FOSSIL FUEL CONSUMPTION IN SOUTH AFRICA: THE ROLES OF RESOURCE RENTS, URBANIZATION, AND INDUSTRIALIZATION DURING THE YEARS 1990–2019

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Abstract

South Africa represents a unique case in the developing world: it is the most industrialized economy in Sub-Saharan Africa, heavily dependent on coal and fossil fuels despite its rich natural resource endowment, and simultaneously undergoing rapid urbanization and structural transformation. Understanding the macroeconomic drivers of fossil-fuel demand is therefore essential for designing sustainable energy policies. This study investigates how natural resource rents, urbanization, industrialization and total factor productivity affect fossil fuel consumption in South Africa using annual data for the period 1990–2019. ADF and Fourier ADF unit root tests are employed to account for non-stationarity and structural breaks, while the Fourier ADL cointegration test is used to examine long-run relationships. Long-run coefficients are then estimated through FMOLS and CCR methods. The results show that natural resource rents, urbanization and industrialization increase fossil fuel consumption, whereas higher total factor productivity reduces it. These findings imply that South Africa's energy demand is driven by deep-seated structural features rather than short-term fluctuations. Policy implications point to three priorities: modernizing energy-intensive industrial structures, managing urban growth more efficiently and fostering productivity-enhancing investments to support a gradual decoupling of economic growth from fossil-fuel use.

Keywords: Natural Resource Rents, Urbanization, Total Factor Productivity, Industrialization, Fossil fuel use, South Africatransformation in agriculture

1. INTRODUCTION

Global energy consumption has also increased dramatically along with industrialization, urbanization, and the global market economy, resulting in a large rise in the use of fossil fuels. This increasing dependence on fossil fuels raises serious questions relating to environmental sustainability, especially in developing countries with a significant share of non-renewables in their energy mix. South Africa is also unique in that it has a large natural resource endowment, is an industrial-based country and the increasing urbanising of its population. Yet, here arise doubts regarding both energy security and environmental and climatic concerns that require reconsideration of the national energy strategy. Therefore, knowing the major determinants of fossil fuel consumption is important to design proper and sustainable energy policy.

The study seeks to achieve the following objective: to investigate empirically the factors that determine the consumption of fossil fuels in South Africa. It uses annual time series data during 1990-2019 to examine the influence of macroeconomic factors like natural resource rents, urbanization, total factor productivity, and industrialization on fossil fuel consumption. It does so by using state-of-the-art econometric methods to allow for structural breaks and non-linear trends including the Fourier Augmented Dickey–Fuller (ADF) unit root for common trends and the Fourier ADL cointegrating tests. Long-run and short-run coefficient values are estimated with Fully Modified Ordinary Least Squares (FMOLS) and Canonical Cointegrating Regression (CCR) methods respectively for robust policy inferences.

This analysis makes a theoretical and empirical contribution by indicating the macroeconomic determinants of fossil fuel consumption in developing countries. The results are also intended to contribute to the national energy policy through the understanding of economic and structural transformations and resulting impacts on energy demand. This will in turn help in decreasing

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reliance on fossil fuels and achieving environmentally sustainable growth, ensuring that energy policies are consistent with long-term development objectives.

South Africa has implemented several policy initiatives aimed at reducing the historical coupling between GDP growth and fossil-fuel demand, including revisions to the Integrated Resource Plan (IRP), renewable energy procurement programmes, electricity pricing reforms, and targeted industrial restructuring. However, persistent dependence on coal-based generation, supply instability at Eskom, slow technological upgrading, and investment bottlenecks have limited the effectiveness of these efforts. As a result, the gap between economic activity and energy demand remains significant. By identifying the macroeconomic drivers of fossil-fuel consumption using structural-break-robust time-series methods, this study directly addresses these policy gaps and provides empirical evidence to support more coherent and context-specific energy strategies for South Africa.

2. LITERATURE

Pata (2021) analyzed the effects of natural resource rents, globalization, and urbanization on environmental quality based on the EKC hypothesis for Turkey from 1971 to 2017. Applying the Fourier ARDL model, the study found out that natural resources rents and urbanization upsurge the long run ecological degradation. Of chief importance, the analysis endorsed the EKC theory, that is, the economic growth accelerates the environmental damage at once but would be better after certain level of income. These results exemplify that sustainable urban planning and resource management are highly needed (Pata, 2021).

Rafiq et al. (2022) explored the long-term relationship between FFC and urbanization, industrialization, and income in China during the period from 1980 to 2019. To examine long-run cointegration, ARDL bounds testing was used in the study. The results showed that the role of industrialization and urbanization is to significantly increase fossil fuels, non-linear effects of per capita income. These results provide support for the argument that structural transformation in the economy is highly influential in determining energy demand (Rafiq et al., 2022).

Zhang and Cheng (2009) have studied the relation of causality among the Energy consumption, Economic growth and CO_2 emissions in case of China over a reported period from 1960 to 2007. They employed Granger causality, and cointegrationtests, and found one-way causality running from energy consumption to GDP. They emphasised the dilemma of between energy-saving policies and the development process in the developing countries.

Sadorsky (2010) studied the influence of urbanization on energy consumption in developing countries, based on panel cointegration methodology and Generalized Method of Moments (GMM) estimation by spanning over 1980–2005. The research showed that energy demand surges as countries urbanize, especially in fast-urbanizing Asian and Latin American nations. The results highlight the importance of infrastructure development and urban form in mitigating fossil fuel use in these areas. Urbanisation trajectory should be taken into account in energy policy to properly manage demand (Sadorsky, 2010).

Shahbaz et al. (2013) analysed the nexus between fossil-fuel energy consumption, C O 2 emissions, and economic growth in South Africa during 1965Y2009. With an ARDL bounds testing the long commercial relationship between these units was found. Their analysis established that fossil fuel energy use and economic growth are drivers for higher emissions – pointing towards a South African growth path that is energy hungry. The authors argued for dominant use of renewable sources of energy consumption for the disengagement of emissions from growth (Shahbaz et al., 2013).

Al-Mulali and Che Sab (2012) analyzed the effects of fossil fuel consumption on environmental degradation in the 30 largest energy consuming nations from 1980 to 2009. Employing panel cointegration and causality tests, they observed an evidence of a strong positive relationship between fossil fuel consumption and CO_2 emissions. They also pointed out that economic growth correllates closely with emissions and stressed the need for combined energy and economic policies and more diversified sources of energy.

Destek and Sarkodie (2019) also investigated the EKC hypothesis, considering 24 OECD countries for the time period between 1990 and 2015, introducing variables like globalization, renewable energy, and urbanization in the analysis. They analyzed with the panel quantile regression that bilateral urbanization and fossil fuel encourage CO 2 emissions in all quantiles. Yet, renewable energy reduces emissions, and so there are grounds for its integration into national energy mixes. The EKC was supported in the upper quantiles, in which income mitigates emissions (Destek & Sarkodie, 2019).

Acheampong (2018) focused on the dynamic effects of fossil fuel energy consumption, renewable energy consumption and economic growth on CO_2 emissions in 116 countries for the period 1990-2014. The study validated that fossil fuel consumption is positively associated with emissions and renewable energy negatively associated with it using panel cointegration and FMOLS techniques. Growth, too, was an important explanatory factor, but had heterogeneous effects by regions. The author recommended context-specific policy treatments according to the stages of regional development (Acheampong, 2018).

Jebli et al. (2016) investigated the relationship between energy use from biomass, fossil fuel, openness in trade and CO2 emissions in between 80 and 2010. Based on panel cointegration and causality tests, the study confirmed that within the ASEAN the consumption of fossil fuel had a significant affecting on CO_2 emissions, whereas the use of biomass energy exerted an insignificant influence. At the same time, trade openness had some negative impact on the environment, suggesting that opening up or deregulating exports could have environmental trade-offs. These results underline the importance of sustainable trade and energy regimes (Jebli et al., 2016).

Saidi & Hammami (2015) investigated the effect of energy consumption, economic growth and CO2 emissions across 58 countries, in panel data analysis spanning 1990 – 2012. The analysis used GMM estimation to deal with possible endogeneity. Their results indicated that fossil fuel use would raise CO_2 emissions, while renewable energy would cut them. Moreover, economic development has been discovered to increase emissions particularly in low-income economies, bringing into focus the trade-off between development and environmental sustainability (Saidi & Hammami, 2015).

Rafiq et al. (2014) investigated the causal link between fossil fuel consumption, trade and carbon emissions in a sample of Asian developing countries for the period 1980–2010. Employing panel VECM they found long-run equilibrium in trade openness and fossil fuel based emissions. The findings show that economic growth and open trade further magnify environmental pressure in the economies studied in turn leading to more energy use. The authors emphasized the need for incorporating clean energy in the development plans (Rafiq et al., 2014).

The association between CO_2 emissions, energy consumption and real output has also been studied while extending the work of (Dogan and Turkekul, 2016) in the US for the period of 1960–2010. Applying ARDL bounds testing and Granger causality test, they identified a long-run relationship between the variables with fossil fuel consumption playing a vital role in emissions generation. The causality is from energy consumption to both output and emissions, which means that targeted emission reduction policies, or focus on maintaining economic growth, should be practised.

Khan et al. (2020) investigated the impact of natural resource rents, energy consumption, and urbanization on CO_2 emissions for G7 countries based on annual time series data between 1990 and 2016. They used panel quantile regression to account for heterogeneity in effects throughout the emission range. They found that fossil fuel energy consumption and resource rents greatly raise emissions, especially among the countries with higher emission levels. The authors pointed out to adopt renewable energy and control the urbanization to mitigate the environmental degradation (Khan et al., 2020).

Shahbaz et al. (2013) analysed the nexus of fossil fuels consumption and carbon emissions in South Africa for the period 1965 to 2009 by applying the ARDL bounds testing approach. Their results showed a long-run equilibrium relationship between Jcasas,_ MAde:* ARTICLE IN PRESS (They and found significant long-run non-optimal energy use and emissions levels. Fossil fuel based energy was particularly identified as one of the major factors contributing to environmental degradation. The research has found out that the switch to renewable energy sources would ensure sustainable growth in the region (Shahbaz et al.

Hossain (2011) examined relationship among economic growth, energy demand, urbanization and CO?2 emissions for the panel of newly industrialized countries for the period 1971-2007. The study discovered that fossil fuel use and rapid urbanization would generate emissions, and energy efficiency would lower them slightly, in respect to which cleaner energy and sustainable urban development are required.

Omri et al. (2014) used a panel data analysis of 1990–2011 on 14 MENA countries to explore the causal relationship between energy consumption, FDI and CO 2 emissions. The GMM estimation was used to control for endogeneity. They found nexus between fossil fuel consumption and pollution and mixed effects of FDI and country's environmental policies. They recommended green FDI policies as well as energy reforms (Omri et al., 2014).

Al-Mulali at all (2012), proceed of energy consumption, urbanization, industrial output on CO_2 emissions among 82 countries for the period 1980–2008. Through the use of panel regression with fixed effects, they established that although energy consumption (mostly derived from fossil fuels) was predominantly responsible for emissions. The influx of population and industrial works also exaggerated the environment impact, especially in the developing countries. The authors stressed for a joint effort by the world nations for supporting renewables usage (Al-Mulali & Sab, 2012).

Rafindadi and Usman (2019) employed a time series data analysis through autoregressive distributed lag (ARDL) bound testing approach to examine the influence of fossil fuel energy on CO_2 emissions in South Africa using data for the period of 1980–2016. The findings indicated a positive long-run relationship between fossil fuel consumption and emissions, and environmental degradation was insignificantly affected by economic growth. The authors said the heavy reliance on coal in South Africa called for quick diversification of the energy mix. They also recommended additional investment in renewables for sustainable development (Rafindadi & Usman, 2019).

The EKC hypothesis was also examined by Aye and Edoja (2017) with a panel data set of 31 Sub-Saharan African countries from 1980-2010. They employed system GMM estimation and indicated that fossil fuel consumption and urbanization significantly aggravate CO_2 emissions, whereas trade openness played a suppressant role. In their results, such EKC hypothesis was only partially supported: income generated an initial deterioration of emissions to subsequently improve the environmental quality at a certain income level. Green technology and urban planning reform were advised in the study (Aye & Edoja, 2017).

Omri (2013) used simultaneous equations systems approach to investigate the Granger-causality relationship between FFC, EG and CO2 emissions for 14 select MENA countries from 1990 to 2011. In this study, we consist of bidirectional causality between fossil fuel consumption and emissions as well as between emissions and economic growth. This would imply complicated interrelations, for which multidimensional policies are recommended. Omri called for diversifying the energy mix and improving energy efficiency in the MENA countries (Omri, 2013).

Churchill and Ivanovski (2020) examined the symmetry or asymmetry nature of the nexus between fossil fuels consumption and environmental degradation for 15 OECD countries using nonlinear ARDL models and annual data over the period 1971-2015. Their results showed the non-linear connection, as adding the fossil fuel has relatively larger effect on the energy related emissions than subtracting the fossil fuel. This underscored the necessity to take stringent measures to control emissions during energy consumption peak times. They highlighted policy consideration of behavioral energy demand dynamics (Churchill & Ivanovski, 2020).

Overall, the existing literature primarily examines the relationship between fossil-fuel use, emissions and growth, often within the Environmental Kuznets Curve (EKC) or decoupling frameworks. Most studies emphasize income effects, trade openness, or renewable energy, yet comparatively few investigate the combined roles of natural resource rents, urbanization, industrialization and productivity in a single-country, resource-rich developing economy. Moreover, earlier works frequently rely on conventional time-series methods that do not account for structural breaks—an important feature of South Africa's volatile energy system. By integrating these macroeconomic drivers within a structural-break-robust econometric framework, this study fills a critical gap in the literature and provides country-specific evidence that extends the predominantly panel-based or emissions-focused research.

3. DATASET, ECONOMETRIC METHOD, AND FINDINGS

The correlations among natural resource rents, urbanization, total factor productivity, industrialization, and fossil fuel consumption are considered here for South Africa in section 3. The analysis is based on annual data from 1990 to 2019. We use the recent developed Fourier ADL cointegration test in the econometrics literature to examine the longrun relationships among the variables.

3.1 Data

This paper seeks to investigate those factors responsible for increasing or decreasing consumption of fossil fuel in South Africa. For this purpose We shall use the model expressed in Equation (3) where:

FOS_t=β_1+β_2NRR_t+β_3 URB_t+β_4 TFP_t+β_5 IND_t+u_t

The model is written below. Here, in this context, we have taken the FOS to represent fossil fuel consumption (combined use of coal, oil and gas).

Fourier ADF tests are employed to capture smooth structural breaks related to Eskom electricity crises, commodity-price shocks and macro-policy shifts over 1990–2022.

NRR means natural resource rents, URB means urbanization, TFP indicates total factor productivity, and IND represents industrialization. FOS were extracted from the Inter. Ener. Agn (IEA), TFP from the "Penn World Table" , NRR and IND from the World Bank database. We have taken natural logarithms of all variables to maintain the consistency and interpretability of econometric exercise.

3.2 Analytical Framework of the Study

We use a range of econometric methods to explore the long-run and short-run associations between fossil

Variable	*Proxy / Measurement*	*Expected Sign*	*Explanation*
FOS	Log of fossil-fuel consumption (coal + oil + gas)	Dependent	—
NRR	Natural resource rents (% of GDP)	+ / –	Extraction intensity may raise consumption; efficient management may lower it
URB	Urban population (%)	+	Urban growth increases residential and transport energy demand
IND	Industry value-added (% of GDP)	+	Industrial production is energy-intensive
TFP	TFP index (Penn World Table)	–	Efficiency and technology reduce energy intensity

Table 1: Variables, Measurements and Expected Signs

fuel consumption, natural resource rents, total factor productivity, urbanisation and industrialisation. For this part of the study, the standard ADF unit root test and Fourier ADF tests will be performed in order to test for presence of a unit root in the series. Then the modern Fourier ADF cointegration test will be used. Third, the FMOLS and CCR estimators will be used to estimate the short-run and long-run coefficients.

3.2.1 Fourier Stationarity Tests

The ADF unit root test does not take into account the possible structural changes that a time series may undergo. Therefore, even if a series is stationary under structural breaks, it may be incorrectly classified as non-stationary when such breaks are not considered. This could result in an inaccurate estimation of the cointegration order or misleading empirical findings. Enders and Lee (2012), in their improved test, emphasized that when a series exhibits one or more structural changes, incorporating low-frequency trigonometric functions—known as Fourier functions—into the model can yield more accurate results. A significant advantage of this test is that it does not require prior knowledge of the number or timing of structural breaks. According to Enders and Lee (2012), the Fourier terms consisting of sine and cosine functions are sufficient to capture such variations, making the selection of an appropriate frequency the only necessary step for implementation. Firstly;

Δy_t=py_(t-1)+β_1+β_2 trendu_t (1)

They utilized the traditional ADF test in its standard form. In the case of the Fourier ADF test, Enders and Lee (2012) extended this model by incorporating Fourier terms.

$$\Delta y_t = py_{t-1} + \beta_1 + \beta_2 \text{trend} + \beta_3 \sin\left(\frac{2\pi kt}{T}\right) + \beta_4 \cos\left(\frac{2\pi kt}{T}\right) + u_t \quad (2)$$

By incorporating trigonometric functions capable of capturing structural breaks, the model has been revised. In this context, t denotes the trend, T represents time, and k indicates the unknown frequency value that must be determined. The appropriate frequency value is selected based on the condition where the sum of squared residuals (MinSSR) is minimized. Therefore, identifying the suitable frequency that yields the MinSSR is of critical importance in this model. The results of the standard ADF and Fourier ADF unit root tests for the variables are presented in Table 1. The Fourier ADF test was chosen because conventional unit root tests, such as the standard Augmented Dickey–Fuller (ADF), have low power when the underlying time series includes structural breaks. Since South Africa experienced major structural changes – including shifts in energy policy, commodity price shocks, and global financial crises – the Fourier approach provides a flexible way to capture unknown, smooth, and multiple breaks using low-frequency sine and cosine functions. This increases the accuracy of stationarity testing without requiring prior knowledge of the number or dates of breaks.

	Level					
Var.	Frq.	MİNSSR	F-Test	Opt. Lag	FADF	ADF
FOS	1	0.011	8.525**	7	-3.437	-1.263
NRR	1	0.231	5.574	1	-3.403	-1.643
TFP	1	0.003	4.717	1	-2.734	-1.398
URB	1	0.001	5.888	3	-2.472	-2.104
IND	1	0.002	7.539*	1	-3.318	-0.760
	Birinci Fark					
Var.	Frq.	MİNSSR	F-Test	Opt. Lag	FADF	ADF
FOS	3	0.012	3.991	1	-5.511	-5.507***
NRR	5	0.288	3.053	0	-6.875	-6.212***
TFP	5	0.004	2.940	0	-2.870	-2.629*
URB	1	0.001	8.743**	7	-3.589*	-4.338***
IND	1	0.003	2.838	1	-4.285	-4.417

Table 1: Results of the Standard ADF and Fourier ADF Unit Root Tests

Note: *"The critical values for the F-test are 1% = 10.35, 5% = 7.58, and 10% = 6.35. The critical values for the Fourier ADF test with k = 1 are 1% = –4.42, 5% = –3.81, and 10% = –3.49; with k = 3 they are 1% = –3.77, 5% = –3.07, and 10% = –2.71; and with k = 5 they are 1% = –3.58, 5% = –2.93, and 10% = –2.60. For the standard ADF test, the critical values are 1% = –3.679, 5% = –2.968, and 10% = –2.623. The symbols ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively, indicating that the series are stationary."*

As shown in Table 1, at level values, the Fourier ADF F-test results for fossil fuel consumption Fossil fuel consumption (FOS) and industrialization (IND) are statistically significant, indicating the presence of a unit root. For the other variables, the standard ADF test confirms the presence of unit roots at level. After first differencing the series, only urbanization (URB) shows a statistically significant F-test result under the Fourier ADF, indicating stationarity. The other variables are found to be stationary at first differences based on the standard ADF test. Therefore, all variables are integrated of order one, I(1).

3.2.2 Fourier ADL Cointegration Test

The Autoregressive Distributed Lag (ADL) cointegration test was first proposed by Banerjee et al. (1998). Later, in a significant contribution to the literature, Banerjee et al. (2017) extended their original model by incorporating Fourier functions through the inclusion of sine and cosine terms. In the Fourier ADL model developed by Banerjee et al. (2017), the constant term is replaced by a deterministic component, and the model is revised accordingly as

$$\Delta y_t = d(t) + \beta_1 y_{t-1} + \gamma_1' x_{t-1} + \emptyset' \Delta x_t + u_t \quad (3)$$

$$d(t) = a_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) \quad (4)$$

In this context, d(t) represents the deterministic component. In the revised model, the lagged values of the variables are included to correct the autocorrelation problem. The alternative hypothesis posits the existence of a long-run relationship among the variables. Therefore, to test for the presence of a long-term relationship, Equation (4) is estimated, and the appropriate frequency value is obtained. The significance of the coefficient of the lagged dependent variable is tested using the standard t-test as follows:

$$H_0: \beta_1 = 0 \quad (5)$$

Although the standard t-test is employed, the critical values provided in Banerjee et al. (2017) are used. The long-run relationship between the explanatory variables and fossil fuel consumption is examined, and the results are presented in Table 2.

	Lag		***Min AIC***	***FADL***
FOS	2	1		-6.407***
NRR	1			
TFP	2			
URB	2			
IND	1			

Table 2: Fourier ADL Cointegration Test

Note:*The critical values for the Fourier ADL cointegration test are −4.90 at the 1% level, −4.16 at the 5% level, and −3.79 at the 10% level. The symbols ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.*

When Table 2 is examined, the optimal frequency value for the Fourier ADL cointegration test is found to be 1. Since the test statistic exceeds the absolute value of the critical value at the 1% significance level, a long-term relationship exists among the variables. Therefore, for South Africa during the relevant period, natural resource rents, total factor productivity, urbanization, and industrialization move together with fossil fuel consumption.

3.2.3 Estimation of Cointegration Coefficients

Since the results of the Fourier ADL test confirm the existence of a cointegration relationship among the variables, both short- and long-term coefficient estimations will be conducted. For this purpose, the Fully Modified Ordinary Least Squares (FMOLS) method developed by Phillips and Hansen (1990), and the Canonical Cointegrating Regression (CCR) estimator proposed by Park (1992), will be employed. The direction and magnitude of the effects of natural resource rents, total factor productivity, urbanization, and industrialization on fossil fuel consumption have been examined. The estimation results are presented

FOS	NRR	URB	TFP	IND	C
		0.165* (0.090)			-0.477
CCR		0.328* (0.132)			0.204

Table 3: Estimation of Long-Run Coefficients

Note:* *indicates significance at the 10% level,** at the 5% level, and *** at the 1% level.*

As seen in Table 3, the FMOLS and CCR results are quite consistent with each other. According to both estimation methods, total factor productivity (TFP) reduces fossil fuel consumption in South Africa, whereas natural resource rents (NRR), urbanization (URB), and industrialization (IND) increase fossil fuel consumption. In terms of coefficients, based on FMOLS/CCR results, a 1% increase in NRR, URB, and IND leads to approximately a 0.12%/0.20%, 0.17%/0.33%, and 0.93%/0.75% increase in fossil fuel consumption (FOS), respectively. Conversely, a 1% increase in TFP results in about a 0.35%/0.38% decrease in FOS. Therefore, for the period under study in South Africa, industrialization (IND) is identified as the most influential factor increasing fossil fuel consumption, while total factor productivity (TFP) is the most influential factor reducing it based on FMOLS and CCR results.

The magnitude of the long-run elasticities reveals important structural characteristics of the South African economy. The industrialization coefficient shows the largest impact, confirming that the country's production structure remains heavily energy-intensive. A 1% rise in industrial activity increases fossil fuel use by nearly 1%, indicating that manufacturing technologies and production processes still rely predominantly on coal-based inputs. Similarly, urbanization exerts a persistent upward pressure on energy demand as expanding cities require additional electricity for residential use, public services, transportation and informal economic activities. The positive elasticity of natural resource rents implies that when resource-based revenues increase, economic activities associated with extraction, processing and distribution intensify fossil-fuel consumption. On the other hand, the negative and significant coefficient of total factor productivity demonstrates that improving efficiency and technology adoption can meaningfully reduce fossil fuel use. These results suggest that energy demand in South Africa is shaped by deeply embedded structural factors rather than short-term macroeconomic fluctuations and that productivity-enhancing reforms hold the strongest potential for long-run mitigation.

The estimated long-run elasticities show that natural resource rents, urbanization, and industrialization exert positive effects on fossil fuel consumption. Specifically, the FMOLS results indicate that a 1% increase in resource rents raises fossil fuel consumption by approximately 0.12%, while urbanization increases it by about 0.17% and industrialization by 0.93%. Conversely, a 1% increase in total factor productivity leads to a reduction of nearly 0.35% in fossil fuel use. The CCR estimates provide similar magnitudes, confirming the robustness of these findings.

Following the estimation of long-term coefficients in the model, the FMOLS/CCR error correction model was applied, and the results are presented in Table 4.

FOS	ECT-1	NRR	URB	TFP	IND
			1.620 (1.716)	-0.262	0.049 (0.316)
CCR		0.072 (0.056)	2.224 (1.621)	-0.457	0.331 (0.591)

Table 4: Estimation of Short-Run Coefficients

Note: ** denotes significance at the 10% level, ** at the 5% level, and *** at the 1% level.*

statistically significant, and within the (0,1) interval for both the FMOLS (-0.644) and CCR (-0.671)

Upon examining Table 4, the error correction term, which indicates the long-run relationship among the residuals, is found to be negative, These empirical patterns align with the realities of South Africa's energy system. The country's dependence on coal-fired power plants, aging generation infrastructure and slow progress in renewable deployment have created structural rigidity in energy supply. Rapid urban expansion—often concentrated in informal settlements lacking efficient transport and housing systems—further intensifies energy pressure. Industrial activity remains clustered in mining, smelting, metal processing and heavy manufacturing, all of which rely on coal-based electricity and imported petroleum products. At the same time, limited technological upgrading and low investment in energy-efficient capital prevent productivity gains from reducing energy intensity at the pace required for decoupling. The short-run coefficients indicate that fossil-fuel consumption responds more rapidly to changes in natural resource rents and economic activity than to productivity improvements, underscoring the need for stronger long-term strategies that reduce structural dependence on fossil energy. Overall, the findings highlight that South Africa's energy transition challenges stem not only from supply-side constraints but also from the macroeconomic and spatial dynamics identified in this study.

4. CONCLUSIONS

This study examined the determinants of fossil fuel consumption in South Africa using annual data for the period 1990–2019 and econometric methods that allow for structural breaks and non-linear adjustments. The results consistently show that industrialization, urbanization and natural resource rents increase fossil fuel consumption, whereas total factor productivity contributes to reducing it. These findings indicate that the country's energy demand is driven primarily by long-standing structural characteristics—an energy-intensive industrial base, fast urban expansion and resource-dependent economic cycles.

From a policy perspective, the results highlight three major priorities. First, the industrial sector requires targeted modernization programmes that replace outdated, coal-dependent technologies with cleaner and more energy-efficient systems. Second, urban planning and infrastructure policies must address the rapid growth of metropolitan areas by improving public transportation, housing quality and energy-efficient construction standards. Third, long-term productivity-enhancing strategies—such as technological diffusion, innovation incentives and energy-efficient capital investments—can help reduce fossil-fuel intensity without compromising growth.

The value added of this paper is two-fold: it delivers structural-break-robust evidence on the macroeconomic drivers underlying South Africa's fossil fuel consumption, and it provides an empirically grounded basis for formulating resilient energy policies. By identifying which variables impose the largest long-term pressures on energy demand, the findings can assist policymakers in devising place-conditioned strategies aimed at gradually decoupling economic growth from fossil-fuel use. In this regard, the lessons offered here can support South Africa's wider energy transition agenda and ensure that national development objectives remain aligned with long-term environmental sustainability.

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Conflict of interests
The authors declare no conflict of interest.

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