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Original Research

Modelling Coal Energy Consumption and Economic Growth: Does Asymmetry Matter in the Case of South Africa?

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Abstract

In accordance with the Intergovernmental Panel on Climate Change (IPCC), Kyoto protocol and the United Nations Sustainable development goals (UNSDGs) on climate action (SDG-13), there has been a need across economies for transition from fossil-fuel-based energy sources such as coal energy consumption to cleaner energy options i.e., a transition to a low-carbon economy. To this end, the present study explores the asymmetric relationship between coal energy consumption, economic growth, rising urban population and emission level in South Africa. The present study span is conducted on an annual frequency basis from 1965-2018. This study applies the novel Non-linear Autoregressive distributed lag methodology (NARDL) for the highlighted variables. Empirical results validate the asymmetric relationship between the variables under review over the study period. The NARDL regression further shows positive shock by GDP increases CO_2 emission level while negative impact affects otherwise in the long run. On the other hand, coal consumption positive shock exhibits a detrimental impact on environmental quality in South Africa. This is insightful for policymakers. The urban population shows non-significant effect on emission levels over the sampled period. The knowledge of both positive and negative shock effects of GDP, coal energy consumption and urban growth is vital for policy

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construction in terms of both economic and environmental sustainability. Thus, policy prescription ranges from energy transition to alternative and cleaner energy sources like renewables and responsible energy consumption (SDG-12) should be pursued in South Africa. More far-reaching environmental policies are highlighted in the concluding section.

Keywords: SDGs, carbon-reduction, green economy, Kyoto protocol, economic growth, South Africa

Introduction

Environmental deterioration is a global issue that has constantly been at the forefront of international discussion. Curbing greenhouse emissions globally by 18 percent which represents an increase from the average of 5 percent reduction as agreed in the 1990 Kyoto protocol is expected to be enforced with effect from December 2020 according to the Doha amendment to the Kyoto protocol [1]. This paper is aimed at empirically investigating the impact of coal energy consumption and economic growth on South Africa's environment. South Africa is appropriate and interesting for this study because it is one of the largest coal-producing and exporting countries in the world with about 77 percent of the country's primary energy being met by coal.

Coal energy plays an important role in meeting the domestic energy demand in South Africa due to its abundance and serves as a source of cheap energy source by international standards. South Africa's coal deposits are relatively shallow with thick seams, which make them easier and, usually, cheaper to mine. At the present production rate, there should be more than 50 years of coal supply left. Conversely, coal has also been the major source of carbon dioxide emission in the country, with the share of CO_2 world emission standing at 1.4% [2]. Therefore, South Africa is faced with the dilemma of reducing carbon dioxide emissions at the cost of energy security. As seen in Table 1, Figs 1 and 2, South Africa is not only contributing to carbon dioxide emission domestically, but by exporting coal to other countries, South Africa further contributes to the global deterioration of the greenhouse emission, thereby making the objectives of the Kyoto protocol a tall order to achieve.

Furthermore, South Africa a major exporter of Coal is further faced with the dilemma of Coal production and economic growth. Coal is a major source of foreign earnings for this country, with Coal earnings

Table 1. Socio-economic and coal consumption fact sheet (2019) for South Africa.

Indicator(s)	Quantity
GDP (constant 2010 Million US$)	430166.00
Population, total (Million)	59.00
GDP growth	0.15%
Coal production (Exajoules)	6.02
Coal consumption (Exajoules)	3.81
Coal export (Exajoules)	2.2
Percentage of world coal consumption	2.4%
Percentage of world coal production	3.6%
Growth in coal consumption	1.4%
Growth in coal production	0.4%
Electricity generation from coal (Terawatt-hours)	217.3
Electricity generation from oil (Terawatt-hours)	1.202
Electricity generation from natural gas (Terawatt-hours)	1.9
Electricity generation from Nuclear Energy (Terawatt-hours)	14.2
Electricity generation from Hydroelectric (Terawatt-hours)	0.8
Electricity generation from Renewables (Terawatt-hours)	12.6

Source: Data for GDP, population and GDP growth was obtained from the World Bank development indicator. Data for all other indicators were taken from [2].

contributing R51 billion to the GDP, 22.5 percent to mining value and employing 91 605 individuals in 2013 [3] by 2020 the number of individuals employed has decreased to 91 459 while contributing only 1.9% of the GDP [4, 5]. The recent [6] report covering the period 2019-2030 has shown consistent commitment to coal plants as a source of electricity generation and employment opportunities in the country, coal will continually play an important role since it has the largest base of installed electricity generation capacity and decommissioning the coal power plant will be accompanied with potential job loss within the country yet the country planned to decommission 11.5 GW of old coal-powered fire plant while constructing new utility-scale wind and solar photovoltaic energy source, with the hope that carbon capture and storage, underground coal gasification, and other clean coal technologies will make the use of coal more environmental friendly.

Despite this expectation, foreign earnings from coal have dropped from 7% in 2011 to 4.6% in 2020 and this is primarily due to a reduction in international demand especially in Europe forcing South Africa to focus its export to Asia especially India which is South Africa's recent largest coal export destination.

Another issue relating to the Coal industry in South Africa is creative destruction of the industry given the continuous fall in the cost of global renewable energy sources coupled with climate change awareness; therefore, India is switching its national electricity system to renewable energy source whilst pursuing the cleaner source of energy and water production due to continuous fall solar PV and wind power cost since 2017 [7, 8].

South Africa cannot continue to hold on to coal as its main source of energy or earning since both foreign and local investors are diversifying their investments away from coal for mining and electricity generation and instead moving towards renewable sources such as gas and Solar energy. The Financial industries have also embarked on policies that restrict or ban investments in coal-related projects, with the four largest banks in South Africa committed to restricting lending to new coal projects. These banks have argued that if South Africa's economy is coal-reliant, the country will not have the incentive to abolish coal as a source

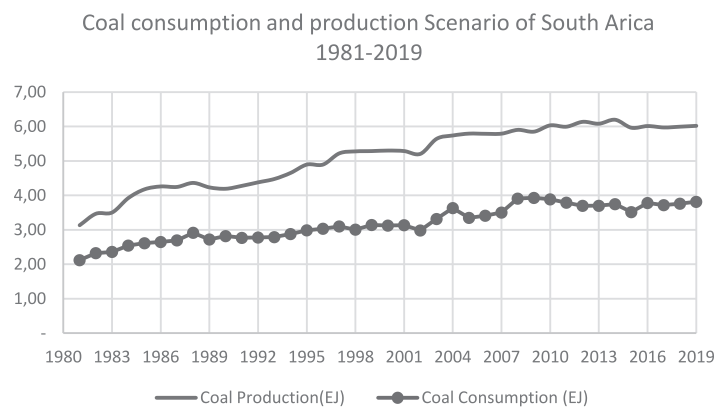

Fig. 1. Trend analysis of Coal consumption and production Scenario of South Arica 1981-2019. Data source: BP Stat Review (2020).

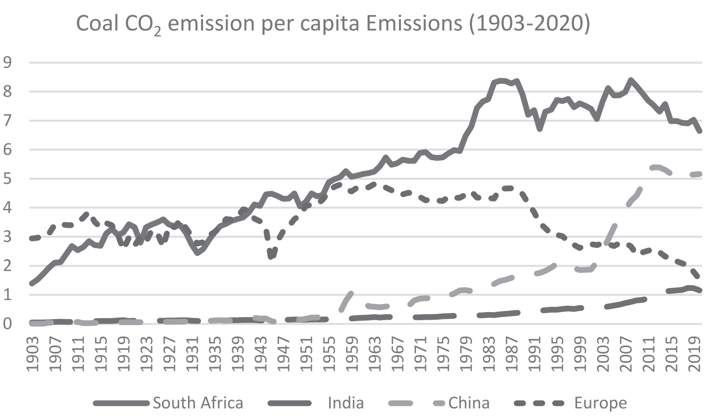

Fig. 2. Trend analysis Coal CO_2 emission per capita Emissions (1903-2020).
Data source: ourworldindata.org/fossil-fuels[2]

[1] Our world in data available at: https://ourworldindata.org/fossil-fuels. Accessed:15/11/2021

of energy and seek for cleaner alternative sources [5]. This reality means that South Africa has no choice than to move away from coal a dirty source of energy and move towards cleaner production just like the rest of the world. Therefore, the current study deviates from conventional ARDL techniques applied to explore the nexus between coal energy consumption and economic growth as seen in the literature such as Odhiambo [9], Adebayo, et al. [10], Shahbaz et al [11], Bildirici and Bakirtas [27], Joshua and Alola [13]. Also, this study differs from other studies that explored the relationship between coal consumption and economic growth using different techniques such as the Granger causality test, Toda Yamamoto test, and other forms of causality tests [14-16]. In this study, we leveraged the novel Nonlinear Autoregressive Distributed Lag (NARDL) model developed by Shin, Yu, and Greenwood-Nimmo [9]. Subsequently, asymmetric cointegration is examined over the study-outlined variables and offers insights into both positive and negative shocks of coal energy consumption, urbanization and CO_2 emission. Therefore, it is imperative to establish an empirical causal link between coal consumption and economic growth considering carbon dioxide emissions from coal production and emissions for South Africa. This study aims to establish the existence and direction of causality, the policy implications, and the future policy options for South Africa.

The next section presents stylized fact on the South African energy mix with respect to coal energy while the subsequent section focuses on reviews of related empirical studies, the third section discusses the data and methodology, the results and discussions were presented in the fourth section while conclusion and policy recommendation was presented in section 5.

Stylized Fact on Coal Energy and Economic Growth: A Synopsis on South Africa

The Republic of South Africa has a serene air-breathing taking environment with dynamic geographical features with a coastline that stretches over 2500 km (1600 miles). The Republic of South Africa is bordered by Namibia on the west coast and the South around the top of Africa and its north Mozambique. The Republic of South Africa (RSA, hereafter) is a well-known and emerging nation enlisted into the prestigious BRICS blocs for its fast-growing economies with rich and promising macroeconomic indices. The RSA prides itself on its natural resources, energy, and financial sector as an open economy.

The RSA is known to depend heavily on its coal energy sector as the key driver for its growth. The energy sector accounts for 15% of South Africa's GDP with coal energy being the major energy resource and opening an avenue for approximately 250,000 employment opportunities for the nation's populace. The RSA demonstrates unique traits that distinguish it from other emerging African countries. The unique characteristic of the South African economy is that the country is also the largest emitter of CO_2 emission in Africa (~45% of the continental total) and 7th in the world (Energy data [17]). Additionally, the share of energy generation from coal energy is approximately 77% of the total energy generation capacity largest consumer of coal in the African bloc. Recent data show that the country's electricity generation is mainly from coal energy sources which account for approximately 90% of the country energy with next nuclear with a share of 5.2% and natural gas with the least share accounting for 3.2%. Additionally, given the increased timing populace in the country, the electricity demand is estimated to increase to more than 56,000MW as outlined by the (DOE, [18]). RSA is ranked as 6th largest producer of coal on a global scale, the country's primary energy is powered by coal energy. The nation of South Africa has been structured energy production and supply system. Although the nation is reliant on coal energy as a primary energy source, the nation has the limited account of crude oil and natural gas deposits. More recently the nations seek to exploit and leverage on its rich sunshine as source of electrification for both its residential and industrial layout (DEM [19]; Bekun et al. [20]). On the other hand, the nation of South African transition to renewable energy is very negligible to the nation's energy mix.

Literature Review

This section will explore discussions on the relationship between energy consumption, economic growth, and environmental degradation using urbanization as the control variable. This interaction is reviewed accordingly below:

The popular notion that environmental pollution or degradation is peculiar to developing countries unlike developed economies is inconsistent with the current global climate change initiative trend. There is a significant negative effect of greenhouse gas deposition on the rest of the world irrespective of who is responsible for what is ravaging the world, whether developed or developing countries are having their fair share of it. Climate change affects global temperature and precipitation patterns. The outcome of this effect, in turn, influences the intensity and, in some cases, the frequency of extreme environmental events such as forest fires, hurricanes, heat waves, floods, drought, and storms. These outcomes do not respect economic boundaries and are not limited to developed or developing economies. The consequences of these environmental degradations have far-reaching impacts on infrastructures, farmland, trees, aquatic life, products, and most importantly, valuable human lives. Hence, the concern and a need to review the consequences of global development and environmental consequences for policymakers, economists, and researchers.

Coal has remained the alternate source of energy both in advanced and emerging economies, thereby displacing conventional sources. Coal is observed to be very cheap and easily available to meet the rising demand for energy that traditional sources are unable to fulfill effectively and efficiently. Given that South Africa is endowed abundantly with a significant amount of coal, in its exploitation and exploration to grow the economy has a record of massive energy-linked degradation. Hence, this literature to review the consumption of coal vis-à-vis economic growth, exploring the pathway of asymmetry in South African economy.

Energy-Growth Nexus Insight

The influential study of Kraft and Kraft [10] on the energy-growth nexus has ignited in-depth discussion which has redefined the shape and scope of energy literature. The concept of energy consumption as a key driver of economic growth and development has spurred reasonable interest to explore the interaction between energy consumption and economic output. For this study, coal consumption will be used to represent energy consumption as it is a major component of the nonrenewable energy source. In light of extensive discussion regarding the role of energy consumption to economic growth, there are four hypotheses (testable) regarding the nexus of coal use and economic growth that can be applied to different countries. They are (i) Growth hypothesis - meaning that causality flows from coal consumption to economic growth. There is an indication by implication of the important role played by coal consumption in attaining economic growth. An increase in coal consumption could result in a rise in economic activities, thereby causing higher GDP growth. (ii) Conservative hypothesis - this explains the causality that is one way running from economic growth to coal use. This hypothesis suggests strongly that coal consumption does not cause the economy to grow and develop, thereby implying that coal conservation policies will not promote economic growth in any form. Hence, increase in economic growth permanently may increase coal consumption permanently. (iii) Feedback hypothesis - this is a case of bidirectional causality running from coal use to economic output and from economic growth to coal use. Both variables complement each other and are interdependent. (iv) Neutrality - this is an opposite of feedback where there are no causal interactions between coal use and economic output. This also suggests that neither conservative nor growth policies with regards to coal consumption will significantly influence the outcome of economic growth in a significant way. From the empirical studies done, there is no consensus reached regarding the link between coal use and economic output, but there is considerable attention on the subject matter in which different causal relationships among these variables under consideration have been established.

Jinke et al. [11], and Wolde-Rufael [12] in their study found evidence in support of the growth hypothesis. This causal relationship was running from economic growth to coal consumption. Govindaraju and Tang [13] in their study found evidence to support the neutrality hypothesis. Implying coal use had no causal relation to economic output and vice versa. Interestingly for India, different results and conclusions ranging from growth, conservative and neutrality hypotheses were produced by Jinke et al. [11] and Bhattacharya et al. [14], and Govindaraju and Tang [13], respectively. In the case of Japan, Wolde-Rufael [12] found unidirectional causality running from coal use to economic output but Jinke et al. [11] showed one-way causality flowing from economic output to consumption of coal. In the same vein, studies from Korea further confirms different results. Wolde-Rufael [12] found from his investigation a conservative hypothesis whereas Jinke et al. [11] in their studies independently found bidirectional and neutrality hypotheses respectively. In the case of Nigeria, Nasiru [15] revealed conservative hypothesis showing causality stemming from economic output to coal use. The United States was confirmed to have feedback causality between the consumption of coal and economic output (2010). Jinke et al. [11] in the case of South Africa, found evidence in favor of neutrality hypothesis whereas Wolde-Rufael [12] found evidence of the feedback hypothesis.

Coal Consumption and Environmental Sustainability

More recently the study of Joshua & Alola [21] explores the theme of coal-led growth while accounting for the role of employment and FDI influx for South Africa using the traditional ARDL approach. The study results include that suggesting that a 1% increase in coal consumption in South Africa translated into a 68% emission in the short run, and 56% in the long run respectively. The study highlights the fact that coal energy consumption is detrimental to the environmental sustainability of the South African economy while FDI influx improves the environmental quality in KSA. The study suggested the need for alternative ad clean energy sources to achieve SDG-13. A similar study for Turley conducted by Alola & Donve [22] outlined the detrimental effect of coal and oil energy on the Turkish economy over study period. The study also failed to validate the EKC hypothesis in Turkey.

Anoruo [16] in his study involving 15 African countries employed panel structure for analysis and found evidence supporting conservative hypothesis. Using the same panel data analysis, Apergis and Payne [23, 24] in their studies of 15 emerging markets and 25 OECD countries respectively found bidirectional hypothesis in both groups. Li and Leung [25] examined regional effects within China using the panel methods of analysis and evidence confirmed differences among the regions. Table 2 gives summary of the existing

Table 2. Summary of empirical review in the relationship between Coal Use and Economic Output using times series approach and panel data analysis.

N	Author(s)	Period	Reviewed Countries	Methodology	Variables	Findings or Causality
	Category A (Time series method using Cross- country analysis)					
1	Lei et al. [26]	2000 - 2010	Top six coal consuming countries	Engle-Granger VECM	Coal Consumption RGDP Coal price	China: Conservation Germany: Feedback India: Neutral Japan: Feedback Russia: Feedback U S: Neutral
2	Wolde-Rufael [12]	1965 - 2006	JUCISK Countries	Toda-Yamamoto Granger causality	Coal consumption Real GDP	Japan: Growth United States: Feedback China: Conservative India: Growth South Africa: Feedback Korea: Neutrality
3	Bildirici and Bakirtas [27]	1980-2011	BRICTS Countries	ARDL Cointegration ECM	Coal consumption Real GDP	Brazil: Growth, Russia: NR, India: Growth, China: Feedback, Turkey: NR, South Africa: NR
4	Jinke et al. [11]	1980-2005	South Africa, India, China, Korea, Japan	Engle-Granger VECM	Coal consumption Real GDP	South Africa: Neutrality India: Neutrality China: Conservation Korea: Neutrality Japan: Conservation
5	Chandran Govindaraju and Tang [13]	1965-2006	China India	Engle-Granger VECM	Coal Consumption RGDP Carbon emissions Squared GDP	China: Neutrality India: Conservation
6	Yang [28]	1957-1997	Taiwan	Engle-Granger No cointegration Granger causality	Coal Consumption Real GNP	Taiwan: Conservation
7	Wolde-Rufael [29]	1952-1999	Shanghai	Toda-Yamamoto Granger causality	Coal Consumption RGDP	Shanghai: Growth
8	Payne [30]	1949-2005	United States	Toda-Yamamoto Granger causality	Coal Consumption RGDP Real gross fixed capital formation Employment	United States: Neutrality
9	Lee and Chang [31]	1954-2003	Taiwan	Johansen-Juselius Cointegration Gregory-Hansen	Coal consumption RGDP per capita	Taiwan: Feedback
10	Bloch et al [32]	1965-2008	China	Johansen-Juselius Granger causality	DS: Coal Consumption RGDP, Price and CO_2 SS: Real GDP Labour Capital Coal Consumption	Demand Side: Growth Supply Side: Growth
11	Kulshreshtha and Parikh [33]	1970-1995	India	Johansen-Juselius Granger causality	Coal Consumption RGDP	NR
12	Rahman et al. [34]	1981-2016	China	FMOLS, Johansen cointegration VECM	Coal, oil, gas consumption, RGDP,	Growth

cross-country empirical review using two categories of studies about coal use and economic output relationship.

Table 2. Continued.

	Category B (Panel data analysis)					
13	Anoruo [16]	1980-2012	15 African countries	Bootstrap Granger causality	Coal consumption Real GDP	Conservation
14	Apergis and Payne [24]	1980-2006	15 Emerging markets	Pedroni cointegration VECM	Coal consumption Real GDP Capital Labour	Feedback
15	Li and Leung [25]	1985-2008	China	Pedroni cointegration Granger causality	Coal consumption Real GDP	Feedback (coastal & eastern region) Conservation (western region)
16	Apergis and Payne [23]	1980-2005A	25 OECD Countries	Larsson et al cointegration VECM	Coal consumption Real GDP Capital Labour	Feedback

Note: JUCISK denotes Japan United States China India South Africa Korea; JUCIS: Japan, United States, China, India and South Africa; BRICTS: Brazil, Russia, India, China, Turkey and South Africa; VECM: Vector Error Correction Model; DS: Demand side model; SS: Supply side model; ARDL: Autoregressive Distribution Lag; ECM: Error Correction Model; NR: Not Related.

Material and Methods

This section presents the data and methodological sequence of the study. The current study aims to investigate the asymmetric effect of economic growth (GDP) and coal consumption (COAL) on carbon dioxide (CO_2) emissions by controlling urbanization (URB). To this end, the study utilizes the annual data for South Africa over the period 1965-2018. The selected time span is restricted due to the availability of data. All the data under consideration is obtained from the World Development Indicator (WDI) database. The following model specification is in line with previous studies such as Gyamfi et al. [35], Joshua et al. [36], and Farhani and Ozturk [37].

$$CO_{2_t} = f\left(GDP_t, COAL_t, URB_{t,}\right) \tag{1}$$

Urbanization is used as a control variable. In doing so, the study aimed to shed light on urbanization role in CO_2 emission for South Africa. For this reason, our present model is conceptually different from other studies In the existing literature, most of the studies such as Joshua et al. [36], Farhani and Ozturk [37], Pachiyappan et al. [38] used the conventional ARDL bounds testing approach to explore the long-run relationship between the variables with a mixed order of integration (either I(0) or I(1). However, the aim of this study is to analyze the short- and long-run asymmetric effect of the aforementioned independent variables on CO_2 emission. To this end, the study applies the novel asymmetric ARDL (NARDL) technique which is proposed by Shin et al. [9]. The NARDL approach is an asymmetric extension of the standard ARDL model, preserving all the advantages of the ARDL model. Thus, it helps us to capture both short- and long-run asymmetries in a variable under consideration. The key advantage of this method is that both co-integration and asymmetry can be determined by using a single equation. Additionally, compared to the Johansen cointegration method which requires a larger sample size to generate significant results, it can provide statistically significant results even for small sample sizes (Ghosh [39]; İçen & Tatoğlu [40]. There are two prerequisites for the ARDL model to be applied: (1) The integration order of the variables must be I(1) (Sarkodie et al. [41]). It means, the independent variables can be stationary at their level I(0) or first difference I(1) while the dependent variable must be I(1). (2) The variables should be cointegrated (Zhang et al., [42]). Furthermore, Granger and Yoon [43] assert the existence of hidden cointegration if there is a long-run relationship between the positive and negative components of the time series data (Katrakilidis & Trachanas, [44]). Also, they showed that hidden cointegration is a special case of symmetric cointegration. The NARDL model helps us to capture the short- and long-run asymmetries in the variables. Hence, the present study employed the asymmetric ARDL modeling approach to determine the asymmetric relation between CO_2 emissions, coal consumption, economic growth, and urbanization in South Africa. Before presenting the NARDL model, the conventional symmetric ARDL (p, q) is written as follows:

$$\Delta CO_{2_t} = \alpha + \sum_{j=1}^{p} \delta_1 \Delta CO_{2_{t-j}} + \sum_{j=0}^{p} \delta_2 \Delta GDP_{t-j} + \sum_{j=0}^{p} \delta_3 \Delta COAL_{t-j} \quad \sum_{j=0}^{p} \delta_4 \Delta URB_{t-j} + \beta_1 CO_{2_{t-1}} + \beta_2 GDP_{t-1} + \beta_3 COAL_{t-1} + \beta_4 URB_{t-1} + \varepsilon_t \tag{2}$$

where Δ shows the first difference, δ and β parameters indicate the short- and long-run multipliers of the ARDL model. The corresponding null hypothesis of "$\beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$" in Eq. (1) is tested by computing F-statistics.

Next, regarding the concept of nonlinearity the NARDL model is given as an extension of Equation (1):

$$y_t = \beta^+ x_t^+ + \beta^- x_t^- \quad (3)$$

whereas asymmetric long-run parameters are shown as β^+ and β^-, and x_t is a kx1 vector of explanatory variables decomposed as:

$$x_t = x_0 + x_t^+ + x_t^- \quad (4)$$

here x_t^+ and x_t^- indicate partial sum processes of positive and negative dynamics in x_t:

$$x_t^+ = \sum_{i=1}^{t} \Delta x_i^+ = \sum_{i=1}^{t} \max(\Delta x_i, 0)$$

$$\text{and} \quad x_t^- = \sum_{i=1}^{t} \Delta x_i^- = \sum_{i=1}^{t} \min(\Delta x_i, 0) \quad (5)$$

Finally, the error correction form of the NARDL model can be written as:

$$\Delta y_t = \varphi_0 + \rho y_{t-1} + \pi^+ x_{t-1}^+ + \pi^- x_{t-1}^- + \sum_{i=1}^{p-1} \sigma_i \Delta y_{t-i} + \sum_{i=0}^{q} (\gamma_i^+ \Delta x_{t-i}^+ + \gamma_i^- \Delta x_{t-i}^-) + \varepsilon_t \quad (6)$$

Where $\pi^+ = -\rho\beta^+$ and $\pi^- = -\rho\beta^-$ denote the asymmetric long-run parameters.[2]

The estimations of the NARDL technique involves the following steps: First, it is crucial and prerequisite to confirm that none of the variables under consideration are integrated of order two, i.e I(2). If this condition does not hold, the calculated F-statistics for testing cointegration will be invalid. Second, Equation (6) can be estimated by using the Ordinary Least Squares (OLS) method. The general-to-specific procedure has been adopted to obtain the final specification of the NARDL model as suggested by Katrakilidis and Trachanas [44]. Starting with maximum lags (*max p = max q = 12*) and dropping all insignificant stationary regressors yields the optimal specification. In practice, the inclusion of insignificant lags is likely to result in inaccurate estimation and could add noise to the dynamic multipliers. Third, testing the presence of the long-run relationship between the level form of variables by using the bound-testing approach proposed by Pesaran et al. [45] and Shin et al. [9]. This refers to the modified F test of the null hypothesis of $\rho = \pi^+ = \pi^-$ in Eq. (5). Fourth, after confirming the presence of a long-run relationship, we investigate the long- and short-run asymmetries effect of real GDP, COAL, and URB on CO_2 emissions within the investigated period. Finally, there is a need to apply several diagnostic tests including normal distribution, heteroscedasticity, and autocorrelation to check the validity of estimated results.

Results and Discussion

This section of this study focuses on the preliminary analysis of basic summary statistics of the underlined variables of interest. This summary statistics comprises of the basic moments of the series namely mean, variance and covariance. Additionally, peakness and normality is tested over the study period. Table 3 shows that GDP has the highest average over the sampled period as well and both minimum and maximum. All variables of interest are positively skewed while the normality assumption is rejected. Subsequently, the avoid the pitfall of spurious analysis stationarity test is examined in Table 4 which presents the conventional ADF and PP unit root test and KPSS stationarity test for confirmation. All stationarity test is in the submission that all variables are the first stationary over investigated period. To ascertain the right path to NARDL we conducted the nonlinearity test reported in Table 5 which confirms the non-linearity of the series of interest. This is in agreement with the preliminary analysis of normality.

Subsequently to investigate for long-run relationship over study variables the asymmetric NARDL bounds test shows asymmetric long-run bound exist between all the variables under review as presented in Table 6. The baseline regression fitted in a carbon-income function with emission as dependent variables while coal energy, economic growth, and urban population are presented in Table 7. The GDP growth-induced emission level is validated in South Africa. This implied that economic expansion has a detrimental effect on South Africa. This outcome is in line with the study of Magazzino et al. [46]. However, in this study case, NARDL is considered that presents both positive and negative effects for adequate policy construction. For instance, a 1% positive shock to GDP exert 0.841% on the environment in South Africa in the long run while a negative shock decreases the emission level in South Africa. The plausible intuition could be a decrease in production level and industrial activities which will reduce emission level (Joshua et al. [30]). In the relationship between GDP growth and emission level, both positive and negative shocks are detrimental to economic growth. This outcome is suggestive for governmental administrators to disentangle economic growth from emissions. Thus, promoting a green economy through the adoption of cleaner energy alternatives such as geothermal, solar, and other renewable energy sources (Khan et al. [47]; Sharif et al. [48]; Xia et al. [49]). Subsequently, coal energy consumption significantly induces emission levels by increasing CO_2 emission over the investigated period. That is a 1% positive shock on coal in the long run increasing the emission level by 0.41% while negative externalities reduce emission level by 0.93%. Interestingly our study finds a non-significant relationship between urban population and CO_2 emission in South Africa. The logic is attributed

2 For want of space further insight on NARDL method formulation see, Shin et al. [9].

to the current domestic thrives by the South African to mitigate climate change issues such as being member of environmental treaties and an awareness program that sensitizes her urban population to the detrimental effect of environmental degradation. This reducing effect of urban population on emission is due to environmental education and investment in research and development in cleaner and green economy pursued target by the country. The South African economic growth path and her urban growth are all-inclusive and have drawn policy attention such as the enaction of the Action Plan for energy, climate for the City of Cape Town and renewable energy technologies have been adopted in its energy portfolio mix by the country. Thus, aligning with her environmental sustainability target. This calls for sound macroeconomic policies on energy conservation policies that are renewable energy driven. By implication, an attempt to deviate from this path will be detrimental to her sustainability goal of green economics without compromise for economic expansion. Furthermore, on the asymmetric causality analysis reported in Table 8, the results corroborate the outcomes of the baseline regression. For instance, there exists an asymmetric relationship between the negative externality CO_2 emission and GDP and vice versa. This implies there exists a negative feedback asymmetric causality emission level and economic growth for South Africa, suggesting that negative externalities have more impact on environmental degradation. We also observed that one-way asymmetric causality between economic growth and CO_2 emission which highlights the impact of the positive shock of economic expansion on environmental degradation in South Africa. Additionally, negative shock on coal energy consumption also stimulates environmental issues in the study area. Indicating that coal energy consumption is detrimental so South Africa's sustainability target

In conclusion of this discussion section, it is obvious that there is a need on the part of government officials and energy stakeholders to formulate macroeconomic policies that are objective and directed to clean energy alternatives to drive the South African economy and make a deliberate transition

Table 3. Summary Statistics.

	CO_2	GDP	COAL	URB
Observations	53	53	53	53
Mean	5.598	26.168	4.042	3.987
Median	5.727	26.125	4.199	3.966
Maximum	6.108	26.786	4.541	4.195
Minimum	4.746	25.398	3.192	3.855
Std. Dev.	0.430	0.386	0.436	0.113
Skewness	-0.648	-0.031	-0.746	0.408
Kurtosis	2.167	2.117	2.106	1.711
Jarque-Bera	5.430***	1.762	6.838**	5.236***
Sum	296.735	1413.095	214.209	215.285
Sum Sq. Dev.	9.615	7.916	9.744	0.672

Source: Authors Computation. ** and *** indicate 5 and 10 percent significance level

Table 4. Unit root tests.

Series	ADF		PP		KSS	
Variable	Level	Difference	Level	Difference	Level	Difference
	T-Stat	T-Stat	T-Stat	T-Stat	KSS Stat	KSS Stat
CO_2	-1.732	-5.921*	-1.679	-5.933*	-1.963	-4.365**
GDP	-1.407	-4.646**	-1.754	-4.546**	-2.938	-4.130**
COAL	-2.250	-6.781*	-2.315	-6.781*	-2.118	-3.973**
URB	-1.603	-4.912*	2.659	-4.824*	-5.684*	-7.892*

Note: ** and * indicate 5 and 1 percent significance level.

Table 5. BDS Test of Nonlinearity .

Variables	Dimensions (m)				
	2	3	4	5	6
CO_2	24.980*	26.181*	27.812*	30.335*	33.716*
GDP	28.347*	29.610*	31.483*	34.408*	38.593*
COAL	23.350*	24.789*	26.676*	29.428*	33.207*
URB	28.634*	29.731*	31.417*	34.232*	38.315*

Note: * denotes the rejection of the null hypothesis at 0.01 significance level.

Table 6. ARDL and NARDL bounds test.

Dep. Variable ΔCO_2	F-stat.	0.05 lower bound	0.05 upper bound	Outcome
ARDL (1,0,1,4) model.	$F_{PSS,linear}$: 3.913**	2.79	3.20	Existence of cointegration
NARDL[a]	$F_{PSS,nonlinear}$: 6.138**	2.45	3.52	Existence of cointegration

Note: * represent significance at 0.01. Asymptotic critical value (CV) bounds are derived from Pesaran et. al, (2001) CV case III and choose k = 4. [a]

Table 7. Asymmetric ARDL test results.

Dependent variable: ΔCO_2			
Variable	Coef.	Std. error	T-ratio [Prob]
Long-run			
constant	5.022*	1.447	3.47 [0.005]
CO_2 (-1)	-0.079*	0.310	-3.48 [0.005]
GDP^+(-1)	0.841**	0.287	2.93 [0.013]
GDP^-(-1)	-2.372**	1.055	2.25 [0.044]
$Coal^+$(-1)	0.408***	0.196	2.07 [0.060]
$Coal^-$(-1)	-0.925*	0.235	-3.93 [0.002]
Urb^+(-1)	-0.018	0.012	-1.63 [0.129]
Short-run			
ΔCO_2(-1)	-0.391**	0.158	-2.47 [0.029]
ΔGDP^+	0.308**	0.131	2.35 [0.037]
ΔGDP^-	0.779***	0.451	1.73 [0.099]
$\Delta Coal^+$	0.739*	0.081	9.15 [0.000]
$\Delta Coal^+$(-2)	0.652***	0.329	1.98 [0.071]
$\Delta Coal^-$	0.552*	0.128	4.31 [0.001]
$\Delta Coal^-(-3)$	-0.391**	0.158	-2.47 [0.029]
$\Delta Coal^-(-4)$	-0.390**	0.183	-2.13 [0.055]
L^+GDP	0.778*	L^-GDP	2.197**
L^+Coal	-0.378**	L^-Coal	-0.856*
L^+Urb	-0.018***	L^-Urb	------

Table 7. Continued.

Diagnostic Test			
R^2	0.955	R-bar^2	0.932
X^2_{NORM}	0.352 [0.839]	X^2_{HET}	1.168 [0.279]
F_{FF}	0.141 [0.931]	X^2_{AC}	23.730 [0.361]
$W_{LR,\ GDP}$	8.508** [0.013]	$W_{SR,\ GDP}$	0.355 [0.562]
$W_{LR,\ Coal}$	6.544** [0.025]	$W_{SR,\ Coal}$	9.770** [0.009]
$W_{LR,\ Urb}$	3.987***[0.069]	$W_{SR,\ Urb}$	4.902** [0.047]

Notes: L^- and L^+ denote the obtained long-term coefficients related to the (-) and (+) changes., $X^2_{NORM,}$ X^2_{AC} and X^2_{HET} are the LM tests for normality, autocorrelation and heteroscedasticity. The F_{FF} is the F-test for the model functional pattern. W_{LR} and W_{SR} are the Wald test stat for the null proposition of the presence of a long-term and short-term symmetry in the model. ***, ** and * denote significance at the 0.10, 0.5 and 0.01 levels.

Table 8. Asymmetric Granger causality tests.

Hypothesis	Fisher statistics	P-value	Decision
$CO_2^+ \not\Rightarrow GDP^+$ (1)	2.225	0.329	Fail to Reject
$CO_2^+ \not\Rightarrow GDP^-$ (2)	0.232	0.890	Fail to Reject
$CO_2^- \not\Rightarrow GDP^-$ (3)	5.260***	0.072	Reject
$CO_2^- \not\Rightarrow GDP^+$ (4)	9.852	0.008	Reject
$GDP^+ \not\Rightarrow CO_2^+$ (5)	6.800**	0.033	Reject
$GDP^+ \not\Rightarrow CO_2^-$ (6)	2.712	0.258	Fail to Reject
$GDP^- \not\Rightarrow CO_2^-$ (7)	5.629***	0.060	Fail to Reject
$GDP^- \not\Rightarrow CO_2^+$ (8)	1.029	0.598	Fail to Reject
$CO_2^+ \not\Rightarrow Coal^+$ (9)	0.471	0.790	Fail to Reject
$CO_2^+ \not\Rightarrow Coal^-$ (10)	2.934	0.231	Fail to Reject
$CO_2^- \not\Rightarrow Coal^-$ (11)	1.232	0.540	Fail to Reject
$CO_2^- \not\Rightarrow Coal^+$ (12)	2.546	0.280	Fail to Reject
$Coal^+ \not\Rightarrow CO_2^+$ (13)	0.566	0.754	Fail to Reject
$Coal^+ \not\Rightarrow CO_2^-$ (14)	3.507	0.173	Fail to Reject
$Coal^- \not\Rightarrow CO_2^-$ (15)	12.611*	0.002	Reject
$Coal^- \not\Rightarrow CO_2^-$ (16)	1.507	0.471	Fail to Reject
$CO_2^+ \not\Rightarrow Urb^+$ (17)	2.317	0.314	Fail to Reject
$CO_2^+ \not\Rightarrow Urb^-$ (18)	13.681*	0.001	Reject
$CO_2^- \not\Rightarrow Urb^-$ (19)	1.248	0.536	Fail to Reject
$CO_2^- \not\Rightarrow Urb^+$ (20)	7.360**	0.025	Reject
$Urb^+ \not\Rightarrow CO_2^+$ (21)	2.254	0.324	Fail to Reject
$Urb^+ \not\Rightarrow CO_2^-$(6 (22)	0.898	0.638	Fail to Reject
$Urb^- \not\Rightarrow CO_2^-$(6 (23)	0.584	0.747	Fail to Reject
$Urb^- \not\Rightarrow CO_2^+$ (24)	0.839	0.657	Fail to Reject

Note: The symbol '' $\not\Rightarrow$ '' denotes that no Granger causality relationship between the variables. Hatemi-J Criterion (HJC) is used for lag selection. ***, ** and * indicate significance at the 0.10, 0.5 and 0.01 levels.

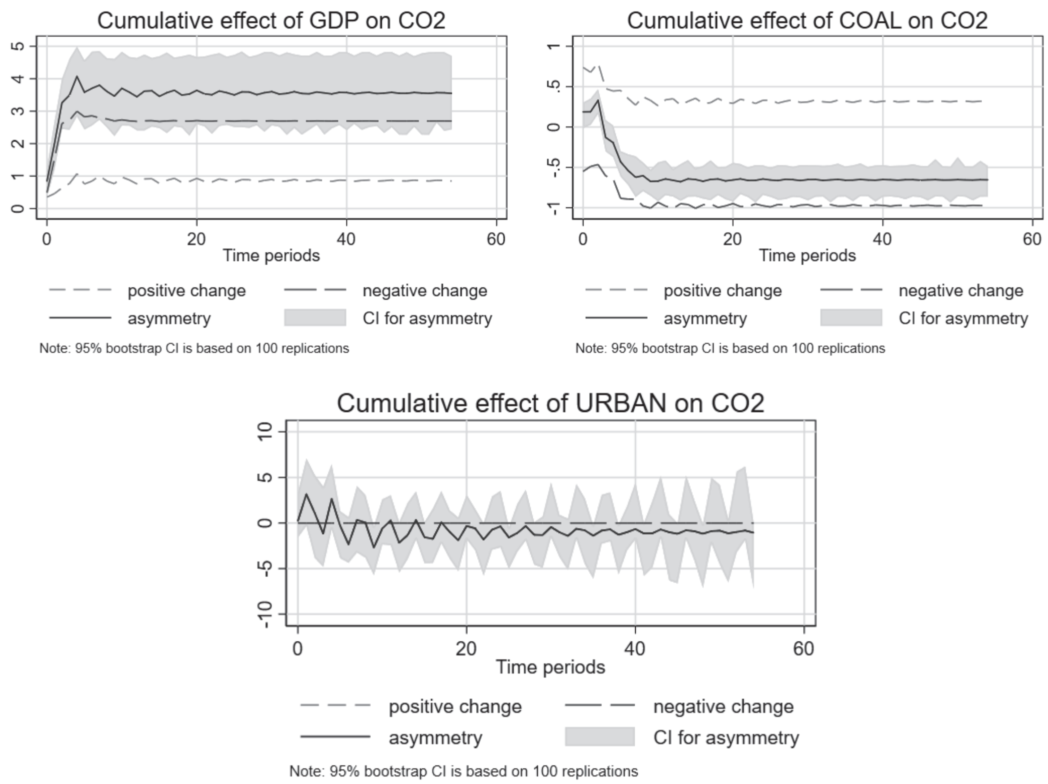

Fig. 3. Dynamic Cumulative effect of independent variables on CO_2 emission.

from dependent on coal energy consumption in her energy mix. The need for more investment in research and development in rural and urban education on environmental hazards should also be pursued in earnest.

Fig. 3 presents the dynamic cumulative effect of GDP, COAL, and URB on CO_2. The NARDL multipliers also support the result of NARDL estimation. According to Fig. 2, there is an asymmetric relationship between GDP and CO_2. The role of a negative shock in GDP dominates its positive shock on CO_2 in the long run. Also, there is an asymmetric relationship between COAL and CO_2 after 1970. The related plot shows evidence for the positive shock of COAL dominates its negative shock on CO_2 in the long run. However, the asymmetric effect of URB on CO_2 is insignificant which also supports the NARDL estimation result in Table 7.

Conclusions

According to the United States, Energy Information Administration [50] highlighted that access to energy is seen as a key catalyst for sustainable development. The extant literature on energy-environment and growth has addressed the pivotal contribution of energy to economic growth. However, there are growing concerns for environmental sustainability from the energy consumption type. Coal energy consumption which stems from non-renewable energy sources raised concern for energy specialists and environmental sustainability. The present study focuses on South Africa by considering a carbon-income function with the inclusion of urban population and economic growth and coal energy consumption using NARDL analysis.

Empirically, the findings highlight the asymmetry of emission levels in South Africa. Its captures the role of economic growth, rising urbanization, and coal energy consumption within the NARDL methodological framework adopted. Thus, evidence of a long-run equilibrium relationship among the study variables is confirmed by applying the bounds testing technique. The result shows that the exogenous determinants of CO_2 emission, namely GDP, coal energy consumption, and urbanization are strongly cointegrated. Therefore, the findings of the specified baseline model support the economic growth-emission-induced hypothesis for South Africa. The evidence explicitly invalidates further economic output expansion drive in the country, as it possesses a significant threat to environmental quality. The evidence showed that the consumption of coal power energy sources is more significantly attributable to higher emission levels in South Africa over time. And furtherance with the empirical results, urban population growth and carbon emission level in South Africa are unconnected. The findings also emphasize the appreciable role of urban dwellers in South Africa in heeding the environmental sensitization goal of their government in improving environmental quality more generally. More significantly, the study empirically demonstrates how GDP and energy consumption from coal are principally responsible for significantly high emission levels in South Africa. And in light of environmental policy awareness, how the urban population has more responsibly helped to eliminate the growing emission levels in the country.

Finally, for policy recommendation, since South Africa ranks high for significant polluters from coal energy consumption, energy policymakers need to design the country's transition roadmap more adequately toward cleaner energy alternatives. Hence phrasal decommission of the coal-fired energy plant and more just labor absorption in the clean energy sector will help sustain the transition. Also, since the country's economic growth ambition is very adversely connected to increased emission levels, a disruptive innovating approach to output production anchored on a cleaner production technique is recommended. Lastly, as coal still dominates the energy mix in South Africa and greatly propels industrial production, South Africa must plan the revolution of its entire energy sector to cut its emission level.

Although the present study explored the nexus between coal energy consumption and urban population economic growth on CO_2 emission for South Africa. There is still room for improvement for future study, the current study is fitted in an asymmetric environment for a single county case. Future studies can consider blocs or economies that are coal energy or other non-renewable energy dependent or top emitters nations to either refute or validate the current study position. Additionally, the future study can advance the current theme in terms of method by considering recent advances in the extant literature. Even more so, the role of technological disruption and the innovative system can be more critically examined, especially in light of the UN SDG goal 7–affordability to cleaner energy – in South Africa.

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Conflict of Interest

The authors declare no conflict of interest.

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