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Coal energy consumption beat renewable energy consumption in South Africa: Developing policy framework for sustainable development

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abstract

Globally we are at a crossroad whereby energy production and consumption in themselves is partly blamed for climate change issues and global warming menace. The question that comes to heart is do we stop seeking energy production and consumption? of course no. Thus, there is a need for innovation on part of economies as they seek energy for sustainable development. This country-specific study focuses on South African, which reflects the above highlights menace in no small measure where her economic growth trajectory is plagued with high CO_2 emission. To this end, we explore the nexus between coal energy consumption, economic growth, renewable energy consumption and CO_2 emission between annual periods of 1980–2017. This study applied a battery of econometric techniques to underscore the relationship between the outlined variables. According to the ARDL bounds test to cointegration in conjunction with Kripfganz and Schneider (2018) critical approximation p-values both affirm long-run equilibrium relationship between study variables. Empirical evidence gives credence to the growth-induced pollution emission in South Africa as reported by the Autoregressive distributed lag Method, fully modified ordinary least squares and dynamic ordinary least squares as robustness test for soundness of analysis. This finding suggests that South Africa's economic growth trajectory is not clean. This preposition is resonated with the result of coal energy consumption also dampening environmental quality. Financial development shows strong statistical strength to improve the quality of the environment. These outcomes are indicative for policymakers as there is urgent need to energy transition from conventional energy based on fossil fuel (coal energy) to renewable energy mix which is more environmentally friendly should be pursued in South Africa.

1. Introduction

The idea that environmental degradation is a developing-country issue and not a developed-country issue is no longer true, in the context of global climate change initiative (SDG-13). Greenhouse gas (GHG) deposition on the earth's surface is already having a negative impact on countries all over the planet, both emerging and industrialized, regardless of who is responsible [1,2]. The burning in Russia, the floods in Australia and Pakistan, the earthquake in Turkey, and the tsunami in Japan are only a few of the global disasters that have occurred recently and could have been caused by environmental degradation. Infrastructure, natural resources including trees, aquatic life, farm land, products and most notably, valuable human lives were all harmed as a consequence of these activities. These occurrences have been a significant point of worry for both policymakers and economists, because global development has environmental feedback consequences. The

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environmental Kuznets curve hypothesis was introduced by Grossman and Krueger [3] to illustrate the connection between environmental destruction and economic growth.

Several industrialized and developing nations use coal as an alternate source of energy to replace conventional sources in order to meet the growing increasing demand for energy that traditional sources are unable to fulfill efficiently. Another rationale for favoring coal use as an alternative energy source is that it is less expensive and more easily available [4]. South Africa is an excellent example of what has been mentioned above. It has everything, including fast growth, massive energy-linked pollution, and a solid financial base. The nation's economic growth began to intensify shortly after democracy was formed in 1994 and proceeded unabated until the country was struck by financial crisis in 2007. Around 2001 and 2007, the annual pace of economic growth was 4.3%. South Africa, on the other side, is a significant CO2 emitter (1% of the world emissions). The apparent explanation for this is the usage of coal, a big source of CO_2, in energy production, as seen in Fig. 1, with renewables accounted for just 2% of total energy production [5].

Likewise, South Africa's financial structure is well-developed, with excellent banking rules, and the country's financial sector has long been listed in the top ten financial sectors in the world. South Africa is a convincing candidate for a separate analysis to determine the impact of coal consumption, economic growth, and financial development on CO_2 emissions in the presence of renewable energy consumption owing to these features. Over the years, several studies have been done investigation the impact of renewable energy consumption, economic growth, financial development on environmental degradation (e.g Refs. [1,2,6–19]. Nonetheless, their findings are mixed due to country(s) of study, time-frame, and techniques employed which give room for further analysis.

This study contributes to the literature in the following way; (i) the study incorporates financial development index into the model which is a broader measurement of financial development; (ii) the current study utilized Bounds test with the Kripfganz and Schneider [20] critical value. The advantage of this approach is that it takes into consideration both the T-statistic and F-statistics in deciding the cointegration among the variables; (iii) the long-run association between CO_2 emissions and the regressor was captured utilizing the ARDL, FMOLS and DOLS; (iv) the present study utilized the Gradual shift causality test to capture the causal linkage among the variables. Compared to several time-domain causality tests, this technique captures the causality in the presence of a break in series.

The study remainder sections of this study are highlighted as follows: Summary of studies is depicted in section 2, data and methodology are presented in section 3, the findings and discussion are portrayed in section 4 and section 5 conclude the paper with detailed policy suggestions.

2. Literature review

This section of the research discusses the studies conducted on the association between energy consumption, economic growth, renewable energy consumption and financial development on environmental degradation.

2.1. Economic growth and environmental degradation

Akinsola and Adebayo [21] observed the causality association between GDP and CO_2 emissions in Thailand from 1971 to 2018 employing the Toda-Yamamoto causality techniques, conventional Granger and wavelet coherence approach. The author suggested the need to adopt strong policies to boost energy conservation and energy utilization services to reduce excessive energy waste. In Pakistan, Khan et al. [9] established a positive connection between GDP and CO_2 emissions between 1982 and 2018. Zhang et al. [22] investigation discovered a unidirectional causal link between GDP and CO_2 emissions in Malaysia between 1960 and 2018. However, for 116 countries, Acheampong [23] employed panel vector autoregression (PVAR) and generalized method of moment (GMM) to examine the causal connexion between GDP and CO_2 emissions covering the period 1990 to 2014. He found a bidirectional causal between these variables. Employing the ARDL technique, Hanif

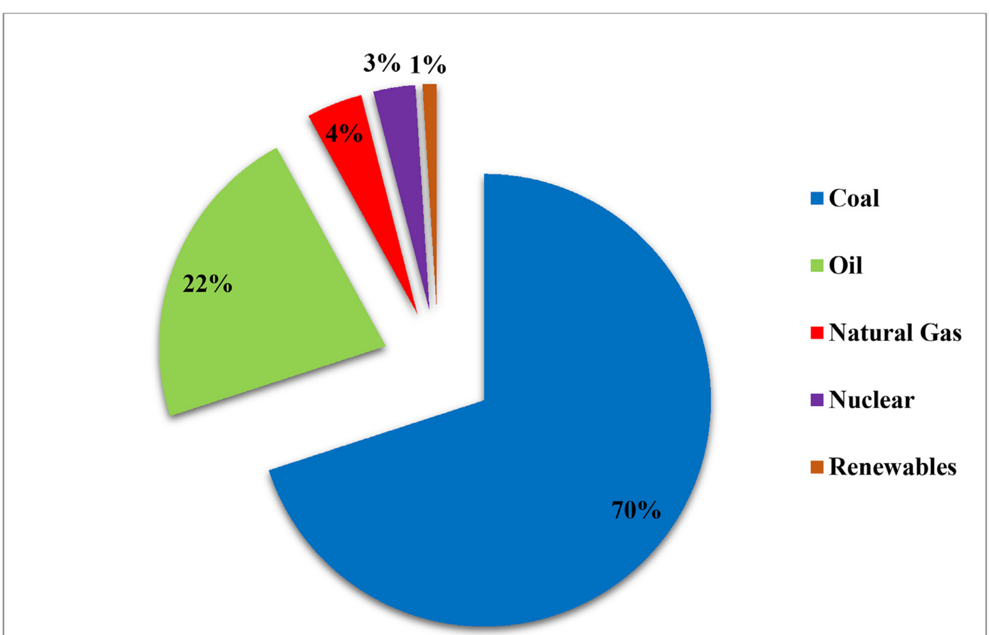

Fig. 1. Total primary energy consumption in South-Africa in 2016.

et al. [24] established a positive connection between GDP and CO_2 emissions for 15 developing Asian nations. Mikayilov et al. [25] establish the link between CO_2 emissions andGDP for Azerbaijan to be positive. Kalmaz & Kirikkaleli [26] also employed the ARDL, FMOLS, DOLS, wavelet Coherence to reveal that CO_2 emission is positively affected by GDP. Dong et al. [27]'s results show CO_2 emission to be positively affected by GDP from 1965 to 2016 for China using ARDL and VECM Granger causality. Ahmad et al. [28] establish a unidirectional causal interaction from GDP to CO_2 emission. Adedoyin et al. (2020, 2020)'s investigation in the BRICS nation between 1990 and 2014. The result reveals a positive link between GDP and CO_2 emissions. A similar outcome was revealed in the done by Adebayo & Odugbesan [29] for South Africa between 1971 and 2016.

2.2. Energy consumption and environmental degradation

Dogan & Aslan [30] found energy consumption to be positively related to CO_2 emissions. For 68 countries, Muhammad [31] concluded that an increase in CO_2 emission is caused by energy consumption increase from the period 2001–2017. Appiah [32] establish a bidirectional causal link from energy consumption to CO_2 emission. Pata [33] employed the ARDL technique with coverage 1971–2014 for Turkey. The author shows that energy consumption increases CO_2 emissions. Mirza & Kanwal [34] used the ARDL and VECM Granger causality. The result shows a bidirectional causal between these variables. The study of Zhang et al. [22] in Malaysia on determinants of CO_2 emissions reveals that energy consumption deteriorates environmental quality. The study of Akinsola et al. [35] in Thailand also corroborates this finding. Further, in Pakistan, the study of Khan et al. [36] established a positive association between energy consumption and CO_2 emissions. Some studies also uncovered insignificant linkage between CO2 emissions and energy consumption. For example, Wolde-Rufael [37] discovered that coal does not stimulate economic development in China and South Korea. In South Africa, a non-causal impact was observed, confirming the findings of Yuan et al. [38] for the Chinese economy. In New Zealand, Fatai et al. [39] discovered a non-causal influence between the series [40]. show that there is no causal association regarding coal use and production in South Africa. According to Ziramba [41]; there is no connection between the series in South Africa.

2.3. Financial development and environmental degradation

Salahuddin et al. [13] established that the relationship between financial development and CO_2 emission in Kuwait tends to be insignificant. Moreover, in the study by Shahbaz et al. [42,43] on the between financial development and environmental degradation. It was established thinteraction at financial development improves the environment quality. Jamel &Maktouf [44] also establish a similar result in Europe, covering the period from 1985 to 2014. Işik et al. [45] applied the ARDL to establish a positive interaction between CO_2 emission and financial development in Greece from the period 1970–2014, which is contrary to the study done by Park et al. [46] for European Union nations showing to be negative. Zafar et al. [47] revealed a bidirectional causality link between these variables. Wang et al. [48] employed the Westerlund Cointegration and CS-ARDL for G7 nations. Results illustrated that financial development tends to increase CO_2. For China, Umar et al. [49] result shows that there is no cointegration between financial development and CO_2 emission. In South-Africa, Adebayo et al. [1] examined the linkage between financial development and CO_2 emissions utilizing yearly data between 1970 and 2017. The empirical findings indicate that financial developments affect CO2 emissions adversely.

2.4. Renewable energy and environmental degradation

Hao et al. [50] using the CS-ARDL to investigate these variables in G7 countries between 1991 and 2017. Results reveal renewable energy negatively affects environmental degradation. A similar result was seen in Waheed et al. [51] for Patiskan, Kirikkaleli& Adebayo [52]; Cheng et al. [53] for BRICS. Dong et al. [54] investigation in BRICS economies reveals a two-way linkage between renewable energy and CO_2 emission. Menyah & Wolde-Rufael [55] study reveals no causal link between renewable energy and CO_2 emission in the US. Mahmoodi [56] inspected the relations between CO_2 emission and renewable energy in 11 developing economies with data covering the period of 2000–2014. There is a negative bidirectional interaction between renewable energy and CO_2 emission. Aydoğan& Vardar [57] scrutinized the relationship between renewable energy and CO_2 emission covering the period from 1990 to 2014, using several panel cointegration techniques to establish the presence of cointegration. The result shows that there is a negative interaction between them. The authors further concluded that the proliferation of more renewable technologies mitigates pollution environmental issues. Within the global context, the study of Kirikkaleli& Adebayo [52] on the association between CO_2 emissions and renewable energy using recent econometric techniques established negative interconnection between renewable energy and CO_2 emissions. The research of Adedoyin et al. [4,15] also established a negative association between CO_2 emissions and renewable energy. Table 1 presents the summary of the reviewed studies.

3. Methodological foundation

3.1. Theoretical background and descriptions of data

This current study investigates the causal and long-run effect of financial development (FD) and coal consumption (CC) on CO_2 emissions and the role of economic growth (GDP) and renewable energy (REN) in South-Africa utilizing a yearly dataset stretching between from the period 1980 to 2017. The variables utilized are altered into their natural logarithm. It conducted to make the parameter transforms to normality (Wang et al. 2021). Table 2 illustrates the name of data, unit of measurement and data source. Moreover, Figs. 2a–2e exemplifies the data trend from 1980 to 2017. Additionally, Fig. 3 presents the study analysis flow. Economic function and econometric model of this study are illustrated in Equations 1 and 2 as follows;

$$CO_{2t} = f(GDP_t, CC_t, REN_t, FD_t) \quad [1]$$

$$CO_{2t} = \vartheta_0 + \vartheta_1 GDP_t + \vartheta_2 CC_t + \vartheta_3 REN_t + \vartheta_4 FD_t + \varepsilon_t \quad [2]$$

In Equation (2), CC, REN, FD GDP, and CO_2, denote coal consumption, renewable energy, financial development, CO_2 emissions and economic growth. The purpose of applying the above indicators are specified here. In line with the study of Ayobamiji & Demet, [67]; Kirikaleli et al. [6,68]; and Odugbesan & Adebayo [17]; GDP is incorporated into the model. The association between GDP and environmental pollution is anticipated to be positive. This infers that a rise in GDP would harm environmental quality i.e. $\left(\beta_1 = \frac{\partial CO_2}{\partial GDP} > 0\right)$. In compliance to study done by Joshua et al. [69]; Bildirici and Bakirtas [70]; and Al-Mulali et al. [71] coal consumption is projected to impact environmental degradation positively.

Table 1
Synopsis of studies.

Investigator (s)	Timeframe	Nation (s)	Technique(s)	Findings
CO_2 and GDP Interconnection				
Khan et al. [9]	1982–2018	Pakistan	ARDL	GDP → CO_2 (+)
Teng et al. [58]	1985–2018	10 OECD economies	Pooled Mean Group estimator	GDP→ CO_2 (+)
Zhang et al. [22]	1960–2018.	Malaysia	Maki co-integration, ARDL bound, ARDL, T-Y causality and Gradual shift causality	GDP→ CO_2
Mehmood [59].	1970–2014	Singapore	ARDL	GDP→ CO_2 (−)
Acheampong [23]	1990–2014	116 countries	PVAR and GMM	GDP ↔ CO_2
Hanif et al. [24].	1990–2013	15 developing Asian countries	ARDL	GDP → CO_2 (+)
Mikayilov et al. [25]	1992–2013	Azerbaijan	ARDL	GDP→ CO_2 (+)
Kalmaz & Kirikkaleli [26]	1960–2016	Turkey	ARDL, FMOLS, DOLS, Wavelet Coherence	GDP → CO_2 (+)
Dong et al. [54]	1965–2016.	China	ARDL and VECM Granger causality.	GDP → CO_2 (+)
Ahmad et al. [28]	1992Q1-2011Q1	Croatia	ARDL and VECM Granger causality.	GDP → CO_2(+)
Adedoyin et al. [4,15]	1990–2014	BRICS economies	PMG ARDL	GDP → CO_2 (+)
Adebayo &Odugbesan, [29].	1971–2016	South Africa	ARDL &Wavelet Coherence	GDP → CO_2 (+)
Salahuddin et al. [13]	1980–2017	South Africa	ARDL	GDP≠ CO_2
Umar et al. [49]	1980–2017	China	Multivariate system	GDP → CO_2 (+)
Ulucak& Khan [60]	1990–2015	BRICS	Panel FMOLS	GDP → CO_2 (+)
Le & Ozturk [61].	1990–2014	47 Emerging Market and Developing Economies (EMDEs)	CMG, AMG, and DCCE estimators	GDP→ CO_2 (+)
Energy Consumption and CO_2 Interconnection				
Dogan & Aslan [30]	1995–2011	EU and candidate countries	LM bootstrap panel cointegration	EN→ CO_2 (+)
Muhammad [31]	2001–2017	68 countries	GMM	EN→ CO_2 (+)
Appiah [32]	1960–2015	Ghana	ARDL & T-Y Causality	EN↔ CO_2 (+)
Pata [33].	1971–2014	Turkey	ARDL	EN→ CO_2 (+)
Mirza & Kanwal [34]	1971–2009	Pakistan	ARDL and VECM Granger causality	EN↔ CO_2 (+)
Haseeb et al. [62]	1995–2014	BRICS	Westerlund Cointegration test, the Dynamic seemingly unrelated regression (DSUR), and Dumitrescu-Hurlin Granger causality test	EN→ CO_2 (+)
Khan et al. [36]	1971–2016	Pakistan	Dynamic ARDL simulations	EN→ CO_2 (+)
Financial development and CO_2 Emissions Interconnection				
Salahuddin et al. [13]	1980–2013	Kuwait	ARDL and VECM Granger causality	FD≠ CO_2
Jamel &Maktouf [44]	1985–2014	European	Panel Causality	FD≠ CO_2
Işik et al. [45]	1970–2014	Greece	ARDL and VECM Granger causality	FD→ CO_2 (+)
Zafar et al. [47]	1990–2014	OCED	Panel FMOLS and Dumitrescu-Hurlin causality	FD ↔ CO_2
Park et al. [46]	2001–2014.	European Union countries	Panel ARDL, Panel FMOLS and Panel DOLS	FD→ EN (−)
Xu et al. [63]	1971–2016	Saudi Arabia	ARDL and VECM Granger causality	FD → CO_2 (+)
Nasir et al. [64]	1982–2014	ASEAN	Panel FMOLS and Panel DOLS	FD → CO_2 (+)
Shahbaz et al. [65]	1955–2016	France	Bootstrapping ARDL	FD → CO_2 (−)
Shen et al. [66]	1995–2017	30 provinces of China	CS-ARDL	FD → CO_2 (+)
Xu et al. [63]	1971–2016	Saudi Arabia	ARDL and VECM Granger causality	FD ↔ CO_2 (+)
Wang et al. [48]	1996–2017	G7 countries	Westerlund Cointegration and CS-ARDL	FD→ CO_2 (+)
Umar et al. [49]		China	Multivariate system	FD≠ FD

(continued on next page)

Table 1 (*continued*)

Investigator (s)	Timeframe	Nation (s)	Technique(s)	Findings
	1980–2017			
Le & Ozturk [61].	1990–2014	47 Emerging Market and Developing Economies (EMDEs)	CMG, AMG, and DCCE estimators	FD → FD (+)
Renewable energy and CO_2 Interconnection				
Hao et al. [50]	1991–2017	G7 countries	CS-ARDL	REN→ CO_2 (−)
Dong et al. [54]	1985–2016	BRICS	CMG, AMG, DCCE estimators and Panel VECM Granger causality.	REN ↔ CO_2 (+)
Waheed et al. [51]	1990–2014	Pakistan	ARDL	REN → CO_2 (−)
Kirikkaleli& Adebayo [52]	1985–2017	Global	FMOLS, DOLS, and CCR, Bayer and Hanck cointegration and frequency-domain causality tests	REN → CO_2 (−)
Cheng et al. [53]	2000–2013	BRICS	Panel OLS methods and Panel quantile regression method	REN → CO_2 (−)
Menyah &Wolde-Rufael [55]	1960–2007	US	Granger causality test	REN≠ CO_2 (−)
Mahmoodi, M [56].	2000–2014	11 developing countries	Panel DOLS	REN ↔ CO_2 (−)
Aydoğan& Vardar [57]	1990–2014	E−7	Panel VECM	REN → CO_2 (−)

Note: EC: Energy Consumption, GDP: Economic Growth, REN: Renewable EnergyCO_2: Carbon Emission, → (+): Positive relationship, → (−): Negative relationship, →: One-way causality, ↔: Bidirectional causality.

Table 2
Variables units and sources.

Variable	Description	Units	Sources
CO_2	Carbon emissions	Metric tonnes per capita	WDI
GDP	Economic growth	GDP Per Capita Constant $US, 2010	
REN	Renewable energy usage	Renewables per capita (kWh)	BP
CC	Coal Consumption	Measured as Coal per capita (kWh)	
FD	Financial Development	A broad measure for financial development by taking into account its efficiency, accessibility, and depth	IMF

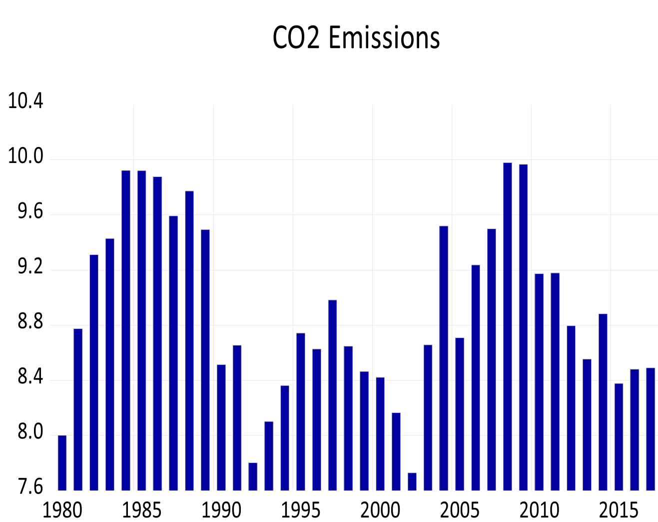

Fig. 2a. CO_2 emissions trend.

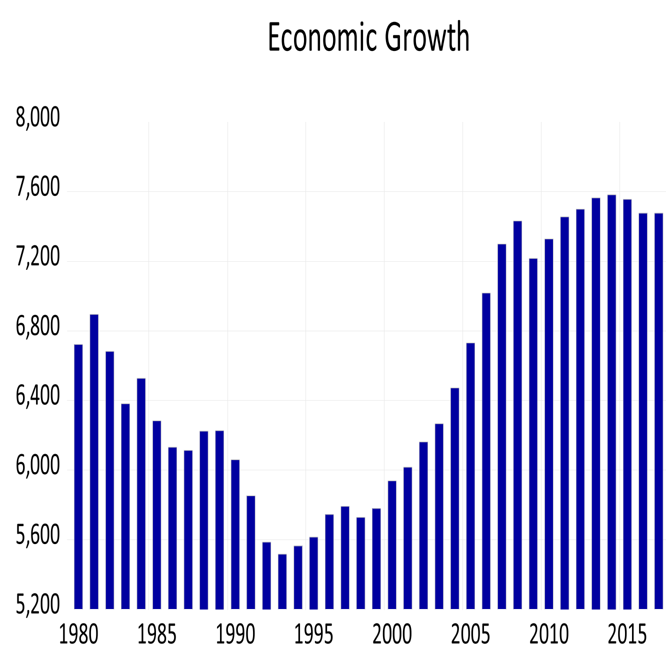

Fig. 2b. Economic growth trend.

Therefore, coal consumption would deteriorate the quality of the environment, i. e, $\left(\beta_2 = \frac{\partial CO_2}{\partial CC} > 0\right)$. Following Kirikaleli et al. [6,68]; Destek and Sarkodie [72,73]; REN is incorporated into the model. Renewable energy is anticipated to improve environmental quality. Thus, the association between REN and environmental degradation is expected to be negative i.e.$\left(\beta_3 = \frac{\partial CO_2}{\partial REN} < 0\right)$. It is expected that financial development would have a detrimental effect on CO_2 emissions [74,75]. Thus, an increase in financial development would also increase environmental sustainability, i.e., otherwise $\left(\beta_4 = \frac{\partial CO_2}{\partial FD} > 0\right)$.

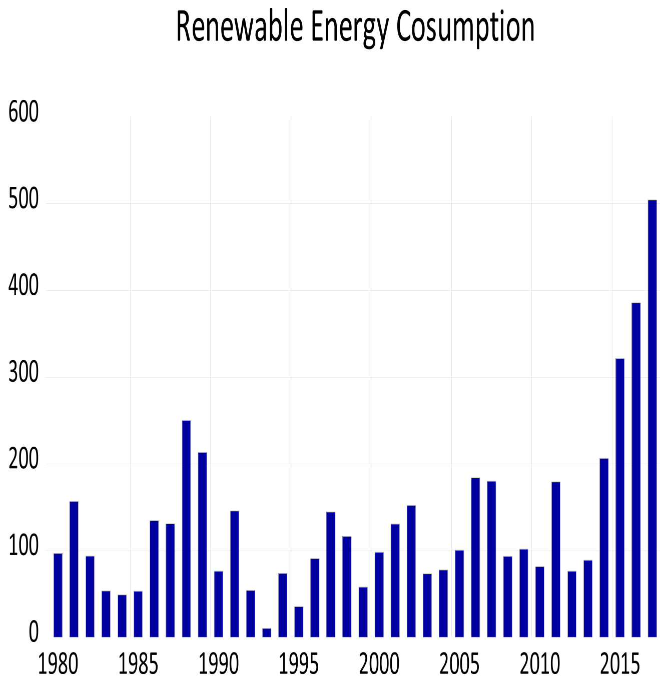

Fig. 2c. Renewable energy trend.

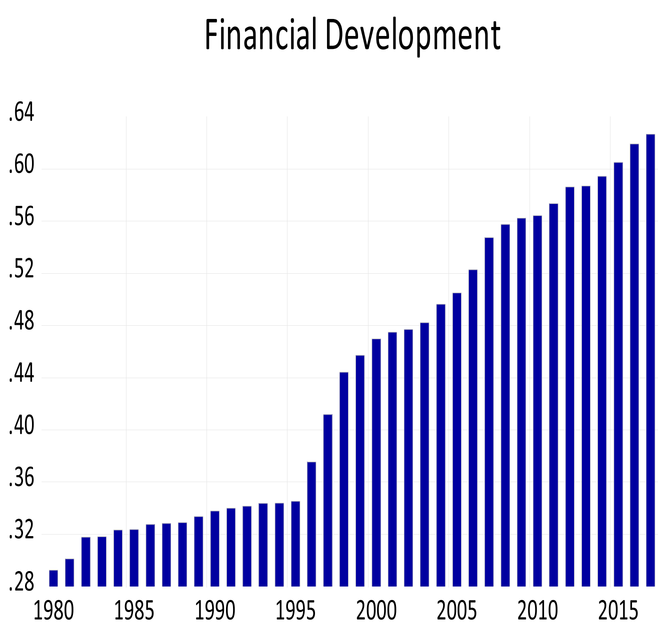

Fig. 2d. Economic growth trend.

3.2. Methodology

3.2.1. Unit root tests

Granger and Newbold, 1974 suggested that the use of non-stationary data for model estimation will produce a spurious regression problem. To investigate stationarity property of the variable used, this study employed the Augmented Dickey-Fuller (ADF) [76] and Phillips–Perron (PP) unit root test [77]. The equation of ADF is shown below as:

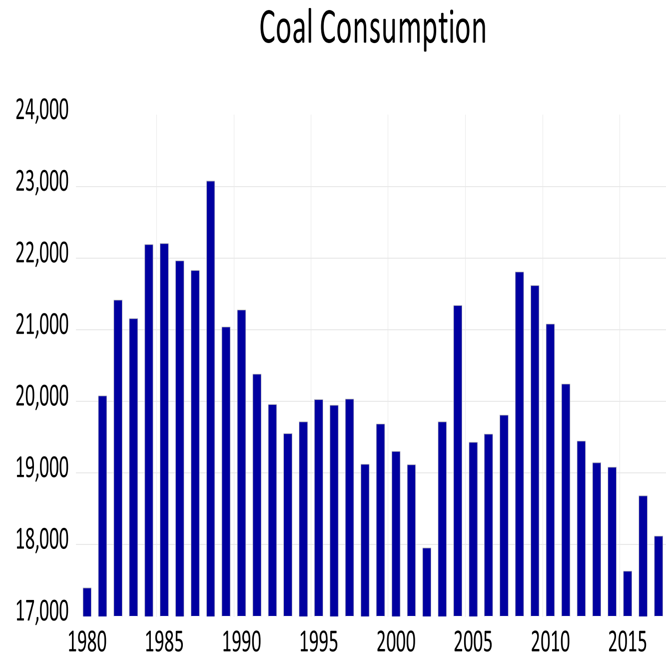

Fig. 2e. Coal consumption trend.

$$\Delta Y_t = \beta_1 Y_{t-1} + \sum_{i-1}^{p} b_1 \varDelta Y_{t-1} + \varepsilon_t \tag{3}$$

Equation (4) explains the PP unit root as shown below as:

$$\Delta Y_t = \beta_0 + \beta_1 t + \beta_2 Y_{t-1} + \varepsilon_t \tag{4}$$

Where; Δ denotes first difference, Yt denotes variable used, t denotes the time trend of the variable, p denotes lags used, ε represents error term. The modified version of ADF is PP unit root, because the residual of the serial correlation and heteroscedasticity were been taken into but PP employs a statistical methods that are non-parametric in nature so as to solve the heteroscedasticity and serial correlation problem. This study used the unit root test, proposed by Ref. [78] in detecting for a single structural break unit root test.

$$\Delta y = \sigma + \hat{u} y_{t-1} + \beta t + DU_t + \sum_{j=i}^{t} d_j \Delta y_{t-j} + \varepsilon_t \tag{5}$$

$$\text{Model B:} \Delta y = \sigma + \hat{u} y_{t-1} + \beta t + \varDelta DT_t + \sum_{j=i}^{t} d_j \Delta y_{t-j} + \varepsilon_t \tag{6}$$

$$\text{Model C:} \Delta y = \sigma + \hat{u} y_{t-1} + \beta t + \varDelta DT_t DU_t + \sum_{j=i}^{t} d_j \Delta y_{t-j} + \varepsilon_t \tag{7}$$

where; DU_t denotes dummy variable for a mean shift occurring at each possible break-date (TB); DT_t denotes the corresponding variable used trend shift. Formally,

$$DUt = \begin{cases} 1 \ldots\ldots\ldots\ldots if\ t > TB \\ 0 \ldots\ldots\ldots\ldots otherwise \end{cases} \text{ and } DUt = \begin{cases} t - TB \ldots\ldots if\ t > TB \\ 0 \ldots\ldots\ldots\ldots otherwise \end{cases} \tag{8}$$

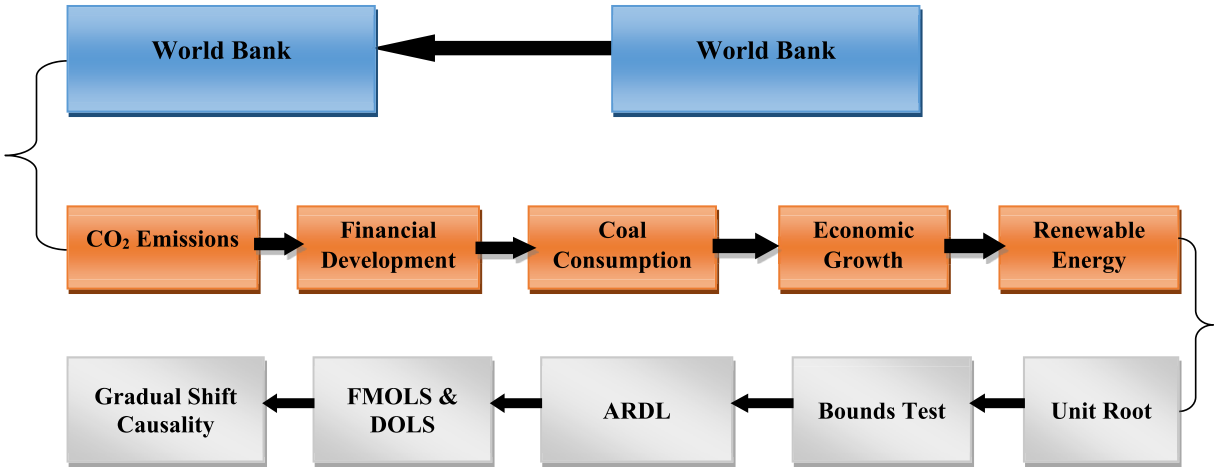

Fig. 3. Analysis flowchart.

3.2.2. ARDL approach

Bounds Auto-Regressive Distribution Lag Model (ARDL) constructed by Pesaran et al. [79] and Pesaran and Shin [80] was been used to capture the long-run cointegration association between the dependent and independent variables. Benefits of the ARDL bounds model over the other conventional or traditional cointegration techniques areas: (i) it can be used when a mixed order of integration exists; (ii) it incorporates both the long and short-run coefficients simultaneously; (iii) it is perfectly fit for small sample size; (iv) accommodating different lag length [67]; (v) autocorrelation problem is removed. The generated F-statistics is been compared to the lower and upper bound critical value. Equation (9) below explains the ARDL bounds model;

$$\Delta CO_{2t} = \theta_0 + \sum_{i=1}^{t} \theta_1 \Delta CO_{2t-i} + \sum_{i=1}^{t} \theta_2 \Delta GDP_{t-i} + \sum_{i=1}^{t} \theta_3 \Delta CC_{t-i} + \sum_{i=1}^{t} \theta_4 \Delta REN_{t-i} + \sum_{i=1}^{t} \theta_5 \Delta FD_{t-i} + \beta_1 CCO_{2t-1} + \beta_2 GDP_{t-1} + \beta_3 CC_{t-1} + \beta_4 REN_{t-1} + \beta_5 FD_{t-1} + \varepsilon_t \tag{9}$$

Null hypothesis and alternative hypothesis are no co-integration and evidence of co-integration, respectively. the null hypothesis is rejected if the F-statistics is more than the lower and upper bound critical values. Equations (8) and (9) illustrate the study's hypotheses;

$$H_0 = \vartheta_1 = \vartheta_2 = \vartheta_3 = \vartheta_4 = \vartheta_5 \tag{10}$$

$$H_a \neq \vartheta_1 \neq \vartheta_2 \neq \vartheta_3 \neq \vartheta_4 \neq \vartheta_5 \tag{11}$$

where H_0 denotes the null hypothesis and H_a illustrates the alternative hypothesis.

The study utilizes the criteria of Kripfganz and Schneider [20] which requires the generated T-statistics and F-statistics to be higher than the corresponding upper critical values, an essential requirement for deciding on cointegration, unlike the prior decision-making criteria that demand the F-statistic higher than the upper critical values for cointegration. Also, the p-values produced should be below the target levels.

Since a long run association is seen, we derive the error correction model (ECM). It was derived by estimating the model's short-run parameters by applying ECM. Hence, incorporating the ECM model into the ARDL model would result in Equation (12) as:

$$\Delta CO_{2t} = \theta_0 + \sum_{i=1}^{t} \theta_1 \Delta CO_{2t-i} + \sum_{i=1}^{t} \theta_2 \Delta GDP_{t-i} + \sum_{i=1}^{t} \theta_3 \Delta CC_{t-i} + \sum_{i=1}^{t} \theta_4 \Delta REN_{t-i} + \sum_{i=1}^{t} \theta_5 \Delta FD_{t-i} + \beta_1 CCO_{2t-1} + \beta_2 GDP_{t-1} + \beta_3 CC_{t-1} + \beta_4 REN_{t-1} + \beta_5 FD_{t-1} + \omega ECT_{t-i} + \varepsilon_t \tag{12}$$

where:$\theta_{i=5}$denote short-run coefficients, ε_t represents the error term, $\beta_{i=5}$ denote long-run coefficients, t denotes the lags lengths, $ECT_{t\text{-}i}$ denotes error correction term, showing the speed of adjustment from a short-run shock to the long-run equilibrium. ω denotes ECM coefficients, which will be negative and significant.

3.2.3. FMOLS and DOLS long-run estimators

For the robustness check of the ARDL coefficients, the Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS) was used. Stock & Watson [81] and Phillips and Hansen [82] developed the DOLS and FMOLS approach respectively. These approaches allow for asymptotic coherence when the effect of serial correlation is investigated.

3.2.4. Gradual shift causality

Sims [83] built a model designed by Toda and Yamamoto [84]; which is anchored on the vector autoregressive (VAR). In calculating for the optimal lag length, p + $_{Dmax}$ is added to the $_{max}$ lag, which is determined by the maximum integration order of the parameters in the VAR model. However, ignoring the structural shifts can cause the VAR model to be unreliable and contradictory [85,86]. Nazlioglu et al. [87] developed the Fourier Toda-Yamamoto causality test, which captures the structural shifts in Granger causality analysis and including the gradual and smooth shift. It can also be called the "gradual-shift causality test". It was developed using single frequency (SF) and cumulative frequencies (CF) respectively, known as Fourier approximation. By adding the TY-VAR analysis and Fourier approximation, the modified Wald test statistic (MWALT) is generated. Assuming the coefficients of the intercept is constant over time, which modifies the VAR model into Equation (13) as follows:

$$y_t = \sigma(t) + \beta_1 y_{t-1} + \ldots + \beta_{p+dmax} y_{t-(p+dmax)} + \varepsilon_t \tag{13}$$

where: y_t denotes CO_2, GDP, CC, REN and FD; σ denotes intercept; β denotes coefficient matrices; ε denotes the error term; t denotes time function. To capture the structural change, the Fourier expansion is introduced and explained as in Equation (14).

$$\sigma(t) = \sigma_0 + \sum_{k=1}^{n} \gamma_{1k} \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \gamma_{2k} \cos\left(\frac{2\pi kt}{T}\right) \quad (14)$$

where: γ_{1k} and γ_{2k} measures the frequency amplitude and displacement respectively; n denotes the number of frequency.

Substituting Equation (6) into Equation (7), the structural shift are thereby put into consideration, defines the Fourier Toda-Yamamoto causality with cumulative frequencies (CF), as follows in Equation (15).

$$y_t = \sigma_0 + \sum_{k=1}^{n} \gamma_{1k} \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} \gamma_{2k} \cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \ldots + \beta_{p+dmax} y_{t-(p+dmax)} + \varepsilon_t \quad (15)$$

where: k denoted approximation frequency. The single frequency components is defined in Equation (16) as follows:

$$\sigma(t) = \sigma_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) \quad (16)$$

We substitute Equation (14) into Equation (17), which defines the Fourier Toda-Yamamoto causality with single frequencies (SF) in Equation (10) as follows:

$$y_t = \sigma_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \ldots + \beta_{p+d} y_{t-(p+d)} + \varepsilon_t \quad (17)$$

Here, the testing of the null hypothesis of non-causality is zero (H_0: $\beta_1 = \beta_\Theta = 0$), the Wald statistic can be used for testing the hypothesis.

4. Findings and discussion

The preliminary analysis of this study is provided in this section, beginning with the stationarity tests by using ADF, PP, and Zivot-Andrew unit root tests. The summary of descriptive statistics and correlation coefficient matrix are been shown below. Table 3 summarizes the descriptive statistics. The outcomes reveal that CC score better on average due to its higher mean value. The standard deviation is a measure of the amount of variation or dispersion of a set of values. Thus, the standard deviation is utilized to check the variable which had more consistent scores. CO_2 has the lowest standard deviation which indicates that the scores are less spread-out from the mean. Thus, CO_2 has more consistent score. Skewness results reveals that the parameters comply with normality. Furthermore, the value of the kurtosis is less than 3 which shows that the series are normally distributed. Moreover, the Jarque-Bera p-value shows that the indicators are normally distributed with exemption of GLO which does not comply with normal distribution. The correlation between the indicators is depicted in Fig. 4 (correlation box) which ranges from blue (positive correlation) to red (negative correlation). Table 4 summarizes the conventional unit root result. The outcomes show that the series are non-stationary at level I(0). Nonetheless, after the first difference, I(1) was under taken, all the series were stationary. Furthermore, time-series are recognized to have break(s), therefore, the current study used Zivot and Andrew unit root test, which captures the stationarity features and a single break in series, and is described in Table 5. The results show that all the series are

Table 3
Descriptive statistics.

	CO_2	CC	GDP	FD	REN
Mean	8.9157	20132.7	6524.06	139.142	133.392
Median	8.7583	19949.6	6331.86	142.252	99.2150
Maximum	9.9794	23074.2	7582.69	192.660	504.190
Minimum	7.7276	17394.4	5517.53	74.1107	10.2330
Std. Dev.	0.6349	1351.01	696.772	39.8826	98.3828
Skewness	0.1502	0.06693	0.23239	−0.23658	2.00121
Kurtosis	2.0580	2.47249	1.63285	1.52143	7.43321
Jarque-Bera	1.5478	0.46896	3.30144	3.81590	56.4819
Probability	0.4612	0.79098	0.19191	0.14838	0.00000
Obs	38	38	38	38	38

stationary at first difference i.e.I(1) with the exemption of REN which is stationary at level i.e. I(0) and first difference i.e. I(1).

Given that the series are integrated at a mixed order, it reasonable for this study to use the ARDL bounds test since it is the most effective approach for long-run equilibrium testing, as seen in Table 6. The outcomes show that there is long-run cointegration among the series. The study also captures the long and short association between GDP, CC, REN, FD ad CO_2 using ARDL techniques. To discover the goodness of fit of the model, various post estimation tests were conducted. The outcomes of various diagnostic tests are presented in Table 6. Results show that there is no problem of heteroscedasticity, residuals are no serially correlated, and no misspecification in the model. Figs. 5a and 5b also depict the CUSUM and CUSUMSQ tests, which is stable at 5% level of significance.

We proceed to estimate the coefficients in the long and short-run between CO_2 emissions and its regressors after the cointegration is confirmed, which is depicted in Table 7. The ARDL long-run and short-run outcome is showed below;

a. Between GDP and CO_2 emissions, there exists a positive interconnection. This infers that keeping other indicators constant, a 1% increase in GDP increases CO_2 by 0.62%. The inference is that the economic growth path of South-Africa is driven by pollutant emission which is astute as the country ranks high amongst pollutant nations globally. This illustrates the nation is still at the scale-stage of her growth path trajectory [29,88]. The result also aligns with the EKC hypothesis, where there is positive

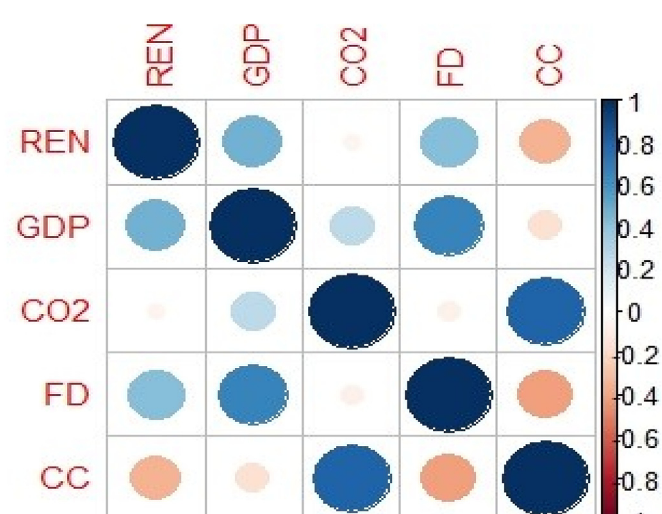

Fig. 4. Correlation among CO_2, CC, GDP, REN and FD

Table 4
Traditional Unit root Tests.

ADF Unit Root Test	At Level I(0)	First Difference I(1)	Decision
	Intercept & Trend	Intercept & Trend	
CO_2	−2.7796	−6.2748*	I(1)
GDP	−2.6353	−4.2225**	I(1)
CC	−4.2815*	−7.0414*	I(1)
REN	−2.0474	−3.7626**	I(1)
FD	−1.5208	−7.4136*	I(1)
PP Unit root Test			
CO_2	−3.0035	−6.2909*	I(1)
GDP	−1.7244	−4.2895*	I(1)
CC	−4.2809*	−7.7208*	I(0), I(1)
REN	−1.7476	−3.7271**	I(1)
FD	−1.5208	−7.9497*	I(1)

Note: * and ** represents 1% and 5% level of significance.

Table 5
Zivot and Andrews Unit root Test.

	At Level I(0)		First Difference I(1)		Decision
	Intercept & Trend	Break-Date	Intercept & Trend	Break-Date	
CO_2	−4.537	2003	−7.608*	1993	I(1)
GDP	−3.876	1999	−4.956***	2004	I(1)
CC	−6.068*	2008	−7.662*	2003	I(1)
REN	−4.295	1997	−5.17**	1993	I(0), I(1)
FD	−4.821	1990	−5.656**	1996	I(1)

Note: *, ** and *** represents 1%, 5% and 10% level of significance.

Table 6
Bound test.

Model	F-statistics	T-Statistics	χ2 ARCH	χ2 RESET	χ2 Normality	χ2 LM	
	6.163*	−5.687*	0.91 (0.54)	0.80 (0.42)	0.91 (0.63)	0.53 (0.59)	
Kripfganz and Schneider [20] critical and P-values							
	10%		5%		1%		PV
F-statistics	2.204	3.320	2.615	3.891	3.572	5.112	0.00
T-Statistics	−2.495	−3.798	−2.843	−4.207	−3.54	−5.021	0.00

Note * represent a 1% level of significance and PV denotes probability value both F-stat and T-stat are greater than critical values.

association between environmental degradation and income per capita. This is a call for a more proactive move for South African stakeholders and policymakers to disengage economic growth from pollutant emission in their energy policy mix. This outcome complies with the study of Akinsola & Adebayo, (2021)

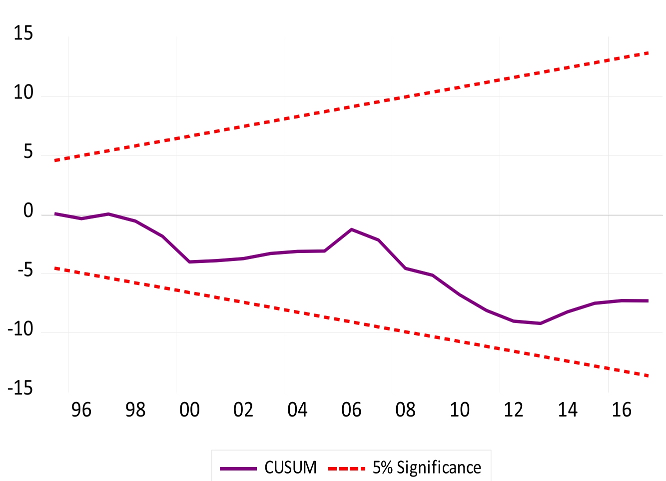

Fig. 5a. Cusum.

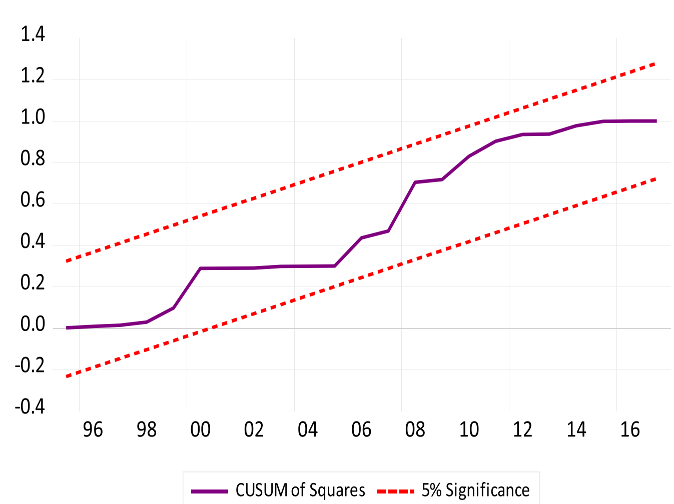

Fig. 5b. Cusum Sq.

for Thailand, Kirikaleli et al. [6,68] for Turkey, Zhang et al. [22] for Malaysia, and Adebayo [89] for Mexico.

b. As anticipated, coal consumption exerts a positive effect on environmental degradation in the short and long-run. This illustrates that a 0.15% increase in CO_2 emissions is due to a 1% increase in coal consumption when other indicators are held constant. The probable reason for this positive association is that 70% of the total energy consumption generated in South-Africa is by utilizing coal, accompanied by nuclear (22%), natural gas (4%) and nuclear (3%) [90] and Coal's byproduct is CO_2 emissions. This result aligns with the study of Joshua & Bekun, (2020) for South-Africa, Bildirici & Bakirtas, (2016) for BRICS countries and Cheng et al. [91] for China but contradict the study of Udi et al. (2020), Wolde-Rufael [37]; Yuan et al. [38]; and Jinke et al. [40] who established an insignificant causal linkage between coal consumption and CO_2 emissions.

c. As expected, there is evidence of an insignificant relationship between renewable energy usage and CO_2 emissions. The reason for this association is because renewable energy constitutes a small percentage of the energy generated in South-Africa. Thus it is vital for the government and policymakers in South-Africa to formulate policies that will encourage renewable energy. This outcome does not comply with the study of Kirikaleli and Adebayo, [6,68]; Nathaniel et al. [18]; and Adedoyin et al. [1] who established that interaction between renewable energy and environmental degradation are negative and significant.

d. Financial development exerts negative and significant impact on CO_2 emissions is seen to be negative. This infers that an increase in financial development enhances the quality of the environment. Thus, keeping other indicators constant 1% increase in financial development mitigates environmental degradation by 0.02%. The negative interconnection suggests that the maturity stage of the financial sector in South Africa has been reached as the sector allocates capital to environmentally sustainable initiatives and also encourages businesses to use new development technologies to raise output levels. Moreover, the financial system in South Africa is highly developed with banking regulations rank outstanding, and the financial sector has long been rated among the financial sectors globally. Therefore, the financial system can be used as a tool to mitigate environmental degradation in South-Africa. This outcome corresponds with the findings of Charfeddine & Kahia, (2019), Odugbesan & Adebayo, (2020) and Khoshnevis & Ghorchi, (2018).

e. As anticipated, the ECT (−0.59%) tends to be negative and statistically significant which reveals that prior period imbalance can be corrected by the succeeding periods.

Moreover, the analysis used the FMOLS and DOLS estimators to check the ARDL estimator in the long-run. The findings from the FMOLS and DOLS was reported in Table 8. The outcomes show that economic growth and coal consumption significantly influence CO_2 emissions, while financial development exerts a negative influence on CO_2 emissions. However, between renewable energy and CO_2 emissions, an insignificant interconnection was established. These results comply with the results of the ARDL long-run estimations.

Finally, in order to capture the causal impact of coal consumption, economic growth, renewable energy, and financial development on CO_2 this research utilizes the Fourier Toda-Yamamoto causality test. The advantage of this test is that it can capture causal linkage between series in the presence of structural break(s). The outcomes are shown in Table 9. The outcomes revealed; (a) One-way causal linkage from CO_2 emissions to GDP. This illustrates that CO_2 emissions is an important predictor of GDP. This outcome aligns with the studies of Magazzino et al. [92] for South Africa but contradict the study of Kirikkaleli and Adebayo [52], for India, Udemba et al. [19] for Indonesia and Awosusi et al. (2021) who established unidirectional causality from economic growth to CO_2 emissions in South Korea. (b) One-way causal linkage from coal consumption to CO_2 emissions. This result infers that Coal consumption is a significant factor in predicting CO_2 emissions in South Africa. This outcomes corroborates the findings of Udemba et al. [19] for India, Awosusi et al. (2021) for South Korea but do not align with the study of Udi et al. (2020), Wolde-Rufael [37]; Yuan et al. [38]; and Jinke et al. [40] who established an insignificant causal linkage between coal consumption and CO_2 emissions. (c) Bidirectional causal linkage between FD and CO_2 implying that both indicators can predict each other. This outcome is consistent with the findings of Shahbaz et al. [42,43] for Malaysia, Islam et al. [93] for Pakistan who found feedback causality between CO_2 emissions and financial development. Though, inconsistent with the study of Shahbaz et al. [94] for Pakistan who established one-way causal linkage from financial development and CO_2 emissions.(d)

Table 8
FMOLS & DOLS.

	FMOLS			DOLS		
Variable	Coefficient	t-Statistic	Prob	Coefficient	t-Statistic	Prob
CC	1.0157*	8.4164	0.000	0.9503*	9.099	0.000
FD	−0.0960*	−3.0078	0.006	−0.0944*	−3.641	0.001
GDP	0.1948**	2.4840	0.018	0.2039**	2.4923	0.017
REN	0.0260	0.4935	0.627	0.0247	0.3416	0.736
R^2	0.92			0.92		
Adj R^2	0.91			0.91		
S.E. of reg	0.013			0.013		

Note: 1% and 5% level of significance is depicted by * and**.

Table 7
ARDL long and short-run estimations.

Long-run Estimation			
Variable	Coefficient	t-Statistic	Prob
CC	0.8213*	6.0579	0.000
FD	−0.0960**	−2.4927	0.021
GDP	0.5479**	2.1375	0.044
REN	0.024	0.2831	0.779
Short-run Estimation			
CC	0.8213*	8.5092	0.000
FD	−0.0255**	−2.6734	0.017
GDP	0.5479**	2.6633	0.014
REN	0.0024	0.3739	0.712
ECT (−1)	−0.5990*	−5.5832	0.000
R^2	0.95		
Adj R^2	0.94		

Table 9
Gradual shift causality test.

Causality Path	Wald-stat	No of Fourier	P-Value	Decision
$CO_2 \rightarrow$ GDP	14.713	3	0.0398**	Reject Ho
GDP $\rightarrow CO_2$	10.932	3	0.1411	Do not Reject Ho
$CO_2 \rightarrow$ CC	5.7894	2	0.5532	Do not Reject Ho
CC $\rightarrow CO_2$	14.245	2	0.0347**	Reject Ho
$CO_2 \rightarrow$ FD	19.221	3	0.0075*	Reject Ho
FD $\rightarrow CO_2$	17.174	3	0.0163**	Reject Ho
$CO_2 \rightarrow$ REN	17.233	3	0.015**	Reject Ho
REN $\rightarrow CO_2$	6.915	3	0.6170	Do not Reject Ho

Note: *, ** and *** represents 1%, 5% and 10% level of significance.

Unidirectional causality from CO_2 emissions to renewable energy consumption. This implies that CO_2 emissions can predict significant variation in renewable energy use.

These outcomes have extensive consequences. Additionally, the pollutant induces economic growth and coal consumption induce pollution are worthy of caution for stakeholder as there is evidence of unidirectional causality.

5. Conclusion and policy directions

The world is confronted with global warming and climate change issues, as there is a continuous need for energy production and consumption. Especially energy from fossil-fuel base. The salient question that comes to heart is do we stop seeking energy consumption (coal energy) consumption. Your guess is as good as mine is, of course is, no. However, there is a need for innovation in seeking energy consumption. South African is a classic example of the outlined economies that thrives on her energy sector especially on coal energy consumption for her economic growth. South African is reputed as top emitters for CO_2 emission globally given it reliant on coal energy consumption for economic growth. However, this growth has environmental implications on environmental sustainability. To this end, we explore the dynamic connection between coal energy consumption, economic growth, renewable energy consumption and CO_2 emission. To achieve this hypothesized relationship between these variables we apply recent and battery of second-generational econometrics methodology that comprises of ARDL bounds test to cointegration in conjunction with Kripfganz and Schneider [20] critical approximation p-values. While for regression, we leverage on the ARDL, FMOLS and DOLS regression estimators while for the direction of causality we applied the Gradual- Shift based on Fourier approximation.

The empirical result shows that economic growth increases CO_2 emissions in South Africa. Similarly, coal energy consumption based on fossil-fuel also degrades the environment in South Africa. These outcomes are revealing and instructive to policymakers. Implying that there is a need for caution in the South Africa growth path and the need to explore alternative cleaner energy sources. This study affirms this need as we show that renewable energy is yet to improve the quality of the environment. This is alarming in South Africa given her track on CO_2 emission. Thus, there is need for more strides for more renewables in her energy mix to engender environmental sustainability. Interestingly financial development reduces CO_2 emission in South Africa. This suggests the need to deepen her financial base especially as it concerns public-private partnerships in clean and sustainable energy consumption to foster clean energy (SDG-7) environment (SDG-13) and ecosystem in South Africa and the continent at large.

In conclusion, it is clear that there is a need to arrive at a balance between South Africans energy mix and its environmental strategies and macroeconomic objectives by designing robust energy conservative policies. This will foster sustainable economic growth without compromise for energy cut rather a paradigm shift to renewables such as photovoltaic, hydro energy wind and thermal energy should be pursued.

CRediT authorship contribution statement

Tomiwa Sunday Adebayo: Conceptualization, Formal analysis, Methodology. **Festus Victor Bekun:** Writing – original draft, Investigation. **Mehmet Altuntaş:** Validation, Visualization, Data curation, Writing – original draft, Writing, Validation, Visualization, Supervision, and Corresponding.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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