.431525
3	134.8813	44.42066	2.300008	-1.018599*	3.745967	0.716393

Source: Author's computation (*) selected number of lags per criterion

The study used the optimal lags selection criterion presented in Table 6 above to select the optimal number of lags to deploy in the study. The result of the AIC revealed 3 lags, whereas the results of the SC criterion revealed that only 1 lag might be utilized in the model. The study will rely on the SC criterion since it is more potent than the AIC criterion. The study continues to check for the possibility of long-run relationships, as presented in Section 4.6 below.

4.6. Cointegration test

Table 7: Johansen Cointegration test

Test	Trace		Maximum Eigenvalue	
	Eigenvalue	Probability	Eigenvalue	Probability
None	0.731819	0.0000***	0.731819	0.0008***
At most 1	0.665383	0.0000***	0.665383	0.0017***
At most 2	0.428553	0.0021**	0.428553	0.1759
At most 3	0.359843	0.0051***	0.359843	0.1194
At most 4	0.275670	0.0125**	0.275670	0.0725*
At most 5	0.138773	0.0133**	0.138773	0.0133**

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

The study conducted the Johansen cointegration test, as shown in Table 7 above, to check for the possibility of long-run relationships among electricity consumption and its determinants. The findings of the Trace and Maximum Eigenvalue tests indicate cointegration relationships between electricity consumption and its determinants in South Africa. Therefore, we conclude that there are long-run relationships between electricity consumption and its determinants, and the study will estimate both short-run and long-run determinants of electricity consumption. The study conducts short and long-run analysis of the determinants of electricity consumption in South Africa as presented in Section 4.7 below, using DOLS and CCR models, respectively.

4.7. Short and long-run analysis of the determinants of electricity consumption in south africa

4.7.1. Dynamic ordinary least squares and canonical cointegration regression results

Table 8: Short-run DOLS and long-run CCR results

Variables	DOLS		CCR	
	Coefficient	Probability	Coefficient	Probability
LEG	-0.789878	0.4026	1.712249	0.0000***
LEP	0.008773	0.0181**	-0.321338	0.0000***
LINF	-0.029154	0.1406	-0.069280	0.0000***
LPOP	0.812555	0.3964	-0.411782	0.0000***
LY	0.624869	0.0000***	0.755157	0.0000***

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

4.7.1.1. Short-run relationships

The short and long-run analyses of electricity consumption and its determinants in South Africa from 1980 to 2023 are presented in Table 8 above using the DOLS and CCR models, respectively. Considering the short-run relationships from the DOLS model, the findings indicate a significant positive impact of electricity prices on electricity consumption at a 5% significance level. A 1% increase in electricity prices in the short run is associated with a 0.01% rise in electricity consumption, *ceteris paribus*. Though the impact is not that huge, these results imply that increases in electricity prices are reasonable for electricity consumption in South Africa; therefore, they cannot be used as an instrument to reduce electricity consumption in the short run. These results are inconsistent with the studies of Ye *et al.* (2018), Bohlmann and Inglesi-Lotz (2021), Al-Bajjali and Shamayleh (2018), Zaman *et al.* (2015), and Wahid *et al.* (2021) that found electricity prices to be detrimental to electricity consumption.

Moreover, the results indicate a significant positive impact of income on electricity consumption in South Africa. A 1% increase in income significantly increases electricity consumption by 0.62%, *ceteris paribus*. These results imply that income increases are suitable for electricity consumption in South Africa since more people will have more money to spend on electricity. These results are consistent with the studies of Kostakis (2020), Azam *et al.* (2016), Wassie and Ahlgren (2023), Ali *et al.* (2021), Huang (2015), Bohlmann and Inglesi-Lotz (2021), and Ye *et al.* (2018) that found income to increase electricity consumption. On the contrary, economic growth, inflation, and population growth are insignificant determinants of electricity consumption in the short run implying that they do not have an impact on electricity consumption during this period.

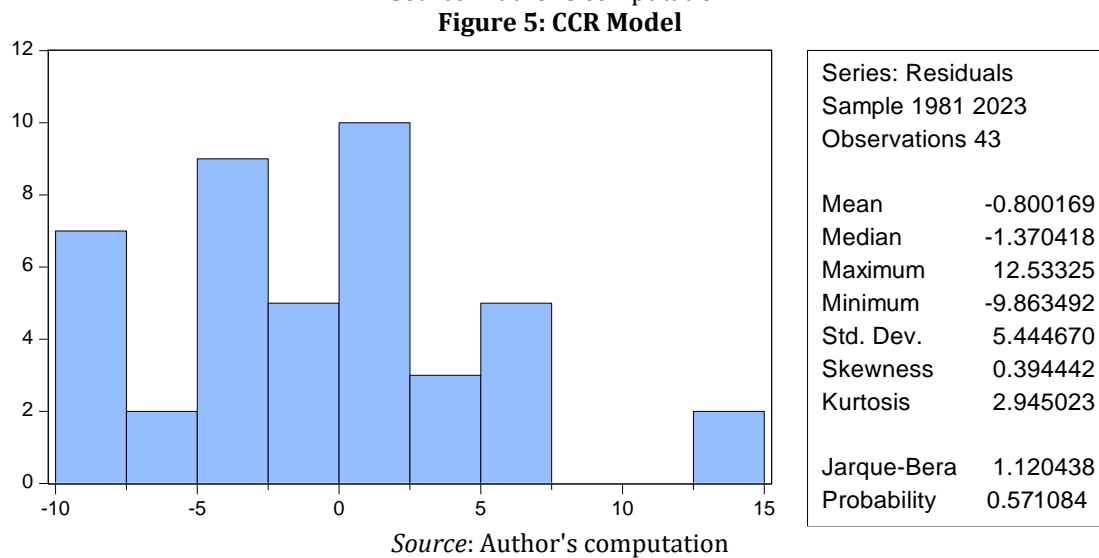
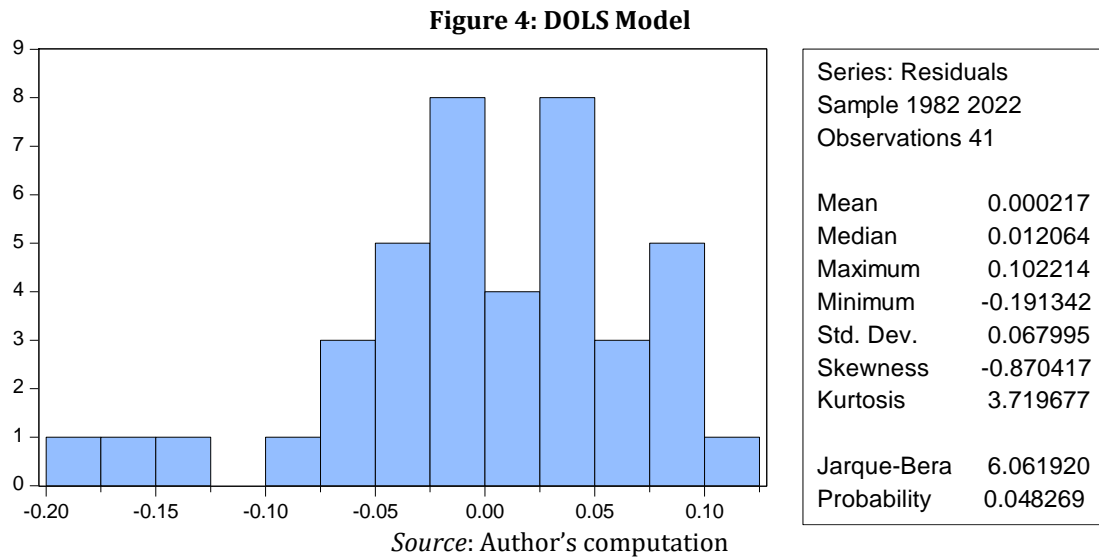
4.7.1.2. Long-run relationships

Furthermore, considering the long-run results of the CCR model, economic growth is associated with increases in electricity consumption in South Africa. A 1% increase in the long run significantly increases electricity consumption by 1.71%, *ceteris paribus*. These results entail that increases in economic growth result in more electricity consumption in South Africa, and this calls for policymakers and Eskom to have a sustainable electricity generation and supply to avoid electricity shortages and load shedding. These results are consistent with the studies of Al-Bajjali and Shamayleh (2018), Dokas *et al.* (2022), Sharma and Kautish (2019), Ismail *et al.* (2017), and Zaman *et al.* (2015) that found an increase in economic growth resulting in more electricity consumption. The results further reveal that income is positively associated with electricity consumption in South Africa in the long run. A 1% increase in income significantly results in electricity consumption rising by 0.76%, *ceteris paribus*. These results imply that increasing income per capita in the country is suitable for electricity consumption as it gives people more buying power to spend on electricity. These results are consistent with the studies of Sakar *et al.* (2019), Kostakis (2020), Azam *et al.* (2016), Wassie and Ahlgren (2023), and Onisanwa and Adaji (2020) that found income to increase electricity consumption.

On the contrary, electricity prices are negatively associated with electricity consumption in South Africa in the long run. A 1% increase in electricity prices significantly results in electricity consumption declining by 0.32% at a 1% significance level, *ceteris paribus*. These results imply that rising electricity prices are detrimental to electricity consumption, and the government, policymakers, and Eskom can utilize electricity prices as an instrument to reduce electricity consumption in the long run. These results are consistent with the studies of Ye *et al.* (2018), Bohlmann and Inglesi-Lotz (2021), Al-Bajjali and Shamayleh (2018), Zaman *et al.* (2015), and Wahid *et al.* (2021) that found electricity prices to be detrimental to electricity consumption. Moreover, the results indicate that population growth is associated with a reduction in electricity consumption in South Africa in the long run. A 1% increase in population growth significantly results in electricity consumption declining by 0.41% at a 5% significance level, *ceteris paribus*. These results imply that population growth is detrimental to electricity consumption, and this might be because of urbanization and energy efficiency practices. These results are inconsistent with the studies of Al-Bajjali and Shamayleh (2018), Ismail and Khembo (2015), Dokas *et al.* (2022), Kwakwa (2018), Onisanwa and Adaji (2020), and Wahid *et al.* (2021) that found population growth to be positively associated with electricity consumption, while consistent with the study of Sehlapelo and Inglesi-Lotz (2022) who found that population growth is negatively related to electricity consumption in South Africa.

Moreover, the results reveal that inflation is negatively associated with electricity consumption at a 5% significance level in South Africa. A 1% increase in the inflation rate significantly results in electricity consumption declining by 0.07%, *ceteris paribus*. The result implies that inflation is detrimental to electricity consumption in South Africa, and this is expected from economic theory, which assumes inflation erodes purchasing power, so people and businesses may find it expensive to purchase more electricity. These results are inconsistent with the studies of Sehlapelo and Inglesi-Lotz (2022), who found inflation to be positively associated with electricity consumption in South Africa. The study performs the residuals normality test as presented in Section 4.7.2 below.

4.7.2. Residuals diagnostics test



The normality diagnostics test of the DOLS and CCR model is presented above in Figures 4 and 5. The DOLS and CCR diagnostics test has probability values that are insignificant at a 5% significance level, indicating that the residuals from the models are normally distributed. We, therefore, conclude that the results from the model are reliable for policy formulation. The study conducts robustness checks, as presented in Section 4.8 below.

4.8. Robustness check

4.8.1. Nonlinear relationships

Table 9: Threshold Auto Regressive (TAR) Model

Variables	Regime 1: LY<8.527719		Regime 2: LY>8.527719	
	Coefficient	Probability	Coefficient	Probability
LEG	0.029440	0.0179**	0.017172	0.2480
LPOP	-0.136994	0.0032***	-0.196166	0.0172**
LEP	0.003242	0.4323	0.013634	0.0443**
LINF	0.007824	0.4761	-0.026521	0.0155**
C	5.190584	0.0000***	5.487620	0.0000***
R ²				0.962540
Adjusted R ²				0.944456

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

The study has employed the Threshold Autoregressive (TAR) model to capture nonlinear relationships between electricity consumption and its determinants in South Africa, as proven by the results of the BDS nonlinearity test proving that there are nonlinear relationships among the variables. Considering the TAR results presented in Table 9 above, in Regime 1, the period of low income, a 1% increase in economic growth is associated with electricity consumption rising by 0.03%, *ceteris paribus*. These results imply that during periods of higher per capita income, an increase in economic growth results in more electricity being demanded in the economy. These results are consistent with the studies of Al-Bajjali and Shamayleh (2018), Dokas *et al.* (2022), Sharma and Kautish (2019), Ismail *et al.* (2017), and Zaman *et al.* (2015) that found an increase in economic growth resulting in more electricity consumption. Population growth is negatively associated with electricity consumption in both regimes. A 1% increase in population growth is significantly associated with electricity consumption declining by 0.14% and 0.20% in regimes 1 and 2, respectively, *ceteris paribus*. The results imply that in the regime of low income and higher income, population growth is detrimental to electricity consumption; however, the impact is enormous in regime 2 of higher income per capita. These results are inconsistent with the studies of Al-Bajjali and Shamayleh (2018), Ismail and Khembo (2015), Dokas *et al.* (2022), Kwakwa (2018), Onisanwa and Adaji (2020), and Wahid *et al.* (2021) that found population growth to be positively associated with electricity consumption, while consistent with the study of Sehlapelo and Inglesi-Lotz (2022) who found that population growth is negatively related to electricity consumption in South Africa.

Furthermore, the results indicate that electricity prices are positively associated with electricity consumption in regime 2 of higher income in South Africa. A 1% increase in electricity prices significantly raises electricity consumption by 0.01%, *ceteris paribus*. These results show that electricity prices are not detrimental to electricity consumption, and as a result, the government, policymakers, and Eskom cannot utilize electricity prices as instruments to reduce electricity consumption in South Africa. These results are inconsistent with the studies of Ye *et al.* (2018), Bohlmann and Inglesi-Lotz (2021), Al-Bajjali and Shamayleh (2018), Zaman *et al.* (2015), and Wahid *et al.* (2021) that found electricity prices to be detrimental to electricity consumption. Conversely, inflation is negatively associated with electricity consumption in regime 2 of high per capita income. A 1% increase in inflation significantly results in electricity consumption declining by 0.03%, *ceteris paribus*. These results imply that inflation is detrimental to electricity consumption in South Africa; even during periods of higher income, electricity consumption is reduced mainly by eroding purchasing power parity. These results are inconsistent with the studies of Sehlapelo and Inglesi-Lotz (2022), who found inflation to be positively associated with electricity consumption in South Africa. The study conducts the residual diagnostics tests as presented in Section 4.8.2 below.

4.8.2. Residuals diagnostics test

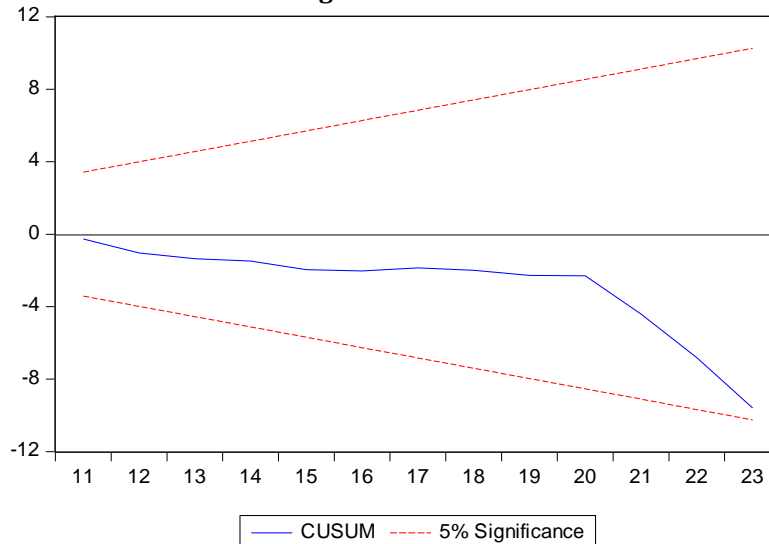
Table 10: Residual diagnostics test

Test	Probability	Interpretation
Breusch-Pagan-Godfrey Heteroskedasticity	0.1520	Residuals are homoscedastic
Breusch-Godfrey LM Serial correlation	0.0988	No serial correlation
Ramsey RESET Test	0.6484	Model correctly specified
Jarque Bera Normality Test	0.5093	The residuals are normally distributed

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

The study conducted the residual diagnostics tests of the estimated model, as shown in Table 10 and Figure 6 above. The findings indicate that the model does not suffer from heteroskedasticity, serial correlation, misspecification, and normality problems since the probabilities are insignificant to reject the null hypotheses. The results of the CUSUM indicate that the model is stable since the red line is within the 5% critical boundaries. We, therefore, conclude that the model estimated, and results obtained are reliable for policymaking.

Figure 6: CUSUM



5. Discussions, limitations, recommendations and conclusion

This study investigated the determinants of electricity consumption in South Africa from 1980 to 2023, employing both linear and nonlinear modeling approaches. Our findings reveal complex relationships between electricity consumption and various economic, demographic, and energy-related factors.

Key findings include:

Economic growth and income per capita positively influence electricity consumption, highlighting the strong link between economic development and energy demand. Electricity prices show a positive short-term but negative long-term relationship with consumption, suggesting different consumer responses over time. Unexpectedly, population growth negatively affects electricity consumption, possibly due to urbanization trends and energy efficiency improvements. Inflation negatively impacts electricity consumption, likely due to reduced purchasing power.

These results have significant implications for energy policy in South Africa: Policymakers must consider the multifaceted determinants of electricity consumption when formulating energy strategies. The positive relationship between economic growth and electricity consumption underscores the need for sustainable energy solutions to support continued economic development. The complex relationship between electricity prices and consumption suggests that pricing mechanisms alone may not be sufficient to manage demand. The negative impact of population growth on consumption warrants further investigation into urbanization patterns and energy efficiency trends.

From a scientific perspective, this study contributes to the literature by: Employing both linear and nonlinear models to capture complex relationships in electricity consumption dynamics. Providing empirical evidence on the determinants of electricity consumption in a developing country context. Highlighting the importance of considering asymmetric effects and regime changes in energy consumption analysis.

While our study provides valuable insights, it has limitations. Future research could benefit from: Incorporating disaggregated data to capture regional and sectoral variations in electricity consumption. Exploring additional variables such as technological advancements and climate factors. Conducting comparative analyses across different African countries to provide broader insights into electricity consumption patterns in developing economies.

In conclusion, understanding the determinants of electricity consumption is crucial for addressing South Africa's energy challenges and promoting sustainable development. Our findings provide a foundation for evidence-based policy decisions and highlight the need for a nuanced approach to energy management that considers the complex interplay of economic, demographic, and energy-related factors.

Funding

This research received no external funding.

Conflicts of interest

The author declares no conflict of interest.

Citation information

Hlongwane, N. W. (2025). Determinants of electricity consumption in South Africa: Insights from linear and nonlinear modeling approaches. *Economics, Management and Sustainability*, 10(1), 6-26. doi:10.14254/jems.2025.10-1.1.

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