Are impacts of renewable energy and globalization on carbon neutrality targets asymmetric in South Africa? A reconsideration using nonlinear ARDL approach

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Abstract
In this paper, we deviate from the existing literature by disentangling the independent variables into their positive and negative changes to capture asymmetric and dynamic multiplier effects of renewable energy and globalization on carbon neutrality targets within the framework of the autoregressive distributed lag (ARDL) model. In doing this, the paper uses South African data for the period 1990 to 2018 and the results show that CO2 emissions respond differently to the positive and negative shocks in renewable energy, globalization, and economic growth. The effect of a positive shock in economic growth is inelastic and positively related to CO2 emissions while a negative shock in economic growth has an elastic and negative effect on CO2 emissions. These results hold for both long-run and short-run periods. In the case of globalization, the positive shock increases CO2 emissions while the negative shock decreases CO2 emissions; although the long-run effect of a negative shock is elastic and insignificant while the short-run negative shock exerts an inelastic and significant effect on CO2 emissions. Furthermore, both the upward and downward shocks in renewable energy consumption transmit a negative effect on CO2 emissions in the long-run and short-run periods. Therefore, the paper suggests among others that to effectively decarbonize the South African economy, the use of subsidies, tax credits, tax holidays, and a host of others on green energy activities need to be enhanced as incentives for promoting cleaner energy production and consumption.

Keywords Renewable energy · Globalization · Carbon neutrality · Nonlinear cointegration test · South Africa

Introduction
Over the years, the factors determining environmental sustainability have been well established. The importance of variables such as renewable energy, globalization, and economic growth as tools to sustain environmental quality become clearer in recent times (see Shahbaz et al. 2017a, b, 2018; Rafindadi and Usman 2019, 2021; Iorember et al. 2021; Usman et al. 2020a, b; Musa et al. 2021). Given an increase in empirical studies, it is realized that a large number of scholars believe that the impact of economic variables such as renewable energy consumption, globalization, and economic growth on environmental sustainability is complicated. Most studies believe that the relationship between economic growth and environmental degradation, for example, is essentially symmetric. In other words, a change in economic growth has the same effect—whether positive or negative on environmental degradation. However, recent studies have cast doubts on the reliability of this assumption, claiming that the relationships among economic variables are possibly marked by asymmetries or nonlinearity (See Usman and Elsalih 2018; Usman 2020; Balcilar et al. 2021a, b; Balcilar and Usman 2021).

The pursuit of economic growth in South Africa has resulted in largely embracing globalization policy to boost
trade and inflows of foreign investments (see Rafindadi and Usman 2019). With the inclusion of South Africa in the emerging economic bloc alongside Brazil, Russia, India, and China, the pace of globalization and liberalization of trade policies become deeper, and this ultimately stimulates economic growth. Specifically, the average growth rate in South Africa rose to 4.3% between 1996 and 1997 while the nominal GDP for 2011 was estimated to be 400 billion USD. However, following the consequences of the COVID-19 pandemic, the GDP growth became negative (i.e., −1.8%) in the third quarter of 2021. This was short-lived, and by the last quarter of the same year, the country recorded 1.4% GDP growth and 1.9% in the first quarter of 2022. Furthermore, South Africa is ranked fourth largest emitter of GHG and seventh top emitter of fossil fuel carbon dioxide in the world. The country emitted 42% of the continental GHG as of 2008 (see IEA 2014). As reported recently by Andrew and Peters (2021), the annual share of global CO2 emission in South Africa dropped to 1.30% in 2020.

While South Africa is richly endowed with various clean energy sources that can replace fossil fuels, most of these sources have remained largely untapped. To reduce the level of emissions in South Africa, it is clear that the country need to accelerate the pace of energy transition toward renewables (see Usman et al. 2020b). In 2003, a white paper on renewable energy in South Africa came into existence. The aim was to ensure equitable levels of investments of national resources in clean energy technologies which include biomass, solar, hydro, and wind. This actually laid the foundation for the promotion of clean energy technologies and created a climate for investing in the renewable energy sector in South Africa. Consequently, in May 2011, the Integrated Resource Plan (IRP) was promulgated, which ambitiously targeted 17,800 MW of renewable energy by 2030, while almost 5000 MW was planned to be achieved by 2019. In implementing the IRP 2019 through the Electricity Regulations Act No. 4 of 2006, it was discovered that in 2017, about 6422 MW of electricity had been procured from 112 Renewable Energy Independent Power Producers bidding windows, which are purely competitive. 3162 MW of electricity generation capacity of 6422 came from 57 IPP projects, which have been connected to the national electricity grid as of June 2017 (see MRE 2021). Furthermore, several energy policies and bid windows have been implemented to reduce the level of emissions and promote the procurement of renewable energy resources. These include the 2003 implementation strategy for the control of exhaust emissions from road-going vehicles in South Africa, climate change response strategies of 2004 and 2005, cleaner energy production strategies of 2005; energy efficiency strategy of 2005 to name but a few.

Theoretically, economic growth causes environmental degradation. This is because as economic activity increases in a way to raise the standard of living of the people, unclean energy utilization is required, which of course increases the level of carbon dioxide concentration in the atmosphere. This argument is a subject matter in the environmental Kuznets curve literature (see Katircioglu and Katircioglu 2018, Usman et al. 2019; Gungör et al. 2021a, b; Usman et al. 2020b; Ike et al. 2020a, b, c; Agbede et al. 2021). Furthermore, on the one hand, it has been established in the literature that globalization may have the potential to improve environmental quality through diminishing natural resources, decreasing deforestation, lowering energy prices, and trading technical knowledge to spur the growth process (Shahbaz et al. 2018; Rafindadi and Usman 2021). Also, Gozgor et al. (2020), in their view, show that the upper level of economic globalization could encourage renewable energy. Globalization, on the other hand, can promote economic activity and thus increase energy consumption and environmental degradation if other parameters remain constant (Cole 2006; Usman et al. 2020b).

Another variable that has been emphasized in recent times as one of the major determinants of environmental sustainability is the consumption of renewable energy. The policy to transit from fossil oil consumption to clean and alternative energy systems has been documented as an appropriate measure to reduce the level of greenhouse gas emissions. This is because renewable energy has little or no environmental degradation effect as demonstrated by Alola et al. (2021), Usman et al. (2022), and Ike et al. (2020a). That is why many countries across the world have adopted renewable energy consumption as a strategy to mitigate environmental degradation.

With the high level of emissions of greenhouse gases, which include CO2 from the use of fossil fuels, particularly coal and petroleum products in South Africa, it is important to properly understand the factors accounting for environmental degradation in this country. To this extent, our paper contributes to the literature by revisiting the effects of economic growth, globalization, and renewable energy consumption on a sustainable environment in South Africa. The nonlinear model through the nonlinear autoregressive distributed lag model (NARDL) developed by Shin et al. (2014) is applied to examine how shocks to economic growth, renewable energy, and globalization change the behaviors of CO2 emissions in South Africa. By this, we relax the assumption of symmetric and linearity which tends to render the previous studies based on a linear model unreliable for a policy decision. This is because if the existing relationship is asymmetric or nonlinear, such a result would be spurious and erroneous.

Therefore, the rest of the paper is organized as follows: “Literature review” provides details of the literature reviewed. “Data and empirical model” is the methodology of the study. The empirical results and discussion are presented
in “Results and discussion” while “Concluding remarks and policy recommendations” concludes the paper with policy recommendations.

**Literature review**

The literature on the impact of economic growth, renewable energy consumption, and globalization is mostly found in the case of linearity which holds that environmental degradation responds linearly to a change in variables such as economic growth, renewable energy, and globalization. In this section, we split the review into three sub-sections:

**Economic growth and environmental degradation**

There is a voluminous literature on the relationship between economic growth and environmental degradation. Most of these studies are conducted within the framework of the EKC. For example, Ozatac et al. (2017) tested whether the EKC hypothesis is valid for Turkey. The results revealed that an increase in economic growth promotes environmental degradation with evidence of a turning point estimated to be 16,648 US dollars in the long run. Katircioğlu and Katircioğlu (2018) examined the role of economic growth in the CO₂ emissions of Turkey. Their results documented a U-shaped association between economic growth and CO₂ emission. This suggests that an increase in economic growth reduces environmental degradation over the studied period. Inglesi-Lotz and Bohlmann (2014) test the EKC hypothesis in South Africa using the ARDL method. They find no evidence in support of the hypothesis, suggesting that the economy is at the early stage of transition. Usman et al. (2019) tested for the EKC in India by incorporating the effects of energy consumption and a democratic regime. The results found that the EKC in India is characterized by an inverted U-shape, and this is fueled by the increase in energy consumption. Furthermore, a paper by Shahbaz et al. (2017b) revealed that a positive shock to economic growth exerts upward pressure on environmental degradation while a negative shock to economic growth dampens environmental degradation. Similarly, Shahbaz et al. (2018) captured the nonlinearity of the effect of economic growth in CEE countries. The results found that a positive shock to the measure of economic growth (i.e., GDP per capita) increases environmental hazards more strongly than the way in which a negative shock of economic growth decreases the level of environmental hazards. In a recent paper, Ali et al. (2021) based on the EKC procedure, reveal that economic growth has a positive effect on CO₂ emissions in Nigeria and this relationship is characterized by nonlinear. Moreover, Akadiri and Adebayo (2022) find evidence supporting the asymmetric effect of economic growth with respect to environmental degradation in India.

**Globalization and environmental degradation**

In recent times, many studies have examined the effect of globalization on environmental degradation (See Ahmed et al. 2016; Shahbaz et al. 2017a, 2018; Rafindadi and Usman 2019; 2021). The results from the existing literature seem to be mixed. Some studies concluded that globalization increases CO₂ emissions through trade and economic growth, while some studies documented that globalization is an instrument to reduce CO₂ emissions. For example, Ahmed et al. (2016) found that a rise in the pace of globalization increases the demand for energy and consequently increases CO₂ emissions. Shahbaz et al. (2017a) found on the basis of the ARDL model that globalization in China has the capacity to reduce the level of CO₂ emissions. Shahbaz et al. (2018) argue that the effect of globalization on the environment is dependent on whether its net effect is positive or negative. Furthermore, Rafindadi and Usman (2019), (2021) discovered that an increase in the pace of globalization is a tool to dampen CO₂ emissions in South Africa. On the basis of linearity, Shahbaz et al. (2018) found that whenever there is the occurrence of a positive change in global, energy consumption would be triggered to rise which increases CO₂ emissions. On the other hand, a negative shock in globalization reduces energy consumption (i.e., decrease in CO₂ emissions).

Furthermore, using the financial aspect of globalization, Ulucak et al. (2020) test for EKC in emerging countries by measuring environmental degradation based on the ecological footprint. The results show no evidence of the EKC hypothesis. However, financial globalization improves the quality of the environment while urbanization reduces environmental quality. Chen et al. (2019) using a panel of 16 CEE countries indicate that globalization enhances environmental quality due to the technological transfer accompanied by all aspects of economic globalization. Sharif et al. (2020) use a novel quantile ARDL to revisit the impact of tourism and globalization on the environment in China. The results perhaps show that globalization condenses the externalities of the environment emanating from the accumulation of carbon dioxide. Examining the role of energy consumption, globalization, and economic activity on CO₂ emission in BRICS, Rahman et al. (2021) show from the two main estimators—FMOLS and DOLS that in the long run, energy consumption from the primary source stimulates environmental degradation while globalization dampens environmental degradation measured by the level of CO₂ emissions.
Renewable energy consumption and environmental degradation

Renewable energy is one of the variables that has been unanimously admitted in the literature to mitigate the effect of environmental pollution (see Apergis et al. 2010; Silva et al. 2012; Shafiei and Salim 2014; Dogan and Ozturk, 2017; Alola et al. 2019; Paramati et al. 2021; Iorember et al. 2020; Usman et al. 2022). Silva et al. (2012) found that a portion of electricity consumption generated from clean energy dampens the level of CO2 emissions in Denmark, Portugal, and Spain; although, in the USA, such effect is insignificant. Dogan and Seker (2016) examined the relationship between renewable energy consumption and environmental quality using a panel of European countries. The results admitted that renewable energy consumption exerts a negative effect on environmental degradation. Conversely, the findings documented by Ben Jebli et al. (2015) show clearly that in sub-Saharan Africa, the effect of renewable energy in reducing environmental degradation is not visible statistically. Furthermore, Paramati et al. (2021) examined the long-run effect of renewable energy and R&D investment on environmental quality in 25 EU member countries. The results suggest renewable energy consumption reduces environmental degradation over the period of the study. In a recent paper by Usman et al. (2022), which applied the GMM estimation of a PVAR revealed that renewable energy and financial development stimulate environmental quality in the EU-28 countries. Iorember et al. (2022) using the PMG/ARDL find renewable energy consumption as a means to stimulate environmental quality in Africa’s OPEC nations. Moreover, Ehigiamusoe and Dogan (2022) applied a battery of techniques to examine how renewable energy and income level interaction affect the level of environmental degradation in low-income countries. The results show that renewable energy reduces emissions but when it interacts with income, its effect becomes positive.

Given the empirical studies reviewed, it is clear that a lot of papers relied on the assumption of linearity without giving a consideration to a situation where the relationship between the variables is nonlinear or asymmetric. In such a situation, the linear models used by the previous studies may not produce sound and valid outcomes for policy analysis. Therefore, in this study, we check for the presence of asymmetries, and hence apply a nonlinear model via the nonlinear autoregressive distributed lag (NARDL) in order to capture the effect of asymmetries in the relationship between economic growth, renewable energy consumption, globalization, and environmental degradation in South Africa.

Data and empirical model

Sources of data

Based on data availability, the study uses South African variables such as renewable energy consumption, economic growth, globalization, and CO2 emissions from 1990 to 2018. The variables’ codes, measurement/description, and their sources are summarized in Table 1 below:

Nonlinear autoregressive distributed lag (NARDL) model

The argument of this paper is that most studies in the extant literature examine the long-run effect of various economic variables based on linear settings with a strong and strict assumption of linearity. This makes the outcomes to be unreliable if the variables have a nonlinear long-run relationship (See Shin et al. 2014). To circumvent this empirically based problem, we depart from a linear rut to a nonlinear rut by employing the nonlinear autoregressive distributed lag (NARDL) model advanced by Shin et al. (2014). The general form of this model is represented as follows:

\[ y_t = \alpha^+ x^+_t + \alpha^- x^-_t + \mu_t \]  

(1)

where \( \alpha^+ \) and \( \alpha^- \) are referred to as the long-run coefficients. The time-series variables \( x^+_t \) and \( x^-_t \) represent the regressors which are decomposed into their partial sum of the positive and negative shocks defined as \( x_t = x^+_t + x^-_t \). Hence,

\[ x^+_t = \sum_{j=1}^{t} \Delta x^+_j = \sum_{j=1}^{t} \text{Max}(\Delta x_j, 0) \]  

(2)

Table 1 Variable, measurement, and source

| Variable and code            | Measurement                                                                 | Source                                      |
|------------------------------|------------------------------------------------------------------------------|---------------------------------------------|
| Carbon dioxide emissions (CO2) | CO2 emissions per capita measured in metric tons                            | World Development Indicators                |
| Renewable energy (RE)        | Share of renewable energy in the total energy use                            | World Development Indicators                |
| Income per capita (GDP)      | Gross domestic production (Constant 2015 USD) per capita                     | World Development Indicators                |
| Globalization (GLO)          | Globalization is measured in terms of three indices: economic, social, and political globalization. Economic globalization is perhaps weighted by 36%, social globalization by 38%, and political globalization by 26% | The KOF Swiss Economic Institute via http://globalization.kof.ethz.ch/ |

Source: Authors’ computation
\( x_t^- = \sum_{j=1}^{t} \Delta x_j^- = \sum_{j=1}^{t} \text{Max}(\Delta x_j, 0) \)  

(3)

From Eqs. (2) and (3), the cumulative partial sums of the positive and negative changes \( x_t \) are represented in the framework of the ARDL \((p, q)\) model advanced by Pesaran et al. (2001) as shown below:

\[
y_t = \sum_{j=1}^{p} \varphi_j y_{t-j} + \sum_{j=1}^{q} \left( \psi_j^+ x_{t+j} + \psi_j^- x_{t-j} \right) + \epsilon_t
\]

(4)

where variable \( x_t \) is \( k \times 1 \) vector of dependent variables, \( \varphi_j \) denotes the autoregressive parameter, and \( \psi_j \) represent the parameters that are nonlinearly distributed, and \( \epsilon_t \) represents the random error term, assumed to be constant in variance with zero mean. The \( p \) and \( q \) are the orders of the lags used in the NARDL model estimations. Therefore, Eq. (4) can be written within the framework of the error correction model with modification so that asymmetries are captured with respect to the direction of the change in \( x_t \), a variable:

\[
\Delta \ln CO_2 = a_0 + \beta_1 \ln CO_{2-1} + \beta_2^+ \ln \text{GDP}^{+1} + \beta_2^- \ln \text{GDP}^{-1} + \beta_3^+ \ln \text{REN}^{+1} + \beta_3^- \ln \text{REN}^{-1} + \beta_4^+ \ln \text{GLO}^{+1} + \beta_4^- \ln \text{GLO}^{-1} + \sum_{j=1}^{q} \delta_j \ln CO_{2-j} + \sum_{j=1}^{q} \omega_j^+ \Delta \ln \text{GDP}^{+j} + \sum_{j=1}^{q} \omega_j^- \Delta \ln \text{GDP}^{-j} + \mu
\]

(5)

where \( \Delta \) is the difference operator. The long-run effect of \( \text{CO}_2 \) emissions is obtained from the estimates of \( \beta \)s normalized on \( \text{CO}_2 \). To normalize Eq. (5), it will be more meaningful and convenient only if cointegration is established between the variables. Therefore, in testing for nonlinear cointegration, we follow the recommendation of Shin et al. (2014) where \( F \)-test \((F_{\text{PSS}})\) proposed by Pesaran et al. (2001) and the alternative \( t \)-test \((t_{\text{BDM}})\) proposed by Banerjee et al. (1998) are applied. The null hypothesis for an asymmetric cointegration test is provided as: \( H_0: x_t^+ = x_t^- = 0 \). Moreover, the short-term adjustment coefficients of the effects of economic growth, renewable energy consumption, and globalization on environmental sustainability are obtained from the second part of the Eq. (5), i.e., \( \sum_{j=1}^{q} \omega_j^+ + \sum_{j=1}^{q} \omega_j^- \) for all \( j = 0, ..., q - 1 \).

Another important component of the nonlinear ARDL modeling technique is the computation of the asymmetric dynamic multipliers effects of a unit change in variables captured in the model. This provides information concerning asymmetric patterns of the relationship between the explanatory variables and dependent variable. The cumulative dynamic multiplier effects of the positive and negative shocks in economic growth, renewable energy, and globalization on \( \text{CO}_2 \) emissions are captured via the following equation:

\[
m_t^+ = \sum_{j=0}^{h} \partial y_{t+j} / \partial x_t^+ \quad \text{and} \quad m_t^- = \sum_{j=0}^{h} \partial y_{t+j} / \partial x_t^- \quad \text{with} \quad h = 0, 1, 2, \ldots
\]

(6)

where when \( h \to \infty, m_t^+ \to x_t^+ \) and \( m_t^- \to x_t^- \), where \( x_t^+ \) and \( x_t^- \) remained as previously defined, i.e., the positive and negative decompositions of the explanatory variables.

Before applying the nonlinear ARDL model, we test for the asymmetric relationship among the variables by performing the long-run and short-run asymmetry tests. This enables us to check whether an asymmetric relationship exists among the variables. To do this, the WALD test with the null hypothesis \( \beta_j^+ = \beta_j^- \) for the long run and \( \omega_j^+ = \omega_j^- \) the short run.

**Results and discussion**

From the time-series plots of the variables presented in Fig. 1, it is clear that the \( \text{CO}_2 \) emission is more characterized by fluctuations and structural breaks among the variables for this study. This can be attributed to the aggressive policy thrust of the government to reduce the level of carbon dioxide. The level of carbon dioxide was low in the 1990s but started rising between 2000 and 2015; hence, South Africa became the largest emitter of \( \text{CO}_2 \) in Africa. The growth of GDP is falling in the 1990s but started rising in the 2000s until the global financial crisis interrupted in 2007/2018. Similarly, globalization trends upward, suggesting the rising pace of globalization in the country. The level of renewable energy consumption is downward trending particularly from 1999 to 2007 before it becomes relatively stabilized. This reveals South Africa’s poor performance in terms of transiting toward a renewable energy pathway.

Table 2 presents the descriptive statistics of the variables employed in this study. From the Table, it can be seen that the mean of renewable energy is the highest, followed by the mean of the GDP while the mean of \( \text{CO}_2 \) emissions is the smallest. In terms of the volatility of the variables, it is found that apart from renewable energy which is highly volatile, the standard deviation of all the remaining variables indicates low volatility. Furthermore, the skewness of the variables shows that, except for renewable energy, which is positively skewed, the remaining variables are negatively skewed with evidence that their values are within the normal range of zero. However, the values of kurtosis are positive and close to the normal range. Consequently, the probability values of the Jarque–Bera statistic indicate that the null hypothesis of the normal distribution cannot be rejected at a 5% level of significance.

Table 3 presents the results of the BDS linearity test of Brock et al. (1987) for nonlinearity. This test focuses
on the residuals of the dynamic interactions of the variables. According to the results, the null hypothesis cannot be true at a 1% level of significance. Hence, we conclude that applying the symmetric model may provide spurious results. To this extent, nonlinear models are appropriate in determining the dynamic relationship that exists between the variables.

Having established the appropriate models for the relationship between the variables, we step further to determine the stationarity properties of the variables using the standard stationarity test and unit root test with structural breaks.\(^1\) From the results of the Zivot-Andrews unit root test with structural breaks as presented in Table 4, it is clear that all the variables are not stationary at their levels. However, determining the dynamic relationship that exists between the variables.

\(^1\)The results of the standard stationarity tests via ADF and PP would be made available upon request from the corresponding author.
after taking their first differences, all the variables become stationary. This means that the variables used in this study follow the I(1) process. Furthermore, we find that the structural break occurs in 2001 for the case of carbon dioxide emissions, 2004 in the case of GDP, 1994 for globalization, and 2002 for renewable energy consumption. The structural break years identified in the results are basically influenced by the macroeconomic policy changes. Particularly, during the period of the study, South Africa has implemented several policies to mitigate the level of carbon dioxide emissions. Some of these policies as shown in Rafindadi and Usman (2019) are the Renewable Energy Policy of 2004; Integrated Clean Household Energy Strategy of 2003; Climate Change Response Strategy of 2004; cleaner energy production strategy of 2005; Implementation Strategy for the Control of Exhaust Emissions from Road-going Vehicles in South Africa introduced in 2003, Energy Efficiency Strategy 2005. All these policies are responsible for the structural breaks identified in the variables’ trends.

Furthermore, Table 5 shows the results of the nonlinear cointegration between the variables employed. The results provide that the F-statistic is 7.1021 which is far greater than the critical value of 3.99. This rejects the null hypothesis of no cointegration between the variables. The implication of the rejection of the null hypothesis is that there is clearly an existence of a long-run relationship between the variables.

Table 6 provides the results of the long-run and short-run coefficients of the function of CO₂ emissions. In the long run, the results provide that a 1% positive shock to economic growth is positively related to a 0.6979% increase in CO₂ emissions while a 1% negative shock to economic growth reduces CO₂ emissions by 5.4099%. This implies that a 1% negative shock to economic growth exerts a stronger effect on environmental degradation than the impact a 1% positive change will exert on CO₂ emissions. This finding is therefore contrary to Shahbaz et al. (2018) and Rafindadi and Usman (2021) who discovered that the impact of a positive change in economic growth is stronger than when its impact is negative. The results further discover that the impact of globalization is asymmetric and the negative change to globalization has a stronger impact. Specifically, a 1% positive change in globalization causes CO₂ emissions to gear up by 0.4058% while its negative change of the same percentage exerts a negative pressure of 2.3804% on CO₂ emissions but insignificantly. This finding is consistent with Shahbaz et al. (2018) who found a different impact of positive and negative change in globalization in BRICS countries concerning energy consumption. Moreover, the results of the impact of renewable energy suggest that renewable energy consumption negatively impacts CO₂ emissions irrespective of the directions of the changes (i.e., positive or negative). A 1% positive change to renewable energy consumption has a 0.0647% effect on CO₂ emissions while its negative change reduces CO₂ emissions by 0.0105%. This result, therefore, suggests that the impact of a positive change in renewable energy consumption has a larger effect on CO₂ emissions than its negative change of the same magnitude. This result is similar to Usman (2022) who found that a positive change in renewable energy is stronger than a positive change of the same size in Nigeria.

Furthermore, for the short-term analysis, the results provide that the previous value of CO₂ emissions reduces environmental degradation in the South African country. The results also find that a 1% positive or negative change in economic growth is said to trigger CO₂ emissions. This result is contrary to Shahbaz et al. (2017b) and Rafindadi and Usman (2021) who found that a positive shock to economic growth affects the environment differently from its negative shock. Also, we find that the effect of a 1% positive shock in globalization is positive and significant (i.e., 0.3002%) in the short run while the effect of a 1% negative shock in globalization is negative and significant (i.e., −0.5545%). This suggests that the negative effect of globalization is larger on CO₂ emissions in the short run. Furthermore, the effect of both positive and negative shocks on renewable energy consumption is asymmetric. A 1% positive shock to renewable energy consumption significantly reduces CO₂ emissions by 0.0479% while a 1% negative shock to renewable energy reduces CO₂ emissions marginally
by 0.0078% but this effect is not significant. The plausible explanation for this result is that renewables are sourced from clean energy such as solar, hydrogen, wind, and geothermal. This kind of energy has no detrimental effects on environmental degradation, and therefore, a fall in its consumption levels may only dampen the magnitude of its impact on CO2 emissions as can be seen in the result presented (i.e., from 0.0479 to 0.0078%). Moreover, the coefficient of a negative shock to renewable energy is not statistically significant. This finding is consistent with Akadiri and Adebayo (2022) that both favorable and unfavorable shocks to renewable energy consumption decrease environmental degradation in India.

Furthermore, we conduct a series of diagnostic tests to determine the fitness and adequacy of the asymmetric ARDL model used. As appeared in Table 6, the first diagnostic test is the Brusch-Godfrey LM test which checks for serial correlation in the model. We find that the null hypothesis of no serial correlation could not be rejected. The test of ARCH for heteroscedasticity and Ramsey RESET confirm that there is no conditional heteroscedasticity in the model and the functional specification is adequate. The normal distribution test of Jarque–Bera indicates that the residuals of the model are normally distributed. Also, to check for the stability of the model, CUSUM and CUSUM of square plots are constructed. The plots, as shown in Figs. 2 and 3, suggest that the model is stable at a 5% significance level.

Dynamic multiple adjustments analysis

Figures 4, 5, and 6 analyze the dynamic multiplier effect of economic growth, globalization, and renewable energy to a 1% variation in CO2 emissions. The thick black line denotes the multiplier effects of a positive shock in explanatory variables to a unitary variation in CO2 emissions. The dotted black line is the multiplier effects of a negative shock in the explanatory variable to a unitary variation in CO2 emissions. The dotted red line is the confidence interval of 95% upon which the significant levels are determined while the horizons are 15. From Fig. 4, it is clear that the effect of a positive shock is less than the effect of a negative shock of economic growth; hence, the overall multiplier effect is negative with evidence of asymmetry which is statistically

### Table 6  Long-run and short-run coefficients

| Variable | Coefficient | Stand. error | p-value |
|----------|-------------|--------------|---------|
| lnGDP$_t$ | 0.6979* | 0.3271 | 0.0510 |
| lnGDP$_{t-1}$ | -5.4099* | 3.0001 | 0.0929 |
| lnGLO$^+_t$ | 0.4058** | 0.1491 | 0.0165 |
| lnGLO$^{-}_{t-1}$ | -2.3804 | 4.2393 | 0.5833 |
| lnREN$^+_t$ | -0.0647** | 0.0272 | 0.0319 |
| lnREN$^{-}_{t-1}$ | -0.0105*** | 0.0021 | 0.0002 |
| ΔlnCO2$_{t-1}$ | -0.7399*** | 0.1419 | 0.0001 |
| ΔlnGDP$_{t-1}$ | 0.5164* | 0.2733 | 0.0796 |
| ΔlnGLO$^+_t$ | 4.0029* | 1.9159 | 0.0560 |
| ΔlnGLO$^{-}_{t-1}$ | 0.3002** | 0.1013 | 0.0102 |
| ΔREN$^+_t$ | -0.5545* | 0.3025 | 0.0815 |
| ΔREN$^{-}_{t-1}$ | -0.0479** | 0.0208 | 0.0373 |
| ΔCNT | -0.0078 | 0.0089 | 0.4026 |
| Constant | 1.7973*** | 0.2996 | 0.0000 |

Model diagnostics:
- $\chi^2$ – SERIAL: 0.2130, 0.6521
- $\chi^2$ – ARCH: 0.7215, 0.4044
- $\chi^2$ – RESET: 0.1241, 0.7303
- $\chi^2$ – NORMAL: 6.4691, 0.0393

Triple asterisks (***) denote 1%, double asterisks (**) denote 5%, and a single asterisk (‘’) denote 1% significance levels.

### Figures

- **Fig. 2** Plot of CUSUM at 5% level of significance
- **Fig. 3** Plot of CUSUM Squares at a 5% level of significance
significant only up to the second horizon. Also, the effects of both the positive and negative shocks to globalization exert positively and significantly on CO₂ emissions. However, although there is evidence of an insignificant asymmetry. For renewable energy, we find that the multiplier effect of a positive shock is negative and significant while the multiplier effect of a negative shock is positive and insignificant. So, the overall multiplier effect is negative with evidence that the asymmetry is statistically significant.

**Concluding remarks and policy recommendations**

This paper contributes to the knowledge by reconsidering whether the asymmetric effect is detected in the impacts of renewable energy consumption and globalization on the goal of carbon neutrality in South Africa over the period 1990 to 2018. To achieve this objective, we apply the non-linear ARDL model to capture the effects of the positive and negative shocks to economic growth, globalization, and renewable energy consumption on CO₂ emissions. The results suggest the presence of asymmetries among the variables employed. The CO₂ emissions respond differently to the positive and negative shocks to all explanatory variables both in the long run and short run. Specifically, economic growth responds positively to CO₂ emissions if the shock to economic growth is positive and negative if the shock to economic growth is negative. However, the effect of the negative shock is stronger. For globalization, its positive shock increases CO₂ emissions while the negative shock reduces CO₂ emissions with a stronger effect coming from negative shock; although the effect of a negative shock is insignificant in the long run. Finally, we find that both the positive and negative shocks to renewable energy consumption have a decreasing effect on CO₂ emissions both in the long run and short run.

Based on these findings, the following policy implications are crafted: First, there is a need to stimulate the growth of renewable energy consumption by encouraging an influx of investments in renewable energy by the public and private investors. In this case, policy instruments such as subsidies like a tax credit and tax holidays could be used to encourage the influx of investments into the renewable energy sector of the economy. Second, economic growth pursuit should be tailored towards green growth. In this case, boosting alternative clean energy consumption and investment should be the priority of policymakers in stimulating growth in the South African economy. What this means is that government has to ensure that necessary technologies are available to help improve production activities towards the path of pollution free. In this case, certain standards of pollution should be set. Firms
that do not meet the standard should be taxed. Third, as much as globalization stimulates economic activity and increases income levels through the transfer of technological advancement, there is a need also to regulate the influx of firms so that their entrance would not constitute a channel of pollution. To this extent, stringent environmental policies and taxes can be introduced to minimize the adverse effect of environmental pollution. Such policies should be aimed at promoting innovation in clean technologies and discouraging dirty technologies from being imported into the country. Also, policymakers should be careful in the use of environmental taxes so that domestic and foreign investors are not forced to relocate to other countries due to the high rate of environmental taxes. Notably, environmental taxes should be such that can partly reduce environmental degradation and can provide incentives for the use of cleaner energy.

Therefore, this study is limited to South Africa’s economy. Future research can consider major economies in Africa to better understand the behaviors of environmental indicators in the continent of Africa. Moreover, since South Africa has implemented several strategies over the years to promote renewable energy and green growth, it is expected that such strategies will have an impact on environmental degradation. Therefore, future research should control for likely structural breaks associated with the trend of variables.

**Author contribution** Maryam Abu-Goodman: conceptualization, formal analysis, investigator, writing—original draft, writing—review and editing. Hasan Güngör: writing—original draft, writing—review and editing validation, supervision, Ojonuguwa Usman: investigation, methodology, data curation, writing—original draft, writing—review and editing.

**Data availability** The datasets generated and/or analyzed during the current study are available in the repositories:
- The carbon dioxide emissions per capita, GDP per capita, renewable energy consumption, forest rents, and crop production are all obtained from the WDI database

**Declarations**

**Ethical approval** Not Applicable.

**Consent to participate** Not Applicable.

**Consent for publication** Not Applicable.

**Competing interests** The authors declare no competing interests.

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