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International Journal of Energy Economics and Policy

Provided in Cooperation with:
International Journal of Energy Economics and Policy (IJEEP)

Reference: Phiri, Andrew/Sesoai, Tsepiso (2024). Renewable, non-renewable energy consumption and economic growth in South Africa : fresh evidence from ARDL and wavelet coherence analysis. In: International Journal of Energy Economics and Policy 14 (4), S. 580 - 589. https://www.econjournals.com/index.php/ijeep/article/download/15406/8061/38019. doi:10.32479/ijeep.15406.

This Version is available at:
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International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2024, 14(4), 580-589.

Renewable, Non-renewable Energy Consumption and Economic Growth in South Africa: Fresh Evidence from ARDL and Wavelet Coherence Analysis

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Received: 09 November 2023 **Accepted:** 21 May 2024 **DOI:** https://doi.org/10.32479/ijeep.15406

ABSTRACT

We examine the relationship between renewable, non-renewable energy consumption and GDP growth in South Africa, with the aim of determining which energy source is most compatible with economic development. We investigate these relationships by applying autoregressive distributive lag (ARDL) models, vector autoregressive (VAR)-based causality tests and wavelet coherence analysis to annual time series data spanning 1985-2022. On one hand, the ARDL and causality analysis indicate positive (negative) relationships between non-renewable (renewable) energy and growth, whilst the causality tests show that none of the energy sources granger causes economic growth and only reverse causality exists. On the other hand, the more powerful wavelet analysis provides evidence that non-renewables are sustainable for long-term growth whilst renewables, at best, have short-term effects on growth which are mainly driven by the adoption of the White policy paper and the subsequent energy efficiency policies. Overall, these findings imply that South African energy regulators have not taken strong enough policy measures to induce a structural change in which long-term growth can be dependent on renewable energy.

Keywords: Renewable Energy; Non-renewable Energy; ARDL; Wavelet Coherence; South Africa
JEL Classifications: C02; C22; O13; Q42; Q43

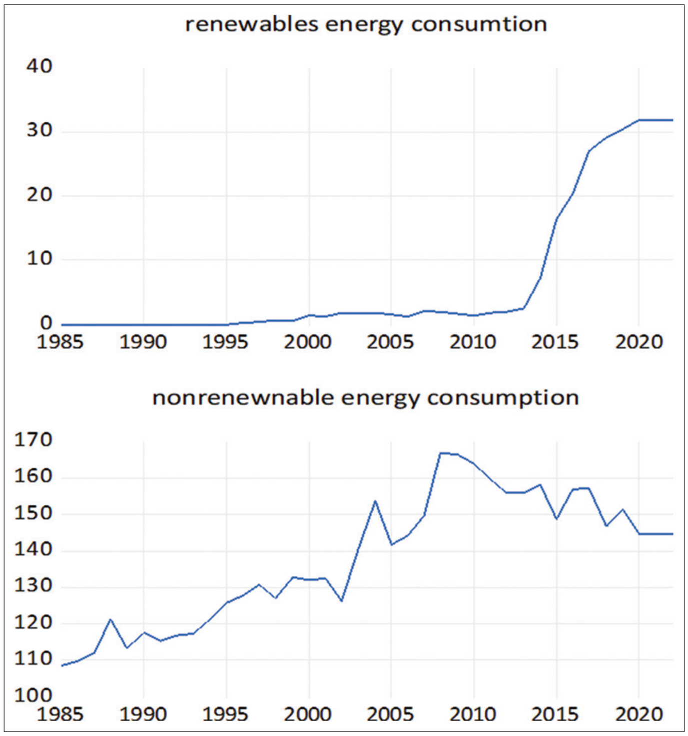
1. INTRODUCTION

In 2018, South Africa became the first sub-Saharan country to join the International Energy Association (IEA). This institutional development is key towards promoting energy security by reducing reliance on dirty energy sources such as coal, oil and natural gases and focusing more on cleaner energy sources such as renewable energies. Currently South Africa stands as Africa's energy hub accounting for over 50% of the continent's production and consumption, and there have been concerns on the levels of greenhouse-gas (GHG) emissions produced by traditional sources of energy. In the most recent 2019 South African Energy Outlook, the IEA suggests the country diversify energy-supply away from coal-based sources which would improve energy efficiency and produce other social benefits such as reduction of illnesses and deaths caused by pollution. In response, South Africa policymakers have committed themselves to reaching net zero emissions by 2050 and these goals are incorporated into the country's 2030 National Development Plan (NDP) which falls in line with the United Nations Sustainable Development Goals (UN-SDG).

Despite South Africa's commitment to reducing reliance on dirty energy usage, as evident by the plethora of policies implemented since the release of the White paper on renewable energy and clean energy development in 2003 (https://www.iea.org/policies?country=South%20Africa), the country remains reliant on dirty energy sources and is currently the highest emitter of carbon emissions in Africa and also ranks amongst the top 15 emitters, globally (https://www.worldometers.info/co2-emissions/co2-emissions-by-country/). And whilst there has been a noticeable decrease (increase) in non-renewable (renewable) energy consumption in the post-2010 era (Figure 1), the reliance on dirty energy consumption remains more than 10-fold that of clean energy-usage. Moreover, South Africa has experiencing worsening power blackouts (i.e. loadshedding) since 2019, of which Akpeji et al. (2020) estimates to lead to economic loss of over R54 million for 24 h of loadshedding. These power interruptions are attributed to the country's heavy reliance on coal-based energy consumption and, interesting enough, this dilemma has rendered renewables as a panacea which can simultaneously address the issues of environmental degradation and loadshedding (Phiri and Nyoni, 2023). In this regard, an important policy question is whether reliance on clean energy as opposed to dirty energy consumption can foster long-term economic growth in the country.

Whilst several academics have investigated the impact of energy consumption on growth in South Africa (Esso, 2010; Menyah and Wolde-Rufael, 2010; Odhiambo, 2010; Bildirici, 2013; Lin and Wesseh, 2014; Kumar et al., 2015; Bhattacharya et al., 2016; Dlamini et al., 2016; Destek and Aslan, 2017; Illesanmi and Tewari, 2017; Ranjbar et al., 2017; Shakouri and Yazdi, 2017; Khobai and Le Roux, 2018; Molele and Ncwanya, 2018; Akadiri et al., 2019; Bekun et al., 2019; Nyoni and Phiri, 2020), there is very little empirical evidence supporting the notion that renewables can foster long-term economic growth. However, most of these previous studies rely on linear cointegration frameworks which produce a singular regression estimate that aggregates the relationship over a specified period of time. Moreover, recent international literature has shown that the energy consumption-growth relationship is possibly nonlinear although various forms asymmetries have been identified in the literature. For instance, Wang and Wang (2020) finds that the renewable energy consumption–growth exhibits regime-switching characteristics in which the 'sign' on the relationship changes after crossing a certain threshold. Baz et al. (2021) account for cyclical asymmetries in which the impact of upward cycles in energy consumption on growth differs from that of downward cycles. Alqaralleh and Hatemi-J (2023) observe locational asymmetries in which the impact of (non)renewable energy consumption on growth depends on a country's level of economic development. Moreover, Shastri et al. (2020) and El-Karimi and El-Houjjaji (2022) describe causality asymmetries in which the causal direction between energy consumption and growth differs across different frequencies.

Figure 1: Time series plot between renewable and non-renewable energy consumption in South Africa (1985-2022)



Our study relies on wavelet coherence techniques to re-examine the relationship between (non)-renewable energy consumption and economic growth in South Africa between 1985 and 2022. This method models the synchronization between a pair of time series in a scale-based manner, revealing co-movement in the time-frequency domain. A unique feature of wavelet analysis is its ability to capture the "sign and strength" of co-movement across varying time periods and frequencies, thereby encompassing different forms of "location," "cyclical," and "time-varying" asymmetries within a unified framework. Additionally, these methods can handle non-stationary data, remain insensitive to chosen time windows, and circumvent potential "regression errors," thus distinguishing them from conventional econometric tools, which depend on selected time spans and contain regression errors (Aguiar-Conraria and Soares, 2014).

To demonstrate the usefulness of these tools against traditional econometric techniques, we compare the findings with those obtained from conventional ARDL and VAR-based causality regressions. On one hand, the ARDL models show significant negative (positive) long-run cointegration relationship between renewable (non-renewable) energy consumption and growth in South Africa and reveal reverse causality from economic growth to energy consumption. On the other hand, the wavelet coherence analysis shows (i) significant positive (negative) low (higher) frequency co-movements between renewable/non-renewable and growth (ii) non-renewables (growth) causing growth (renewables) at lower frequencies whilst at higher frequencies both non-renewables and renewables cause growth. Furthermore, higher-frequency co-movements emerge at two break points, the first in the early 2000's corresponding to which coincides with adoption of the White policy paper and subsequent policies aimed at reducing (increasing) dirty (clean) energy consumption, and the second during the more severe loadshedding experienced since the COVID-19 pandemic. We conclude that these two structural breaks are responsible for the sign and causal switching dynamics observed between (non)renewable energy and growth across different times and frequencies.

Altogether, the findings from the wavelet analysis (i) encompass those from the ARDL and causality analysis, (ii) reconcile previous contradicting results obtained in previous South African studies and (iii) present novel evidence identifying two important structural breaks which have affected the renewable energy consumption – growth relationships. More importantly, the findings imply that whilst non-renewable energy consumption does not cause long-term growth and the economy is still dependent on dirty energy for growth, the implemented energy policies and loadshedding dilemma are driving forces in creating short-run causal effects from clean energy consumption to economic growth. However, these short-term causal effects of renewables on growth are not being translated into the long-run due to structural bottlenecks.

The rest of the study is structured as follows. Section discusses the literature review. The third section outlines the methodology. The fourth section presents the data and empirical analysis. The fifth section concludes the study.

2. LITERATURE REVIEW

From a theoretical perspective, the prospect of energy as an additional factor of production gained tract following the energy crisis in the 1970's. Several authors suggested a capital-labour-energy production function in which energy enhances the productive capabilities of physical and human capital by increasing the rate at which inputs are transformed into outputs (Griffin and Gregory, 1976; Berndt and Wood, 1979; Fuss, 1977, Magnus, 1979; Williams and Laumas, 1981; Hunt, 1984; Solow, 1987; Kummel, 1989). The general consensus within these extended production functions is that if capital and energy are complements (substitutes) in the production process, then increases in energy prices would decrease (increase) capital formation and ultimately lower (enhance) output productivity (Apostolakis, 1990). Papageorgiou et al. (2017) further extends the energy input variable into "clean" and "dirty" sources and finds that the substitution effects between clean and dirty energy inputs plays an important role in determining whether energy inputs are enhancing or diminishing long-run sustainable growth.

Another theoretical dimension of the energy-growth nexus concerns the causal effects, of which there are four direction outcomes or hypotheses associated with the variables. Firstly, the growth hypothesis asserts that increases in energy consumption causes real output growth that energy conservation or expansionary policies will affect economic growth (Kraft and Kraft, 1978). Secondly, the conservation hypothesis stipulates that economic growth causes energy consumption hence implying that the demand for energy is driven largely by the growth and energy conservation or expansionary policies have little or no effects on real growth (Ozturk, 2010). Thirdly, the feedback hypothesis states that there is bidirectional causality between energy consumption and economic growth whilst the last hypotheses, the neutrality hypothesis, asserts that energy consumption does not significantly have an impact on economic growth, implying that independent policy approaches should be taken in managing/governing energy consumption and economic growth (Payne, 2010).

Naturally, empirical studies examining the energy consumption-growth relationship have used different econometric methods to establish the sign and/or causal effects between the variables (Ozturk, 2010), Payne (2010), Omri (2014), Serbi (2015), Tiba and Omri (2017), Mutumba et al. (2021) for extensive surveys of the international literature). Some studies distinguish between renewable and non-renewable energy consumption as a means of comparing the impacts of dirty and clean use on economic development (Apergis and Payne, 2012; Adams et al., 2018; Rahman and Velayutham, 2020; Tugcu et al., 2021; Qin and Ozturk, 2021; Salari et al., 2021) whilst other studies account for different forms of nonlinearities such as threshold effects (Chen et al., 2020; Wang and Wang, 2020; Dabboussi and Abid, 2022), location asymmetries (Akram et al., 2021, Alqaralleh and Hatemi-J, 2023) and cyclical asymmetries (Baz et al., 2021; Abbasi et al., 2022; Afroz and Muhibbullah, 2022; Guliyev, 2023).

For the case of South Africa, there have been 17 country-specific studies published between 2010 and 2022. Most of these studies use linear cointegration techniques such as the DOLS, FMOLS, VECM and ARDL models to estimate the sign of the energy-growth relationship with (i) 3 studies finding a *positive total energy consumption-growth* relationship (Kumar et al., 2015; Illesanmi and Tewari, 2017; Bekun et al., 2019) (ii) 1 study find a *negative total energy consumption-growth* relationship (Menyah and Wolde-Rufael, 2010) (iii) 1 study find a *positive renewable energy consumption-growth* relationship (Khobai and Le Roux, 2018) (iv) 1 study find a *negative renewable energy consumption-growth* relationship (Shakouri and Yazdi, 2017), and (v) 2 studies find an *insignificant renewable energy consumption-growth* relationship (Bhattacharya et al. 2016; Nyoni and Phiri, 2020).

Other studies investigate linear causality effects between energy consumption and growth with (i) 6 studies finding *total energy consumption causing economic growth* (Wolde-Rufael, 2009; Menyah and Wolde-Rufael, 2010; Odhiambo, 2010; Lin and Wesseh, 2014; Bekun et al., 2019; Akadiri et al., 2019) (ii) 1 study finds *economic growth causes total energy* (Bildirici, 2013) (iii) 2 study finds *bi-directional causality between energy consumption and growth* (Illesanmi and Tewari, 2017; Akadiri et al., 2019) (iv) 1 study shows *no causality between renewable/non-renewable energy consumption and growth* (Destek and Aslan, 2017).

There are also three studies which have investigated nonlinearities in the energy consumption growth relationship for South Africa. Esso (2010) used a threshold cointegration model to demonstrate sign switching effects between energy consumption on growth between 1970 and 2007 and find a positive (negative) effects found before (after) 1988. Ranjbar et al. (2017) used frequency domain causality tests to show that economic growth granger causes energy consumption between 1966 and 1979 whilst reverse causality is found in the post-democratic period of 1994-2012. Nyoni and Phiri (2020) use nonlinear ARDL (NARDL) model to investigate possible cyclical asymmetries between renewable energy and growth and find insignificant nonlinear cointegration effects.

Our study re-examines the empirical evidence using traditional ARDL methods, VAR-based causality tests and wavelet coherence analysis. On one hand, the ARDL and causality models have been extensively used in the previous South African studies to capture the linear cointegration effects between (non)renewables and growth (Wolde-Rufael, 2005; 2009; Menyah and Wolde-Rufael, 2010; Odhiambo, 2010; Bildirici, 2013; Kumar et al., 2015; Shakouri and Yazdi, 2017; Khobai and Le Roux, 2018; Akadiri et al., 2019; Bekun et al., 2019). On the other hand, the wavelet coherence is a more powerful tool which allows us to account for several form's asymmetries relating to time and frequency variation and despite this method gaining popularity in energy studies (Mutascu, 2018; Mata, 2020; Magazzino et al., 2021; Adebayo et al., 2022; Phiri and Nyoni, 2023), it has not been used to investigate the (non)renewables-growth relationship. Notably, the wavelet analysis is virtuous for producing results that are insensitive to the selected time window and free from any possible 'regression errors' (Aguiar-Conraria and Soares, 2014). This is in contrast to the output obtained econometric models used in the literature whose output results are dependent on the selected time period and contain regression errors. Therefore, output produced from wavelets are more robust and 'permanent' compared to those produced from econometric methods used in previous studies. We discuss these estimation techniques in detail in the following section.

3. EMPIRICAL FRAMEWORK AND ESTIMATION TECHNIQUES

3.1. ARDL Model

We base our empirical framework on the energy-capital-labour constant elasticity of substitution (CES) production function specified in Griffin and Gregory, 1976; Berndt and Wood, 1979; Fuss, 1977, Magnus, 1979; Williams and Laumas, 1981; Hunt, 1984; Solow, 1987; Kummel (1989); Toman and Jemelkova, 2003 i.e.

$$Y = f(E, K, L) \tag{1}$$

Where Y is output, E is total energy consumption, K is capital and L is labour. We further follow Papageorgiou et al. (2017) and segregated total energy consumption into renewable (RE) and unrenewable (NRE) components and capture their potential effects on output using the following augmented three-factor production functions:

$$Y = f\,(RE, K, L) \tag{2}$$

$$Y = f\,(NRE, K, L) \tag{3}$$

And In log-linearizing regressions (#) and (#), we present our baseline empirical specifications:

$$Y_t = \alpha_0 + \beta_{10}RE_t + \beta_{20}K_t + \beta_{30}H_t + e_t \tag{4}$$

$$Y_t = \alpha_1 + \beta_{11}NRE_t + \beta_{21}K_t + \beta_{31}H_t + e_t \tag{5}$$

Where the α's and β's are regression intercepts and coefficients, respectively, whilst e_t is well-behaved error term.

3.2. ARDL Model

We firstly use an ARDL model to estimate the long-run and short-run cointegration relationships between GDP growth (Y) and energy consumption (E) whilst controlling for physical capital (K) and labour employment (L). In its baseline form the ARDL model can be specified as:

$$Y_t = a_0 + a_1 Y_{t-1} + a_2 E_{t-1} + a_3 K_{t-1} + a_4 H_{t-1} + \sum_{i=1}^{p-1} b_{1i} Y_{t-i} + \sum_{i=1}^{p-1} b_{2i} E_{t-i} + \sum_{i=1}^{p-1} b_{3i} K_{t-i} + \sum_{i=1}^{p-1} b_{4i} H_{t-i} + \varepsilon_t \tag{6}$$

Following Pesaran et al. (2001), we conduct a three-step modelling process:

Step 1: Test for bounds cointegration test by testing the null hypothesis of H_0: $a_1 = a_2 = a_3 = a_4 = 0$ in equation (1) by computing the standard F-test and use the non-standard critical values developed by Pesaran et al. (2001).

Step 2: Estimate the long-run regression of form $Y_t = \beta_0 + \beta_1 E_t + \beta_2 K_t + \beta_3 H_t + e_t$ where the long-run coefficients are computed as $\beta_1 = a_2/a_1$, $\beta_2 = a_3/a_1$, $\beta_3 = a_4/a_1$. In line with endogenous theory, all coefficients are expected to be positive i.e. $\beta_1 > 0$, $\beta_2 > 0$, $\beta_3 > 0$.

Step 3: Estimate the associated error correction model of form:

$$\Delta \lg(Y)_t = c_0 + ECT_{t-1} + \sum_{i=1}^{p-1} c_{1i} GDP_{t-i} + \sum_{i=1}^{p-1} c_{2i} E_{t-i} + \sum_{i=1}^{p-1} c_{3i} K_{t-i} + \sum_{i=1}^{p-1} c_{4i} H_{t-i} + \varepsilon_t \tag{7}$$

Where the coefficient γ measures the speed of adjustment to equilibrium after a "shock" to the system, and the coefficient is expected to be negative. Following Banerjee et al. (1998), Pesaran et al. (2001) propose the use of the t-statistic of the error correction term, γ, as an additional test for cointegration i.e. BDS cointegration test.

3.3. VAR-based Causality Tests

To further test for causality in the Granger (1969) sense, we specify the following VAR (p) model:

$$Y_t = \sum_{i=1}^{n} \alpha_{i,i} Y_{t-j} + \sum_{j=1}^{n} \beta_{1,i} E_{t-j} + e_{1t} \tag{8}$$

$$E_t = \sum_{i=1}^{n} \alpha_{2,i} Y_{t-j} + \sum_{j=1}^{n} \beta_{2,i} E_{t-j} + e_{2t} \tag{9}$$

Where α and β are the VAR regression coefficients which are estimated by OLS, i, is the optimal lag length determined by minimization of the AIC and BIC and the e_{ti} are regression residuals. To test for causality from inflation to nominal interest rates (i.e. the traditional Fisher effect), we impose the following restriction, $\beta_{1,1} = \beta_{1,2} = \ldots = \beta_{1,j} = 0$ on equation (8) which results in the following restricted regression.

$$Y_t = \sum_{i=1}^{n} \alpha_{i,i} Y_{t-j} + e_{1t} \tag{10}$$

Whereas to test for reverse causality from interest rates to inflation (i.e. NeoFisher effect), we impose the following restriction, $\alpha_{2,1} = \alpha_{2,2} = \ldots \alpha_{2,j} = 0$, on equation (9) which results in the following restricted regression:

$$E_t = \sum_{i=1}^{n} \beta_{2,i} E_{t-j} + e_{2t} \tag{11}$$

Thereafter, we extract the sum squares of residuals (SSR) for the unrestricted regression (8) and (9) as well as the restricted regressions (10) and (11), and compute the following F-statistic:

$$F = \frac{(SSR_R - SSR_{UR})/q}{SSR_{UR}/(n-k)} \tag{12}$$

Where q is the number of restrictions, n is number of observations and k is the number of independent variables in the equation. The calculated F-statistics are compared against the critical values tabulated in the conventional F-tables. Significant causality effects are confirmed if the obtained F-statistic exceeds its associated 10% critical value at the relevant degrees of freedom.

3.4. Wavelet Coherence

Lastly, we employ continuous wavelet analysis can be considered a major step-up from time series based econometric techniques such as the VAR, and present a multiresolution analysis of signal or time-series in time-frequency space. Lau and Weng (1995) present an excellent analogy to explain the concept of wavelet transforms applied to time series data by comparing this transformation process to converting a two-dimensional written musical score into three-dimensional audible music tones, characterized by frequency, time position and duration, and intensity. In practice, these transforms convolute a time series with a set of complex-valued 'daughter wavelets' defined as:

$$W_x(s,) = \int_{-\infty}^{\infty} x(t)\frac{1}{\sqrt{s}}\psi*(\frac{t-\tau}{s})dt \tag{13}$$

Where * is the conjugate of the complex number, τ and s are the translation and dilation parameters responsible for amplitude and phase dynamics in time-frequency space. The mother wavelet which is responsible for the shape of the daughter wavelets is defined as the following Morlet et al. (1982) function:

$$\psi(t) = \pi^{-\frac{1}{4}}\exp(i\omega t)\exp(-\frac{1}{2}t^2) \tag{14}$$

Where ω_0 is set at 2π to ensure optimal joint time-frequency resolution. We can then compute the wavelet power spectrum (WPS) of the time series as:

$$W_m^s(s) = \frac{\partial t}{\sqrt{s}}\sum_{n=0}^{N-1} x_n\psi*((n-m)\frac{\partial t}{s} \quad \text{n=0,…., N-1, m=0,…., N-1} \tag{15}$$

Where δt is a uniformed time step. The WPS is a representation of the enrgy distribution of the series in a time-frequency plance and is analogous to the variance.

The wavelet coherence analysis between a pair of time series across a time-frequency plane and is closely related with the concept of Fourier coherency (Torrence and Combo, 1998; Aguiar-Conraria and Soares, 2014). Given the WPS for a pair of time series x(t) and y(t) (i.e. $W_{xx} = |W_x|^2$ and $W_{yy} = |W_y|^2$,) their cross-wavelet transform (CWT) can be defined as $(WPS)_{xy} = W_{xy} = |W_{xy}|$, from which the wavelet coherence, is computed as:

$$R_{y.x}(s) = \frac{|S(W_{x,y})|}{[(S|W_x|^2)(S|W_y|^2)]^{\frac{1}{2}}} \tag{16}$$

Where S is a smoothing operator in both time and scale. The phase-difference dynamics are determined as:

$$\phi_{(x,y)} = Arctan^{-1}(\frac{I\{W_x\}}{\Re\{W_x\}}) \tag{17}$$

Where $\pi < \phi_{x,y} < -\pi$ and provides information on (i) whether the pair of series are in-phase (positive) or antiphase (negative) synchronized and (ii) whether x leads y or vice-versa.

4. DATA AND RESULTS

4.1. Data Description

Our study makes use of annual time series spanning from 1985 to 2022 for 5 variables which are sourced from three databases. Firstly, we use the GDP growth (Y) from the World Bank Development Indicators. Secondly, we source the non-renewable energy consumption (NONRENEW) and Renewable energy consumption (RENEW) from the BP online database. Lastly, we use physical capital (K) and labour employment in millions of people (K) from the Penn World Tables 10.1 (i.e. PWT 10.1). The descriptive statistics (correlation matrix) for data are reported in Panel A (Panel B) of Table 1 and reflect some stylized facts of the series. For instance, on average, South Africa has been more dependent on non-renewable energy compared to renewable energy and this has been accompanied with by relatively low average GDP growth rate of 1.99 over the sample period. Moreover, the correlation coefficients further indicate that positive (negative) co-movement between non-renewable (renewable) energy consumption and economic growth. We treat these latter findings as preliminary results which we use for comparison purposes with our main empirical estimations.

4.2. ARDL Results and Granger Causality Tests

We begin by presenting the ARDL regression results which are summarized in Table 2. In Panel A, we present the long-run coefficient estimates, and as can be observed, we report a positive (negative) coefficient on the non-renewable (renewable) energy variable which is a finding similarly obtained from the correlation coefficients. Considering that non-renewables form a large portion of total energy consumption in South Africa, these results should not be surprising as several studies have a found a positive effect of total energy consumption on economic growth for the country (Kumar et al., 2015; Bekun et al., 2019). We further note a negative renewable-growth relationship which has been similarly found in Shakouri and Yazdi (2017). In Panel B, the reported short run coefficient is insignificant for non-renewables whilst there is a switching effect from positive to negative effects as one moves from lower to higher lags for the renewable energies coefficient. Lastly, the bounds cointegration and BDM error correction test, as reported in Panel C, produce F- and t- statistics which confirm significant ARDL effects at all levels of significance. However, the reported diagnostic tests provide evidence of non-normality in the regression errors (i.e. Jarque-Bera test) and instabilities in the regression parameters (i.e. CUSUM squares test) hence warranting

Table 1: Descriptive statistics and correlation matrix

	GDP	Nonrenew	Renew	K	L
Panel A: Descriptive statistics					
Mean	1.99	137.89	6.62	1583842	14.63
Median	2.40	140.93	1.41	1070285	13.84
Maximum	5.60	166.98	31.81	2816883	19.00
Minimum	−6.34	108.52	0.00	812018	9.56
SD	2.41	17.61	11.22	819738	2.81
Skewness	−1.12	-0.061	1.54	0.54	0.015
Kurtosis	5.08	1.75	3.58	1.46	1.94
Jarque-Bera	14.86	2.52	15.48	5.59	1.79
Probability	0.00	0.28	0.00	0.06	0.41
Panel B: Correlation matrix					
GDP	1.00				
NONRENEW	0.14	1.00			
RENEW	−0.27	0.39	1.00		
K	−0.03	0.83	0.78	1.00	
L	−0.17	0.76	0.78	0.92	1.00

Notes: Authors own computation

Table 2: ARDL regression results

Regression estimates	Renewable	Non-renewable
Panel A: Long-run		
K	−1.88E-0.6	−1.24
	(0.05)*	(0.00)***
L	0.72	−1.25
	(0.04)*	(0.72)
E	−0.09	0.16
	(0.04)*	(0.01)**
Panel B: Short-run		
ΔY(-1)	−0.89	1.37
	(0.00)***	(0.00)***
ΔY(-2)		0.85
		(0.00)***
ΔY(-3)		0.69
		(0.00)***
ΔK	−1.69E-06	−8.23E-06
	(0.21)	(0.00)***
ΔL	0.65	0.64
	(0.13)	(0.17)
ΔE	−0.08	0.12
	(0.17)	(0.06)*
ΔE(-1)		−0.16
		(0.00)***
Panel C: Cointegration tests and diagnostics		
F-bounds test statistic	5.05***	6.33***
BDS t-statistic	−6.76***	−7.86***
$\chi_{\text{normality}}$	0.00***	0.00***
$\chi_{\text{serial.correlation}}$	0.53	0.21
$\chi_{\text{heteroscedasticity}}$	0.12	0.25
$\chi_{\text{functional.form}}$	0.10	0.49
CUSUM	Passed	Passed
CUSUM.SQ	Failed	Failed

"***", "**", "*" denote the 1%, 5% and 10% critical values, respectively. Only P values are report for diagnostic tests

further analysis which account for possible asymmetries in the relationship.

In turning to the granger causality tests presented in Table 3, we observe that the null hypothesis of no causality from energy consumption to GDP is rejected for both non-renewable and renewable energy sources whilst reverse causality is confirmed at a 10% significance level. In other words, there exist reverse causality from GDP to energy consumption which is a result in support of the conservation hypothesis. Notably, the study of Bildirici (2013) confirms such causal effects from GDP growth to total energy consumption for South Africa albeit over a different sampled time period of 1978-2010.

Table 3: Granger causality tests

Null hypothesis	F-statistic	Probability
RENEW→GDP	0.42	0.78
GDP→RENEW	2.50	0.06*
NONRENEW→GDP	0.51	0.73
GDP→NONRENEW	2.65	0.05*

"***", "**", "*" denote the 1%, 5% and 10% critical values, respectively. Optimal lag set at 4 as determined by minimization of SC information criterion

Overall, the findings from these linear cointegration and causality analysis indicate a positive (negative) relationship exists between non-renewables (renewables) and growth with conservation hypothesis. In other words, the various energy policies undertaken by the South African energy authorities have not been growth stimulating and the energy sector is primarily driven by economic growth which, in turn, is outcome of fiscal and monetary policies. At best very short-run positive effects of renewable energy on growth are observed at earlier lags which turn negative at long lags and over the long-run. These results indicate existing "bottlenecks" in the economy which cannot transform the short-run gains of renewable energies into long-run growth effects.

4.3. Wavelet Coherence Analysis

We now present the empirical findings from the wavelet coherence analysis which are captured in spectrum plots with the time (frequency cycles) measured on the horizontal (vertical) axis. The wavelet plots present an exceptional analytical tool measuring the strength (weak or strong), direction (positive or negative) and causality of the co-movement between a pair of time series at any time period and at any frequency. The strength of the co-movement is captured by colour contours ranging from blue (strong coherency) to red (strong coherency) which are surrounded by a faint wite line denoting the 5% significance level. The direction and causality of the relationship are then determined by the arrow orientation within the colour contours whose outcomes are summarized as follows. A positive or in-phase co-movement with energy consumption leading (lagging) economic growth is shown by1, ↗, → (↘) whilst a negative co-movement (in-phase) with energy consumption leading (lagging) economic growth is shown by ↓, ↙, ← (↖).

Figures 2 and 3 present the wavelet coherence plot between non-renewable (renewable) energy consumption and economic growth in South Africa over a time window of between 1985 and 2022 and at frequencies ranging from 0 to 64 years. From the onset, we observe significant cyclical correlation, as indicated by the green colour contours, occurring existing at four levels of frequency bands i.e. 0-4, 4-8, 8-16 and 16-32 year cycles. Notably these significant oscillations occur over different time periods/horizons and consist of different phase dynamics which are summarized in Table 4 for convenience sake.

On one hand, we identify 3 bands of significant frequency cycles for the renewables-growth co-movement, with first (second and third) at 16-32 (8-16 and 0-4) year cycles stretching across 1985-2022 (2000-2022 and 2019-2022) time period indicating in-phase (anti-phase) or positive (negative) dynamics with energy leading growth. On the other hand, we find 4 bands of significant frequency cycles for the renewables-growth co-movement, with i) two lower (higher) frequency bands existing at 16-32 and 8-16 (0-4 and 4-8) year cycles found between 1985-2022 and 1985-2002 (2003-2009 and 2017-2022) which are inphase/positive (antiphase/negative) with growth leading (lagging) energy consumption.

Interestingly, our findings from the wavelet analysis tie together several contradicting results obtained in previous studies. For instance, our findings of i) a positive effect of renewables/non-renewables on growth at low frequencies concur with the findings of Kumar et al. (2015), Illesanmi and Tewari (2017), Bekun et al. (2019) ii) a negative effect of renewables/non-renewable on growth at higher frequency cycles are line with the findings of Esso (2010), and Shakouri and Yazdi (2017) iii) causal effects from non-renewable energy consumption to economic growth at all frequencies is similarly obtained in Wolde-Rufael (2010), Menyah and Wolde-Rufael (2010), Odhiambo (2010), Lin and Wesseh (2014), Bekun et al. (2019), Akadiri et al. (2019) iv) no significant phase dynamics existing at higher frequency cycles between 1985 and 2022 which is comparable with the insignificant coefficient

Figure 2: Wavelet coherence between renewable energy and GDP

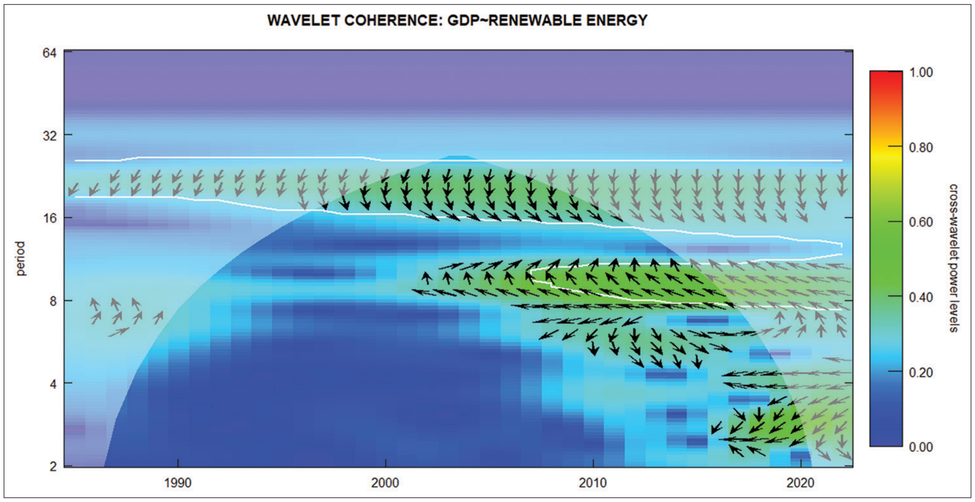


Figure 3: Wavelet coherence between non-renewable energy and GDP

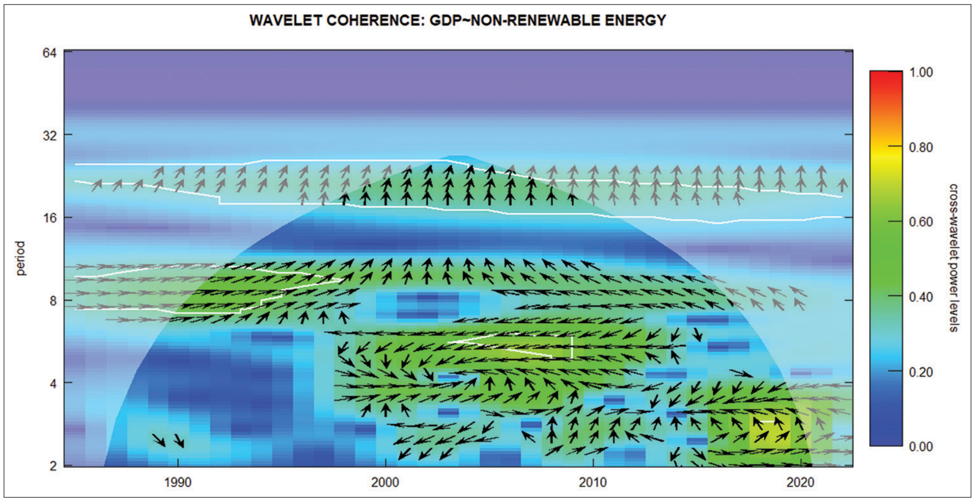


Table 4: Summary of phase dynamics in wavelet coherence plots

Frequency band	Phase dynamics	Renewables	Non-renewables
16-32 year cycles	Time period	1985-2022	1985-2022
	Sign	Positive	Positive
	Lead/lag	Y→E	E→Y
8-16 year cycles	Time period	2000-2022	1985-2000
	Sign	Negative	Positive
	Lead/lag	Y→E	E→Y
4-8 year cycles	Time period	N/A	2003-2009
	Sign	N/A	Negative
	Lead/lag	N/A	E→Y
0-4 year cycles	Time period	2019-2022	2019-2022
	Sign	Negative	Negative
	Lead/lag	Y→E	Y→E

estimates or lack of causality effects reported in Bhattacharya et al. (2016), Destek and Aslan (2017) and Nyoni and Phiri (2020).

Altogether, our findings provide evidence of sign and casual switching dynamics across different frequencies. For renewables, we observe a change from positive effect on economic growth with causal reflects remaining unchanged. For non-renewable we observe both sign and causal switching dynamics in its co-movement with economic growth across different frequency components. Furthermore, we note that whilst low-frequency co-movements between (non)renewable energy consumption and growth exist across the entire time period, higher-frequency co-movements emerge at two break points, the first in the early 2000's corresponding to which coincides with adoption of the White policy paper and subsequent policies aimed at reducing (increasing) dirty (clean) energy consumption, and the second during the more recent loadshedding.

5. CONCLUSION

Currently, South Africa is faced with a dual energy crisis attributed to the country's overreliance on dirty energy sources. One on hand, there is the problem of global warming of which South Africa is one of the world's largest emitters of carbon emissions, whilst, on the other hand, there is the loadshedding caused by insufficient supply of dirty energy to meet the economy's demand. Renewables have been increasing considered a panacea to South Africa's domestic and global energy problems and hence academics and policymakers are interested in determining the sustainability of renewable energy consumption for economic development.

We examine whether renewables or non-renewables energies are a sustainable source of economic growth in South Africa using linear ARDL cointegration, VAR-based causality tests and wavelet coherence analysis over a sample period of 1985-2022. Whilst the linear methods find a positive (negative) effect of non-renewable (renewable) on economic growth with non-renewables (economic growth) causing economic growth (renewables), the wavelet analysis further show significant switching dynamics from low frequency to higher frequency with higher frequencies appearing at dates corresponding to the adoption of the White policy paper and the loadshedding experienced during the COVID period. Notably the findings from the wavelet encompass those from the ARDL model and further "harmonize" inconsistent results obtained in previous South African studies.

Collectively, our findings imply that whilst South Africa's dependence on dirty energy sources creates short-run negative effects on economic growth the lowering of economic makes economic agents to increase their consumption of renewable energy. However, these short-run correlations do not translate into long-run effects hence highlighting bottlenecks which are preventing renewable energy being sustainable for long-run growth. Overall, these findings indicate that South African energy regulators have not taken strong enough measures to ensure that renewables contribute to sustainable growth. Therefore, without key actions in the energy sector that can create structural change which can enable renewable energy to sustain long-term economic growth (or to make long term growth dependent on clean energy), the current implemented policies can only produce transitory and not permanent effects.

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