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Carbon Emissions, Renewable Energy Consumption, Trade and Financial Development Linkages in SADC Countries: Evidence from a Nonlinear ARDL Analysis

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Abstract

This study analyzes the relationship among carbon emissions, renewable energy consumption, trade openness, and financial development. To achieve this objective, the annual data of eleven SADC countries were used, spanning 1990 to 2022, depending on their availability. A descriptive statistic is presented, followed by unit root tests. Then, the NARDL method was applied to investigate the co-integration relationship between series. Several findings have been obtained. In the long-term, a positive shock on renewable energy consumption reduces CO_2 emissions in Lesotho, Madagascar, Mozambique, South Africa, Tanzania, and Zimbabwe, except for the Seychelles. A positive change in trade openness also decreases CO_2 emissions only in Tanzania and increases them in Eswatini and Mozambique. In the case of financial development, positive shocks increase carbon dioxide emissions in Tanzania. A negative shock on renewable energy use also decreases CO_2 emissions in many countries namely, Comoros, Lesotho, Madagascar, Mauritius, Mozambique, and Tanzania. The same shock on trade openness reduces CO_2 emissions in South Africa and adversely increases them in Mauritius and Tanzania. Negative changes in financial development also have a mixed effect. On the one hand, it contributes to reducing carbon emissions in Tanzania and Zimbabwe, and on the other hand, it promotes atmospheric pollution in Madagascar, Mauritius, Mozambique, and the Seychelles. Short-term dynamics have also been investigated. Policy implications have been proposed.

Keywords

CO_2 Emissions, Renewable Energy Consumption, Trade Openness, Financial

Development, NARDL, SADC

1. Introduction

The impact of climate change and the imperative to transition toward cleaner energy sources are crucial global concerns. In this context, the countries of the Southern African Development Community (SADC) have also been striving to reduce their carbon emissions and promote the use of renewable energy to fuel their economic development. Indeed, these countries have tried gradually to decrease their emission levels and reduce global warming to respect the Kyoto Protocol. Simultaneously, international trade plays a vital role in the transfer of technologies and resources to support this transition. Furthermore, financial development is a key factor that can stimulate investments in renewable energy projects and reduce carbon emissions.

Fossil fuel consumption, land-use changes, and agriculture (mostly from soils and livestock) have been detected as main contributors to total greenhouse gases (GHG) emissions at 61%, 18%, and 14%, respectively, leading to climate change (Stern, 2004). According to the International Renewable Energy Agency (IRENA, 2023), carbon dioxide emissions in 2022 were 7.46 $MtCO_2$[1] for Botswana, 0.41 $MtCO_2$ for Comoros, 1.3 $MtCO_2$ for Eswatini, 3.13 $MtCO_2$ for Lesotho, 4.40 $MtCO_2$ for Madagascar, 4.25 $MtCO_2$ for Mauritius, 8 $MtCO_2$ for Mozambique, 404.05 $MtCO_2$ for South Africa, 16 $MtCO_2$ for Tanzania, 8.92 $MtCO_2$ for Zambia, and 8.85 $MtCO_2$ for Zimbabwe.

Extensive ecological research has examined the aforementioned determinants that can mitigate carbon dioxide emissions. One major strand of research is that non-renewable energy consumption increases CO_2 emissions (Bhattacharya, Churchill, & Paramati, 2017; Lau et al., 2019; Sharif et al., 2019). Other strands reveal that renewable energy, so-called clear energy use, reduces carbon dioxide emissions across countries (Chen et al., 2022; Alvarez-Herranz et al., 2017; Bekun et al., 2019).

Another strand of literature found an inconclusive effect of trade on CO_2 emissions. Some studies have posited that trade openness reduces CO_2 emissions (Liu et al., 2017; Apergis et al., 2018; Zhang et al., 2017; Al-Mulali et al., 2015; Al-Mulali & Ozturk, 2015) and conversely, other perspectives have emphasized the opposite effects (Fang et al., 2019; Gozgor & Can, 2017; Gözgör & Can, 2016; Tiba et al., 2016). Furthermore, many studies have introduced financial development as a key determinant of CO_2 emissions. In this regard, some authors found that financial development mitigates environmental degradation (Shoaib et al., 2020; Shahbaz et al., 2020; Zhang, 2011; Tamazian & Rao, 2010). Some scholars have argued that financial development can foster carbon emissions (Wang et al., 2019; Islam et al., 2013; Sadorsky, 2011).

Different datasets and methodologies (see literature review in Section 2) have

[1]Metric tonnes CO_2.

been used in aforementioned studies to examine the relationship between CO_2 emissions, renewable energy use, trade openness, and financial development. Most of these earlier studies assume that the co-integration relationship between nonstationary series is typically symmetric, failing to investigate a potential nonlinear relationship. However, a nonlinearity linkage may be detected between the variables under study, namely carbon emissions, renewable energy consumption, trade openness, and financial development (see Udeagha and Breitenbach, 2023 for large development). Previous studies based on a linear framework had no additional data to make consistent conclusions and predictions. This reason leads us to believe that the aforementioned series may present a nonlinear and asymmetric link.

Based on the literature mentioned above, this study investigates the effect of renewable energy use, trade openness, and financial development on carbon emissions in SADC countries. What is the effect of renewable energy consumption on CO_2 emissions in SADC selected countries?

Beyond the results of others' works, our contributions are threefold: first, we use a more flexible nonlinear dynamic framework of Shin et al. (2014) to capture positive and negative shocks of exogenous variables on CO_2 emissions in long-short-term, in eleven on sixteen SADC countries. SADC countries may experience structural breaks or shifts in the relationships between variables due to changes in policies, economic conditions, or external shocks. The NARDL approach can accommodate such structural breaks. The second is the use of a multivariate framework in contrast to the bivariate approach. Third, by providing insights into the nonlinear and dynamic relationships between variables, the NARDL approach can inform policy decisions aimed at promoting sustainable development and mitigating climate change in SADC countries. Indeed, to the best of our knowledge, no study has simultaneously investigated the relationship between CO_2 emissions, renewable energy consumption, trade openness, and financial development in SADC countries.

The rest of work is as follows: Section 2 reviews the literature, Section 3 displays the data and methodology, and Section 4 presents the results and discussion. Section 5 concludes the paper with policy implications.

2. Literature Review

Most studies using CO_2 emissions as dependent variables refer to the Environmental Kuznets Curve (EKC) hypothesis. Extensive literature exists on the relationship between per capita income and CO_2 emissions through the EKC hypothesis. These studies test for linear, quadratic, or cubic relationship (Grossman & Krueger, 1991, 1995; Stern, 2004; Dinda, 2004). This study does not concern the literature but rather the conflicting results between renewable energy consumption and carbon dioxide emissions. In most cases, empirical results show a negative and significant effect of renewable energy consumption on carbon emissions indifferently to methodology used and sample choice.

Relationship between CO_2 emissions and natural resources

The demand for natural resources has escalated alongside rapid urbanization and industrialization, raising concerns about potential exploitation and environmental degradation (Chen et al., 2018; Balta-Ozkan et al., 2015). Wu et al. (2018) underscored the ecological risks posed by natural resource exploitation driven by economic growth. Several studies have established a direct relationship between natural resource consumption and economic growth indicators (Ahmed et al., 2016; Badeeb et al., 2017; Ben-Salha et al., 2021; Shahbaz et al., 2017).

Balsalobre-Lorente et al. (2018) conducted a study on selected EU countries, revealing that CO_2 emissions can be influenced by natural resources and renewable electricity, suggesting that importing fossil fuels from countries with rich natural resources could help regulate emissions. However, Destek and Sarcodia (2019) cautioned against the overconsumption of natural resources, which can strain a country's biological capacity and intensify its ecological footprint. Baloch et al. (2019) investigated the relationship between natural resources and CO_2 emissions in BRICS economies and found that while natural resources may not significantly impact emissions in Brazil, India and China, they play a notable role in South Africa's emissions. Moreover, natural resources were identified as contributing to the reduction of carbon levels in Russia, thereby mitigating environmental pollution.

Allard et al. (2018) used quantile regression spanning 1994 to 2012 across 74 countries and found evidence supporting the N-shaped EKC, except for upper-middle-income countries. They observed negative relationships between Renewable Energy Consumption (REC) and CO_2 emissions. Anwar et al. (2021), who conducted quantile regression, FMOLS, DOLS, and FE-OLS from 1980 to 2013 in ASEAN countries, demonstrated varying support for the EKC across different quantiles. They found REC and CO_2 emissions to be negatively correlated, whereas non-renewable energy consumption (NREC) showed positive correlations with CO_2 emissions. Balsalobre-Lorente et al. (2018), employing panel least squares from 1985 to 2016 in Germany, France, Italy, Spain, and the UK, supported the N-shaped EKC, with REC and CO_2 emissions displaying negative relationships. Bekun et al. (2019) use PMG/ARDL models from 1996 to 2014 in 16 EU countries and indicated negative correlations between REC and CO_2 emissions, whereas NREC showed positive correlations. Cai et al. (2018) applied ARDL from 1965 to 2015 in G7 countries and found a negative correlation between REC and CO_2 emissions for Germany and the US. Chen et al. (2019) also used ARDL from 1980 to 2014 in China, supporting the EKC hypothesis, with REC and CO_2 emissions exhibiting negative correlations. According to Dong et al. (2018b), they conducted ARDL/FMOLS/DOLS from 1993 to 2016 in China, revealing support for the EKC hypothesis, with negative correlations observed between nuclear energy, REC, and CO_2 emissions. Inglesi-Lotz and Dogan (2018) employed DOLS from 1980 to 2011 in Sub-Saharan countries, indicating no support for the EKC hypothesis, with REC showing negative correlations with CO_2 emissions, whereas NREC showed positive correlations with CO_2 emissions. Liu et al. (2017) used VECM from 1970 to 2013 in Indonesia, Malaysia, the Philippines, and Thailand, indicating no support for the EKC hypothesis, with REC showing negative correlations with CO_2 emissions, whereas NREC showed positive correlations with CO_2 emissions. Dogan and Seker (2016) employed DOLS from 1980 to 2012 in EU countries, indicating support for the EKC hypothesis, with negative correlations observed between REC and CO_2 emissions, whereas NREC showed positive correlations with CO_2 emissions. Dong et al. (2018a) used CCEMG from 1990 to 2014 across 128 countries and different geographical clusters and found positive associations between economic growth and CO_2 emissions, whereas REC showed negative correlations with CO_2 emissions. Ma et al. (2021) conducted FMOLS and DOLS from 1995 to 2015 in France and Germany, indicating support for EKC hypothesis, with REC showing negative correlations with CO_2 emissions, whereas NREC showed positive correlations with CO_2 emissions.

Relationship between CO_2 emissions and financial development

The impact of financial development on CO_2 emissions has been extensively studied, yielding mixed results and contrasting perspectives. One school of thought suggests a negative relationship between financial development and CO_2 emissions. For instance, Dogan and Seker (2016) found that financial sector development enhances environmental quality by minimizing emissions, a conclusion echoed by Shahbaz et al. (2017) in their study on France. Similarly, Saidi and Mbarek (2017) extended this context to emerging economies, suggesting that higher financial development could lead to improved environmental quality. In line with these findings, Haseeb et al. (2018) and Park et al. (2018) observed significant mitigation of environmental pollution in the European Union due to financial development.

On the other hand, another group of researchers supports a positive relationship between financial development and CO_2 emissions. For instance, Al-Mulali et al. (2015) found that financial development increases CO_2 emissions across 23 EU countries, whereas Farhani and Ozturk (2015) observed increased CO_2 emissions due to financial development in Tunisia. Javid and Sharif (2016) reached similar conclusions in the context of Pakistan. Furthermore, Salahuddin et al. (2018) revealed a positive and significant impact of foreign direct investment and financial development on CO_2 emissions in Kuwait. In Saudi Arabia, Xu et al. (2018) observed an increase in CO_2 emissions associated with financial development. Similarly, Zakaria and Bibi (2019) examined the association between institutional governance, financial inclusion, and environmental pollution, concluding that financial development intensifies environmental degradation. Overall, the literature on CO_2 emissions stemming from financial development presents diverse and sometimes conflicting findings, underscoring the need for further research in this area.

Relationship between CO_2 emissions and trade openness

The impact of trade openness on CO_2 emissions has been extensively studied, however, a clear consensus remains elusive. While openness is recognized as a crucial driver of economic growth and development, its influence on environmental quality, particularly in terms of CO_2 emissions, is subject to debate (Acheampong & Boateng, 2019; Shahbaz et al., 2017). Grossman and Krueger (1995) argued that trade openness can have both positive and negative effects on environmental quality, depending on national strategies and the level of development. Recent studies have delved into the environmental implications of trade liberalization using panel data (Shahbaz et al., 2017).

Shahbaz et al. (2017) found empirical evidence supporting the positive impact of trade openness on CO_2 emissions based on panel data from developed economies. In contrast, Acheampong and Boateng (2019) suggested that trade openness reduces CO_2 emissions in the USA, Brazil, Australia, and India but increases them in China. Similarly, Cole et al. (2011) emphasized the significance of trade openness and its environmental consequences, particularly in China, where impurities play a crucial role. Chang (2012) supported this argument, highlighting the importance of studying pollutants in assessing the environmental impact of trade openness and foreign direct investment.

On a country-specific level, Tiwari et al. (2013) explored the dynamic causal link between India's trade openness and CO_2 emissions, revealing a positive correlation between the two variables. Ling et al. (2015) identified trade openness as a contributing factor to environmental quality improvement in Malaysia. Conversely, Solarin et al. (2017) confirmed that globalization accelerates CO_2 emissions in Malaysia. Meanwhile, Xu et al. (2018) investigated the impact of trade openness on carbon emission in Saudi Arabia, concluding that trade openness leads to increased CO_2 emissions.

The inconclusive response to the impact of renewable energy consumption, financial development, and trade openness on CO_2 emissions can be largely explained by the limitations of traditional linear methods. Due to these conflicting results, our work used the NARDL (Nonlinear Autoregressive Distributed Lag) approach because the effect of renewable energy consumption, trade openness, and financial development could result on an asymmetric shock on CO_2 emissions.

3. Data and Methodology

3.1. Data

This study examines the asymmetrical linkages between carbon dioxide emissions (metric tons per capita), financial development (domestic credit to private sector % of GDP), trade openness (% of GDP), renewable energy consumption (% of total final energy consumption).

The data of these variables used are annual and from World Development Indicator (World Bank, 2022). The dataset concern SADC (Southern African Development Community) countries, spanning 1990 to 2022 and the choice of the study period depends on the availability of the data. All variables are transformed into their natural logarithmic form to facilitate the interpretation of the results.

3.2. Theoretical Framework

Since the work of Grossman and Krueger (1991), several studies have verified the hypothesis of the environmental Kuznets curve (EKC). This hypothesis states that the relationship between economic growth and environmental pollution changes from positive to negative and is represented by an inverted U-shape (Munir et al., 2020; Sun et al., 2020). According to some studies (Copeland & Taylor, 2004; Majeed & Luni, 2019), in the early stages of development, economic growth leads to increased emissions of carbon and other greenhouse gases, which then reduce with improved research, education, public awareness, and technology. The aim of this work is not to investigate the EKC hypothesis but the relationship between CO_2 emissions, renewable energy use, trade openness, and financial development.

The verification of the EKC hypothesis is partly due to the effects of international trade based essentially on the theory of comparative advantages (Arrow et al., 1995; Stern et al., 1996). This theory states that each country specializes in the intensive production of goods and services for which it has abundant factors of production. So, developed countries specialize in activities that are intensive in capital and human capital. Developing countries specialize in intensive activities in natural resources and unskilled labour. These specializations would be the main explanation of the EKC hypothesis (Coulibaly, 2014). Efforts to reduce pollutant emissions in developed economies could be explained by the transfer of polluting activities to poor countries. Financial development is a key determinant of environmental quality. It reduces the level of carbon emissions by offering financial support to domestic firms to install clean and modern technologies in the production process (Aye & Edoja, 2017). Moreover, when companies develop and institutionalize their environmental responsibilities, it helps to contain carbon emissions.

Renewable energy consumption is considered a crucial determinant of CO_2 emissions. It is less polluting and helps manage increased energy demand (Le, Chang, & Park, 2020). In addition, renewable energies reduce carbon emissions, as they do not emit pollution and can replace traditional technologies that depend on the consumption of fossil fuels (Bilgili et al., 2016; Majeed & Luni, 2019).

$$CO_2 = f\left(REC, TRA, FD\right) \quad (1)$$

where, CO_2, REC, TRA and FD represent CO_2 emissions, renewable energy consumption, trade openness and financial development respectively.

3.3. Methodology

In this section, we will firstly present the nonlinear and asymmetric co-integration test and secondly, we will adopt the wavelet analysis.

The NARDL Bounds Test for Co-Integration

This study uses the nonlinear autoregressive distributed lag model (NARDL) method developed by Shin et al. (2014) because it relaxes the restriction that the time series considered should have the same order of integration. This relax makes that this approach allows a combination of I(0) and I(1) integrations. It makes the distinction between the long-term and short-term asymmetrical impacts of independent variables on the dependent variable within an error correction framework (Shahbaz et al., 2017). In addition, this approach captures the nonlinear and asymmetric co-integration between variables. Finally, this method is still valid in multivariate models and displays a graph of cumulative dynamic multipliers.

This paper uses the NARDL method to analyze the asymmetric nonlinear impact of GDP per capita, renewable energy consumption, financial development on CO_2 emissions in selected SADC countries. The relationship between the above-mentioned variables is also analyzed using the wavelet-based approach based on time-frequency domain.

According to Shahbaz et al. (2017) and Kassi et al. (2023), the NARDL model proposed by Shin et al. (2014) for asymmetric error correction model can be written as follows:

$$\begin{aligned}\Delta CO_{2t} &= \alpha_0 + \delta CO_{2t-1} + \gamma^+ REC_{t-1}^+ + \gamma^- REC_{t-1}^- + \varphi^+ TRA_{t-1}^+ \\ &\quad + \varphi^- TRA_{t-1}^- + \iota^+ FD_{t-1}^+ + \iota^- FD_{t-1}^- + \sum_{k=1}^{p} \omega_k \Delta CO_{2t-k} \\ &\quad + \sum_{k=0}^{q} \eta_k^+ \Delta GDP_{t-k}^+ + \sum_{k=0}^{q} \eta_k^- \Delta GDP_{t-k}^- + \sum_{k=0}^{q} \lambda_k^+ \Delta REC_{t-k}^+ + \sum_{k=0}^{q} \lambda_k^- \Delta REC_{t-k}^- \\ &\quad + \sum_{k=0}^{q} \pi_k^+ \Delta TRA_{t-k}^+ + \sum_{k=0}^{q} \pi_k^- \Delta TRA_{t-k}^- + \sum_{k=0}^{q} \theta_k^+ \Delta FD_{t-k}^+ + \sum_{k=0}^{q} \theta_k^- \Delta FD_{t-k}^- + \varepsilon_t\end{aligned} \tag{2}$$

where α_0 is the specific intercept for each county; δ, γ^+, γ^-, φ^+, φ^-, ι^+, ι^-, ω_k, η_k^+, η_k^-, λ_k^+, λ_k^-, π_k^+, π_k^-, θ_k^+, θ_k^- represent the coefficients to be estimated; Δ and $\sum$ are the difference and sum operators, REC^+, TRA^+, FD^+ are the positive partial sum while REC^-, TRA^-, FD^- denote the negative partial sum. p represents the optimal lags for the dependent variable (CO_2) and q those of independent variables (REC, TRA, FD) which will be determined by the Akaike information criterion (AIC) and $\varepsilon_t \sim \mathrm{IID}\left(0,\sigma^2\right)$.

Following Shin et al. (2014) and Shahbaz et al. (2017), we now consider the partial sums of renewable energy consumption, trade openness and financial development. These independent variables are decomposed into their positive changes (REC^+, TRA^+, FD^+) and negative changes (REC^-, TRA^-, FD^-) like follows:

$$REC_t^+ = \sum_{k=1}^{t} \Delta REC_k^+ = \sum_{k=1}^{t} \max\left(\Delta REC_k, 0\right); \tag{3}$$

$$REC_t^- = \sum_{k=1}^{t} \Delta REC_k^- = \sum_{k=1}^{t} \min\left(\Delta REC_k, 0\right); \tag{4}$$

$$TRA_t^+ = \sum_{k=1}^{t} \Delta TRA_k^+ = \sum_{k=1}^{t} \max\left(\Delta TRA_k, 0\right); \tag{5}$$

$$TRA_t^- = \sum_{k=1}^{t} \Delta TRA_k^- = \sum_{k=1}^{t} \min\left(\Delta TRA_k, 0\right); \tag{6}$$

$$FD_t^+ = \sum_{k=1}^{t} \Delta FD_k^+ = \sum_{k=1}^{t} \max\left(\Delta FD_k, 0\right); \tag{7}$$

$$FD_t^- = \sum_{k=1}^{t} \Delta FD_k^- = \sum_{k=1}^{t} \min\left(\Delta FD_k, 0\right) \tag{8}$$

Equations (3)-(8) describe the positive and negative change in variables.

The long-term asymmetric coefficients are estimated like this: $G^+ = -\left(\gamma^+/\delta\right)$, $G^- = -\left(\gamma^-/\delta\right)$, $\Upsilon^+ = -\left(\varphi^+/\delta\right)$, $\Upsilon^- = -\left(\varphi^-/\delta\right)$; $\mathrm{I}^+ = -\left(\iota^+/\delta\right)$, $\mathrm{I}^- = -\left(\iota^-/\delta\right)$; where G^+, Υ^+ and I^+ represent the long-term impacts of the positive partial sums while G^-, Υ^- and I^- are the long-term impacts of the negative partial sums.

The specification of model (2) accounts both for short and long-term dynamics in NARDL framework has more advantages than the model (1).

Hypotheses

We test the existence of asymmetric long-term co-integration using the Shin et al. (2014) bounds test. It is a joint test of all the lagged levels of regressors: The *F-test* in Pesaran et al. (2001). Under the null hypothesis of the F-statistic tests that H_{1a}: $\delta = \gamma^+ = \gamma^- = \varphi^+ = \varphi^- = \iota^+ = \iota^- = 0$. The null hypothesis supposes the absence of a long-term relationship between the variables. If we reject the null hypothesis of no co-integration, a long-term relationship exists among the variables and the alternative hypothesis is H_{1b}: $\delta \neq \gamma^+ \neq \gamma^- \neq \varphi^+ \neq \varphi^- \neq \iota^+ \neq \iota^- \neq 0$. In order to investigate the nonlinear effects in the long-term parameters, we use the Wald tests in the model (2) as follows:

$$H_{2a}:\ G^+ = G^-;\ H_{2b}:\ \Upsilon^+ = \Upsilon^- \ \text{ and } H_{2c}:\ \mathrm{I}^+ = \mathrm{I}^- \tag{9}$$

Hypothesis H_{2a}, H_{2b} and H_{2c} suppose a symmetrical impact of renewable energy consumption, the trade openness and financial development respectively. If we cannot reject the hypothesis above (H_{2a}, H_{2b} and H_{2c}) after performing the Wald test, a restricted version of the NARDL model (2) is performed as:

$$\begin{aligned} \Delta CO_{2t} = {} & \alpha_0 + \delta CO_{2t-1} + \gamma REC_{t-1} + \varphi TRA_{t-1} + \iota FD_{t-1} + \sum_{k=1}^{p} \alpha_{1,k} \Delta CO_{2t-1} \\ & + \sum_{k=0}^{q} \alpha_{2,k}^+ \Delta REC_{t-k}^+ + \sum_{k=0}^{q} \alpha_{3,k}^- \Delta REC_{t-k}^- + \sum_{k=0}^{q} \alpha_{4,k}^+ \Delta TRA_{t-k}^+ \\ & + \sum_{k=0}^{q} \alpha_{5,k}^- \Delta TRA_{t-k}^- + \sum_{k=0}^{q} \alpha_{6,k}^+ \Delta FD_{t-k}^+ + \sum_{k=0}^{q} \alpha_{7,k}^- \Delta FD_{t-k}^- + \xi_t \end{aligned} \tag{10}$$

The long-term symmetrical dynamics is shown by the restricted Equation (10). So, the impacts of the renewable energy consumption, the trade openness and the financial development on the long-term CO_2 emissions are represented by $G = -\left(\gamma/\delta\right)$, $\Upsilon = -\left(\varphi/\delta\right)$ and $\mathrm{I} = -\left(\iota/\delta\right)$, respectively. The Wald test to investigate the short-term asymmetry (symmetrical) impact is based on these following hypotheses:

$$H_{3a}:\ \sum_{k=0}^{q}\alpha_{2,k}^{+}=\sum_{k=0}^{q}\alpha_{3,k}^{-},\ H_{3b}:\ \sum_{k=0}^{q}\alpha_{4,k}^{+}=\sum_{k=0}^{q}\alpha_{5,k}^{-},\ H_{3c}:\ \sum_{k=0}^{q}\alpha_{6,k}^{+}=\sum_{k=0}^{q}\alpha_{7,k}^{-} \tag{11}$$

If we cannot reject hypothesis H_{3a}, H_{3b} and H_{3c}, we assume symmetrical impacts of renewable energy consumption, trade openness and financial development on short-run CO_2 emissions. The following equation shows the NARDL model with only symmetrical impacts in the short-run and asymmetrical impacts in the long-run as:

$$\begin{aligned}\Delta CO_{2t} &= \alpha_0+\delta CO_{2t-1}+\gamma^{+}REC_{t-1}^{+}+\gamma^{-}REC_{t-1}^{-}+\varphi^{+}TRA_{t-1}^{+}+\varphi^{-}TRA_{t-1}^{-}\\ &\quad+\iota^{+}FD_{t-1}^{+}+\iota^{-}FD_{t-1}^{-}+\sum_{k=1}^{p}\alpha_{1,k}\Delta CO_{2t-1}+\sum_{k=0}^{q}\alpha_{3,k}\Delta REC_{t-k}\\ &\quad+\sum_{k=0}^{q}\alpha_{4,k}\Delta TRA_{t-k}+\sum_{k=0}^{q}\alpha_{5,k}\Delta FD_{t-k}+\upsilon_t\end{aligned} \tag{12}$$

When the Wald test fails to reject the long and short-term asymmetries, we use the following restricted model:

$$\begin{aligned}\Delta CO_{2t} &= \alpha_0+\delta CO_{2t-1}+\gamma REC_{t-1}+\varphi TRA_{t-1}+\iota FD_{t-1}+\sum_{k=1}^{p}\alpha_{1,k}\Delta CO_{2t-1}\\ &\quad+\sum_{k=0}^{q}\alpha_{2,k}\Delta REC_{t-k}+\sum_{k=0}^{q}\alpha_{3,k}\Delta TRA_{t-k}+\sum_{k=0}^{q}\alpha_{4,k}\Delta FD_{t-k}+\mu_t\end{aligned} \tag{13}$$

The long-term coefficients measure the relationship between the positive and negative changes of independent variables in the long-run equilibrium. The asymmetric dynamic multiplier effects are estimated by the following equations:

$$\begin{aligned}&mREC_k^{+}=\sum_{k=0}^{\tau}\frac{\partial\Delta CO_{2,t+k}}{\partial\Delta REC_{t-k}^{+}},\ mREC_k^{-}=\sum_{k=0}^{\tau}\frac{\partial\Delta CO_{2,t+k}}{\partial\Delta REC_{t-k}^{-}},\ \tau=0,1,2,\cdots\\ &mTRA_k^{+}=\sum_{k=0}^{\tau}\frac{\partial\Delta CO_{2,t+k}}{\partial\Delta TRA_{t-k}^{+}},\ mTRA_k^{-}=\sum_{k=0}^{\tau}\frac{\partial\Delta CO_{2,t+k}}{\partial\Delta TRA_{t-k}^{-}},\ \tau=0,1,2,\cdots\\ &mFD_k^{+}=\sum_{k=0}^{\tau}\frac{\partial\Delta CO_{2,t+k}}{\partial\Delta FD_{t-k}^{+}},\ mFD_k^{-}=\sum_{k=0}^{\tau}\frac{\partial\Delta CO_{2,t+k}}{\partial\Delta FD_{t-k}^{-}},\ \tau=0,1,2,\cdots\end{aligned} \tag{14}$$

where if $\tau\to\infty$, then $mREC_k^{+}\to G^{+}$, $mREC_k^{-}\to G^{-}$, $mTRA_k^{+}\to\Upsilon^{+}$, $mTRA_k^{-}\to\Upsilon^{-}$, $mFD_k^{+}\to\mathrm{I}^{+}$, $mFD_k^{-}\to\mathrm{I}^{-}$. G^{+}, Υ^{+} and I^{+} represent the coefficients of positive shocks while G^{-}, Υ^{-} and I^{-} are the negative shocks of independent variables in the long-term.

The asymmetric relationship between CO_2 emissions, natural resource, financial development and globalization have been investigated by several empirical works (Adebayo et al., 2022; Roy, Rej, & Rajaiah, 2023; Ibrahim et al., 2022; Shahbaz et al., 2017).

4. Results and Discussions

In this section, first, the descriptive statistics of variables will be presented as well as the results of the unit root tests, taking or not into account structural breaks. Second, we will analyze the results of co-integration and symmetry tests. Finally, we will report the NARDL long and short-term results and interpretations.

Results and interpretations

Table 1 shows the results of the descriptive statistics for each country. We note that trade openness is less volatile for Botswana (0.110), Comoros (0.065), and Mauritius (0.109); CO_2 is less volatile for Eswatini (0.076), Lesotho (0.056), Madagascar (0.021), Mozambique (0.067) and renewable energy consumption is less volatile for Tanzania (0.041) and Zimbabwe (0.095). The table also shows that the distribution is asymmetric according to the skewness.

Table 1. Descriptive statistic.

	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis
			BOTSWANA				
CO_2	2.3132	2.2092	3.0919	1.5695	0.4294	0.4852	2.2782
GDP	8.5588	8.5734	8.7773	8.2768	0.1566	−0.3215	1.8539
REC	3.5083	3.4716	3.8768	3.2339	0.2345	0.3059	1.5623
TRADE	4.5549	4.5346	4.8345	4.3544	0.1104	0.6769	3.0808
FD	3.0432	3.0647	3.6840	2.2390	0.4566	−0.2588	1.6999
			COMOROS				
CO_2	0.2348	0.2211	0.4048	0.1514	0.0763	0.9129	2.8463
GDP	7.1201	7.1095	7.2322	6.9999	0.0717	−0.0722	1.9123
REC	4.1055	4.1158	4.3089	3.9038	0.1248	−0.2703	1.9159
TRADE	3.6141	3.5767	3.7611	3.5012	0.0656	0.7793	2.7026
FD	2.0745	1.9937	2.8008	1.4089	0.4946	0.2295	1.5299
			ESWATINI				
CO_2	0.6485	0.6320	0.8233	0.4687	0.0761	0.5899	3.4588
GDP	7.9492	7.9602	8.2747	7.6538	0.2094	0.0193	1.4839
REC	4.2294	4.2522	4.5246	3.8696	0.1522	−0.4997	3.9476
TRADE	4.7475	4.7841	5.1693	4.3778	0.2479	−0.0393	1.6287
FD	2.8466	2.9495	3.1081	2.1754	0.2442	−1.1342	3.3841
			LESOTHO				
CO_2	0.2438	0.2169	0.3458	0.1893	0.0561	0.5394	1.6546
GDP	6.7292	6.7584	7.0391	6.2860	0.2291	−0.2997	1.7985
REC	3.8951	3.9299	4.0409	3.6755	0.1284	−0.5630	1.7745
TRADE	4.9571	4.9613	5.0975	4.8353	0.0827	0.1619	1.8948
FD	2.6789	2.7851	3.1240	1.6593	0.3932	−1.2767	3.8382
			MADAGASCAR				
CO_2	0.1015	0.0971	0.1496	0.0651	0.0217	0.4533	2.1332
GDP	6.1428	6.1341	6.3032	6.0275	0.0487	0.7959	5.5445
REC	4.4233	4.4283	4.4699	4.3345	0.03331	−0.9997	3.5839
TRADE	3.8934	3.9179	4.3088	3.4775	0.2516	−0.2458	1.7317
FD	2.3353	2.3185	2.8739	1.8958	0.2632	0.1047	2.0319

Continued

			MAURITIUS				
CO_2	2.3678	2.5445	3.3009	1.0994	0.7686	−0.3236	1.6063
GDP	8.8044	8.7967	9.3019	8.2455	0.3243	−0.1317	1.7525
REC	2.8901	2.8343	3.8515	2.1905	0.5521	0.4135	1.7549
TRADE	4.7484	4.7843	4.9207	4.4529	0.1099	−0.7435	2.9701
FD	4.1929	4.2672	4.6529	3.4983	0.3376	−0.5070	2.1395
			MOZAMBIQUE				
CO_2	0.1301	0.0981	0.2629	0.0690	0.0675	0.9511	2.3030
GDP	5.9396	5.9972	6.4035	5.3174	0.3869	−0.2737	1.5781
REC	4.4768	4.5250	4.5464	4.3577	0.0697	−0.5902	1.7382
TRADE	4.2311	4.1914	4.8457	3.6307	0.3353	0.1243	1.9097
FD	2.6338	2.5201	3.4834	1.9555	0.4762	0.2840	1.5698
			SEYCHELLES				
CO_2	4.0619	4.2007	6.0848	2.1983	1.0361	−0.2446	2.1257
GDP	9.3296	9.3156	9.6650	9.0608	0.1727	0.3224	2.1177
REC	0.3358	0.1988	1.4465	−0.3424	0.5284	0.7758	2.2669
TRADE	4.8679	5.1670	5.4162	3.9661	0.5206	−0.6531	1.7479
FD	2.8306	3.0122	3.3277	1.9830	0.4441	−0.7946	2.2325
			SOUTH AFRICA				
CO_2	7.1443	7.5702	8.4392	5.7188	0.8738	−0.3731	1.6011
GDP	8.5801	8.6273	8.7424	8.3592	0.1444	−0.2332	1.3661
REC	2.5681	2.4561	2.9224	2.2793	0.2420	0.3498	1.3823
TRADE	3.8760	3.9119	4.1892	3.5357	0.1730	−0.4541	2.2291
FD	4.7176	4.7689	4.9587	4.2758	0.1515	−0.9601	3.7913
			TANZANIA				
CO_2	0.1361	0.1347	0.2224	0.0645	0.0564	0.2534	1.5226
GDP	6.5351	6.5148	6.9449	6.2224	0.2534	0.2543	1.5623
REC	4.5038	4.5099	4.5557	4.4381	0.0414	−0.4019	1.6762
TRADE	3.6998	3.7557	4.1849	3.1772	0.2925	−0.1180	1.9775
FD	2.1453	2.4219	2.6813	1.0787	0.5391	−0.9358	2.3678
			ZIMBABWE				
CO_2	1.0357	0.8771	1.7634	0.6056	0.3381	0.7899	2.3920
GDP	7.2300	7.2560	7.4882	6.7151	0.2003	−0.7660	2.9234
REC	4.3138	4.3602	4.4123	4.1548	0.0959	−0.5347	1.5971
TRADE	4.2065	4.2364	4.6961	3.8212	0.2073	0.1304	2.3690
FD	2.8673	2.9182	4.4404	1.6558	0.6157	0.0750	3.7519

Note: Author calculation.

The next step is to determine the integration degrees of series (see **Table 2**). For that, this study employed the Augmented Dickey-Fuller (ADF) (Dickey & Fuller, 1979) and Zivot-Andrews (ZA) (Zivot & Andrews, 2002) unit root tests to determine the degrees of integration for each series. The particularity of the last unit root test is that it takes into account the structural breaks. The stationarity analysis reveals that variables are I(0) and I(1). None of these series is integrated at order 2 or I(2), hence the NARDL approach is employed to investigate the co-integration among variables because its application requires that the series be integrated at order 0 or 1 (Shin et al., 2014).

Table 2. Unit root tests.

Variables	CO_2	*REC*	*TRAD*	*FD*
		BOTSWANA		
ADF (Level)	0.143	−2.613**	−0.260	2.058
ADF (First diff)	−5.654***	−5.029***	−4.999***	−4.048***
ZA (Level)	−5.507**	−3.889	−7.975***	−3.880
Break Year	2009	2006	2011	1999
ZA (First diff)	−7.000***	−7.236***	−5.435**	−7.070***
Break Year	2012	1995	2014	1997
		COMOROS		
ADF (Level)	0.994	0.089	0.369	0.841
ADF (First diff)	−5.984***	−5.824***	−7.172***	−5.848***
ZA (Level)	−5.473**	−5.680**	−7.228***	−4.001
Break Year	2006	2010	2011	2003
ZA (First diff)	−6.686***	−7.482***	−9.903***	−8.226***
Break Year	2006	2000	2010	2008
		ESWATINI		
ADF (Level)	0.348	−3.448**	−0.712	−1.195
ADF (First diff)	−7.693***	−2.863*	−4.573***	−5.039***
ZA (Level)	−5.108*	−11.019***	−2.896	−3.002
Break Year	2013	2006	2008	2005
ZA (First diff)	−9.818	−9.074***	−5.941***	−8.957***
Break Year	1996	1997	2004	2001
		LESOTHO		
ADF (Level)	0.548	−0.755	−3.048**	−1.282
ADF (First diff)	−5.677***	−5.772***	−4.406***	−5.233***
ZA (Level)	−5408***	−5.414	−7.404***	−8.904***
Break Year	2008	2010	2006	2002
ZA (First diff)	−6.855***	−6.353***	−5.360***	−8.537***
Break Year	2019	2013	2007	2003
Variables	CO_2	*REC*	*TRAD*	*FD*

Continued

MADAGASCAR				
ADF (Level)	−1.337	−2.149	−2.137	−0.036
ADF (First diff)	−7.436***	−4.731***	−6.599***	−4.324***
ZA (Level)	−5.076**	−3.455	−3.795	−6.262***
Break Year	2001	2004	2003	2019
ZA (First diff)	−9.270***	−7.265***	−6.985***	−5.457***
Break Year	2002	2010	2005	1995
MAURITIUS				
ADF (Level)	−1.454	−1.293	−1.618	−2.105
ADF (First diff)	−4.470***	−5.916***	−5.371***	5.912***
ZA (Level)	−2.894	−6.515***	−4.220	−5.610***
Break Year	1998	1998	2015	2017
ZA (First diff)	−6.156***	−10.075***	−5.471***	−6.613***
Break Year	1999	2012	2005	2017
MOZAMBIQUE				
ADF (Level)	−2.090	−2.345	−3.084	−2.387
ADF (First diff)				
ZA (Level)	−2.903	−3.312	−4.087	−2.075
Break Year	2006	2003	1998	2016
ZA (First diff)	−5.977***	−6.583***	−5.819***	−5.137***
Break Year	2016	2016	2013	2010
SEYCHELLES				
ADF (Level)	−2.242**	−1.636	−0.329	−2.386
ADF (First diff)	−4.058***	−3.941**	−4.152***	−2.869
ZA (Level)	−2.945	−3.411	−4.202	−4.941***
Break Year	1998	1999	2006	2004
ZA (First diff)	−6.135***	−4.540**	−7.428***	−6.547***
Break Year	2011	2015	1997	1996
SOUTH AFRICA				
ADF (Level)	−0.766	1.401	−1.466**	−0.682
ADF (First diff)	−3.024	−2.846	−5.285***	−4.120***
ZA (Level)	−4.510**	−3.283	−4.734**	−3.296
Break Year	2009	2007	2009	2016
ZA (First diff)	−6.079***	−5.520***	−4.912**	−4.759**
Break Year	2002	2003	2007	2016

Continued

TANZANIA				
ADF (Level)	−0.519	−0.397	−4.106***	−1.088
ADF (First diff)	−4.235***	−4.442***	−3.545**	−4.042***
ZA (Level)	−4.350	−2.585	−4.822**	−3.860
Break Year	2010	2010	2011	2005
ZA (First diff)	−4.922**	−5.305***	−4.198*	−7.026***
Break Year	2014	2011	1997	1995
ZIMBABWE				
ADF (Level)	−0.759	−1.308	−1.433	−3.407**
ADF (First diff)	−3.870***	−5.502***	−5.627***	−5.769***
ZA (Level)	−3.892	−3.116	−4.455**	−4.267*
Break Year	2010	2009	2010	2005
ZA (First diff)	−5.263***	−6.856***	−6.014***	−10.111***
Break Year	2008	1995	2018	2001

ZA null hypothesis is that the series has a unit root with structural break(s) against the alternative hypothesis that they are stationary with break(s).

Table 3 presents the co-integration results. To investigate the long-term relationships between variables, the F_{PSS} (Shin et al., 2014) and t_{BDM} (Banerjee et al., 1998) tests were applied. The F_{PSS} test statistics values are greater than the upper critical value at 1% level of significance for all countries except for Lesotho and Zimbabwe which are significant at 5% level and Eswatini at 10% level of significance. According to the Banerjee et al. (1998) test, the results confirm those of Shin et al. (2014) above. These results confirm the hypothesis H_{1c}. Both tests reinforce co-integration relationship between the series.

Table 3. Co-integration tests.

Countries	F_{PSS}	t_{BDM}
Botswana	4.103***	−1.105
Comoros	4.880***	−2.123
Eswatini	3.210*	−3.026
Lesotho	3.895**	−0.783
Madagascar	6.122***	−3.990*
Mauritius	14.200***	−1.685
Mozambique	16.139***	−2.520
Seychelles	5.725***	−5.237***
South Africa	4.111***	−3.898*
Tanzania	6.039***	−2.156
Zimbabwe	3.727**	−2.708

Note: F_{PSS} denotes the Pesaran et al. (2001) F-test and t_{BDM} the Banerjee et al. (1998) t-test. The critical values for the F-test are [2.88; 3.99] at 1% level, [2.27; 3.28] at 5% level and [1.99; 2.94] at 10% level. The critical values for t_{BDM} using t-Bounds test are −5.04 at 1% level, −4.43 at 5% level and −3.82 at 10% level (see Banerjee et al., 1998: p. 276). ***, ** and * indicate significance at 1%, 5% and 10% level, respectively.

After confirming for co-integration, Wald statistics were used to confirm whether this co-integration is linear or non-linear. Several framework of asymmetrical impacts of renewable energy consumption, trade openness and financial development on CO_2 emissions in the long-term (rejection of H_{2a}, H_{2b} and H_{2c}) and the short-term (rejection of H_{3a}, H_{3b} and H_{3c}) have been detected. Table 4 reports the Wald symmetry tests results which lead to the appropriate models (unrestricted or restricted) for each country. Hence, Botswana and Seychelles correspond to the restricted model 12, Zimbabwe to the unrestricted model 2 while Comoros correspond to the restricted model a, Eswatini and Mozambique to the restricted model b, Lesotho and Tanzania to the restricted model c, Madagascar to the restricted model d and Mauritius to the restricted model e.

Table 4. Wald symmetry tests results.

	REC		*TRAD*		*FD*		Conclusion
Countries	W_{LT} test	W_{ST} test	W_{LT} test	W_{ST} test	W_{LT} test	W_{ST} test	Unrestricted or restricted NARDL models
Botswana	0.149	5.223**	2.436	5.559**	0.419	6.397**	Rest. NARDL model 12
Comoros	4.926**	5.654**	0.059	1.833	2.022	3.085*	Rest. NARDL model a
Eswatini	0.082	0.601	4.927*	9.841***	1.550	1.193	Rest. NARDL model b
Lesotho	0.060	0.297	0.042	7.112**	0.558	2.761	Rest. NARDL model c
Madagascar	2.728	28.562***	3.330*	0.125	2.210	0.897	Rest. NARDL model d
Mauritius	1.668	3.985*	0.033	0.136	0.535	0.969	NARDL model E
Mozambique	0.949	0.490	15.22***	13.035***	1.834	0.504	Rest. NARDL model b
Seychelles	3.215	13.591***	0.998	3.264*	3.936	8.191***	Rest. NARDL model 12
South Africa	9.434**	0.635	1.334	0.608	4.208	0.316	Rest. NARDL model h
Tanzania	0.008	2.421	1.655	3.621*	8.057	1.693	Rest. NARDL model c
Zimbabwe	6.817**	4.223***	7.095***	9.792***	7.018**	7.873**	Unr. NARDL model 2

Note: ***, ** and * indicate significance at 1%, 5% and 10% level, respectively. W_{LT} and W_{ST} denote the Wald long and short-term tests. Rest. is for restricted and Unr. is for unrestricted models.

Our findings reinforce the importance of taking into account asymmetry when one investigates the relationship between CO_2 emissions, renewable energy consumption, trade openness and financial development. Table 3 provides more information.

Table 5 displays the long and short-term estimation results. According to the long-term results, we can note that a positive shock to renewable energy consumption lead to a rise of CO_2 emissions in one country (Seychelles), and adversely decrease CO_2 emission in six countries at % level (Lesotho, Madagascar, Mozambique, South Africa, Tanzania and Zimbabwe). In contrast, a negative shock of renewable energy consumption decreases CO_2 emissions in six countries (Comoros, Lesotho, Madagascar, Mauritius, Mozambique, and Tanzania). The renewable energy consumption has a symmetric, negative and significant effect on CO_2 emissions on Eswatini case.

Table 5. Results of the NARDL models.

NARDL long-term coefficients										
Countries	REC^+	REC^-	REC	$TRAD^+$	$TRAD^-$	$TRAD$	FD^+	FD^-	FD	Const
Botswana	-	-	1.480	-	-	0.920***	-	-	−2.011*	1.501***
			(2.665)			(0.272)			(1.010)	(0.312)
Comoros	0.052	−2.668***	-	-	-	1.796**	-	-	−0.482**	−1.779***
	(0.464)	(0.668)				(0.840)			(0.201)	(0.090)
Eswatini	-	-	−1.026*	2.635***	−0.371	-	-	-	0.848**	−0.469***
			(0.499)	(0.597)	(0.255)				(0.347)	(0.110)
Lesotho	−0.275	−0.519**	-	0.332	0.404	-	0.183	−0.059	-	−1.684***
	(0.447)	(0.192)		(0.334)	(0.396)		(0.113)	(0.066)		(0.035)
Madagascar	−3.298***	−5.262***	-	0.108	−0.269	-	−0.079	0.57**	-	−2.613***
	(0.662)	(0.917)		(0.081)	(0.200)		(0.271)	(0.210)		(0.049)
Mauritius	0.142	−0.673***	-	0.411	0.513*	-	−0.004	0.239*	-	0.224***
	(0.368)	(0.084)		(0.255)	(0.265)		(0.167)	(0.133)		(0.041)
Mozambique	−8.947***	−3.510***	-	0.885***	−0.136	-	0.017	0.532***	-	−2.541***
	(2.951)	(0.449)		(0.095)	(0.107)		(0.060)	(0.093)		(0.041)
Seychelles	0.405**	−0.048	-	−0.071	0.041	-	0.312	0.415**	-	0.941***
	(0.179)	(0.127)		(0.146)	(0.185)		(0.214)	(0.191)		(0.066)
South Africa	−1.607***	−0.238	-	0.103	−0.305*	-	0.199	−0.157	-	1.877***
	(0.221)	(0.174)		(0.200)	(0.142)		(0.219)	(0.124)		(0.059)
Tanzania	−5.659	−12.086***	-	−1.034*	0.729**	-	0.643***	−0.396**	-	−2.409***
	(4.864)	(2.665)		(0.503)	(0.335)		(0.210)	(0.136)		(0.190)
Zimbabwe	−5.366***	8.539	-	1.176	0.248	-	0.053	−0.314*	-	0.261
	(1.317)	(5.242)		(0.742)	(0.310)		(0.093)	(0.173)		(0.197)
NARDL short-term coefficients										
Countries	ECM(−1)	REC^+	REC^-	REC	$TRAD^+$	$TRAD^-$	$TRAD$	FD^+	FD^-	FD
Botswana	−0.497***	-1.380	-1.498	-	0.124	-0.299	-	-1.001**	1.076**	0.747***
	(0.157)	(1.278)	(0.897)		(0.349)	(0.282)		(0.423)	(0.445)	(0.157)
Comoros	−0.649***	-0.347	-1.731***	-	-	-	1.165**	-0.312**	0.143	-
	(0.150)	(0.280)	(0.477)				(0.444)	(0.127)	(0.174)	
Eswatini	−0.804***	-	-	−0.825*	1.530**	−0.296	-	-	-	-0.348
	(0.241)			(0.400)	(0.555)	(0219)				(0.362)
Lesotho	−0.474**	-	-	−0.246*	0.157	0.192	-	-	-	-0.800**
	(0.170)			(0.133)	(0.159)	(0.177)				(0.291)
Madagascar	−1.424***	−4.699***	−7.496***	-	-	-	−0.383	-	-	0.815**
	(0.268)	(0.945)	(1.601)				(0.253)			(0.277)
Mauritius	−0.496***	0.070	−0.334***	-	-	-	0.254**	-	-	0.111***
	(0.100)	(0.184)	(0.066)				(0.105)			(0.0189)
Mozambique	−1.017***	-	-	−3.570***	0.500***	−0.138	-	-	-	0.585***
	(0.125)			(0.686)	(0.112)	(0.105)				(0.341)
Seychelles	−0.405***	0.025	−0.401***	-	−0.028	0.171**	-	−0.011	0.381***	-
	(0.117)	(0.055)	(0.077)		(0.058)	(0.078)		(0.092)	(0.098)	
South Africa	−1.205***	-	-	−0.420*	-	-	0.162	-	-	−0.771**
	(0.280)			(0.294)			(0.209)			(0.322)

Continued

Tanzania	−0.734*** (0.194)	-	-	−8.879*** (1.823)	−0.760*** (0.252)	0.536** (0.203)	-	-	-	0.473*** (0116)
Zimbabwe	−0.536** (0.221)	−1.224 (0.759)	−0.441 (1.463)	-	−0.944** (0.318)	0.479** (0.183)	-	0.116* (0.062)	−0.169*** (0.055)	-

Note: ***, ** and * indicate significance at 1%, 5% and 10% level, respectively. Standard errors are in brackets.

Furthermore, positive shock to trade openness affects positively and significantly CO_2 emissions in Eswatini and Mozambique and negatively affect significantly carbon emissions in Tanzania. Adversely, a negative shock to trade openness positively affects Mauritius and Tanzania respectively at 10% and 5% level of significance while the same shock decrease CO_2 emissions in South Africa at 10% level of significance. Botswana and Comoros show a symmetric effect of trade openness on carbon emissions. These effects are positive and significant at 1% level.

Carbon emissions increase in reaction to financial development positive shock only for Tanzania at 1% level of significance. However, a negative shock to financial development increases carbon emissions in Madagascar, Mauritius, Mozambique and Seychelles. Adversely, the negative shock also reduces carbon emissions in Tanzania and Zimbabwe at 5% and 10% level respectively. Regarding for symmetric case, our results show that financial development negatively affects carbon emissions in Botswana and Comoros (significant at 1% and 5% respectively), unlike its adverse effects in Eswatini (significant at 5% level).

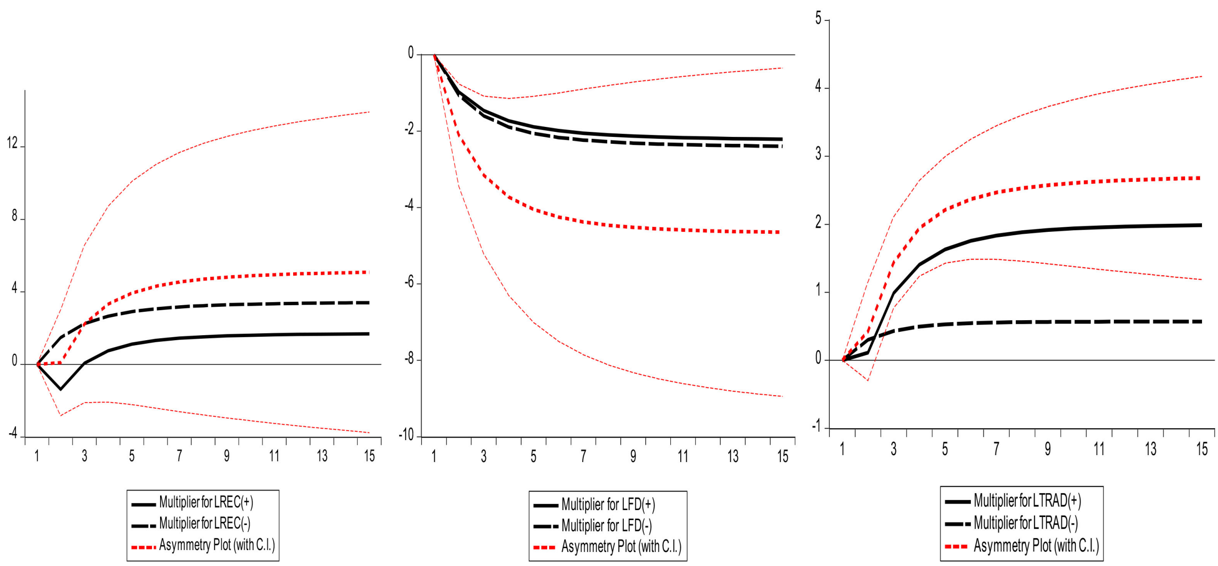
According to the short-term dynamics, a positive shock to renewable energy consumption hampers carbon emission in Madagascar, in one hand. This shock is significant and negative only for Madagascar. In other hand, a negative shock to renewable energy consumption affects negatively and significantly environmental variable meaning that a negative shock reduces carbon emission in Comoros, Madagascar, Mauritius and Seychelles. Our result is in line with those of Bhattacharya et al. (2017); Sinha and Shahbaz (2018). **Table 4** also shows that the effect of renewable energy consumption on CO_2 emissions is symmetrically significantly negative for Eswatini, Lesotho, South Africa (at 10% level) for Mozambique and Tanzania (at 1% level). Regarding for symmetric effects, we can observe that our result is similar to Dong et al. (2018b); Charfeddine and Kahia (2019) and Vo et al. (2020). In order to reduce CO_2 emissions, governments should proceed by encouraging Research and Development (R&D), financial incentives for renewable energy projects, creating and maintaining energy storage devices.

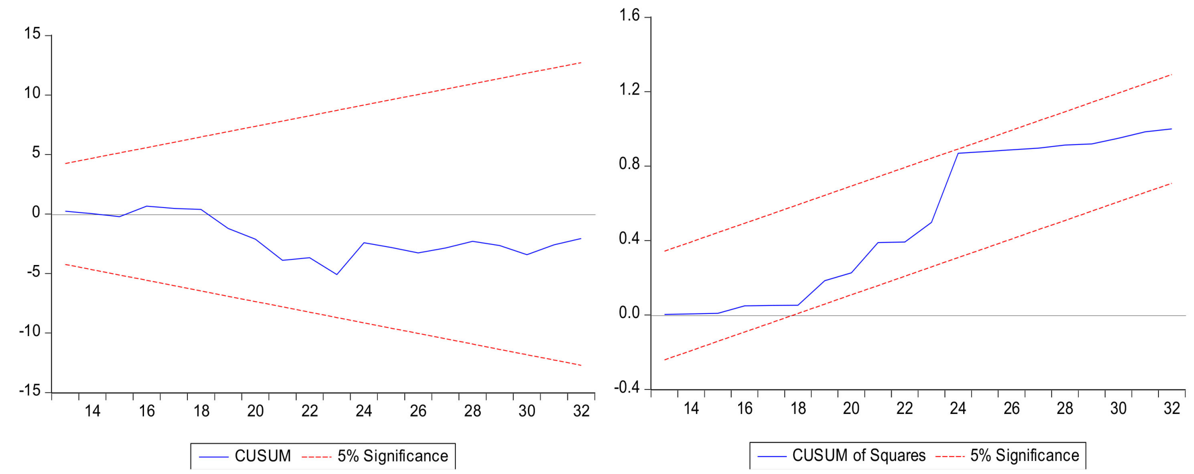
Furthermore, a positive shock on trade openness plays a catalyst role in CO_2 emissions in Eswatini and Mozambique respectively at 5% and 1% level of significance. We also find that a positive shock on trade openness presents a negative effect on CO_2 emissions for Tanzania and Zimbabwe respectively at 1% and 5% level of significance. By contrast, a negative shock to trade openness leads to a positive and increasing effect on carbon emissions in Seychelles, Tanzania and

Zimbabwe (at 5% level for the three countries). Only Comoros and Mauritius present symmetric and positive effects of trade openness on CO_2 emissions. This positive effect means that trade openness improves the efficiency of the environment (Acheampong, 2018; Sbia et al., 2014).

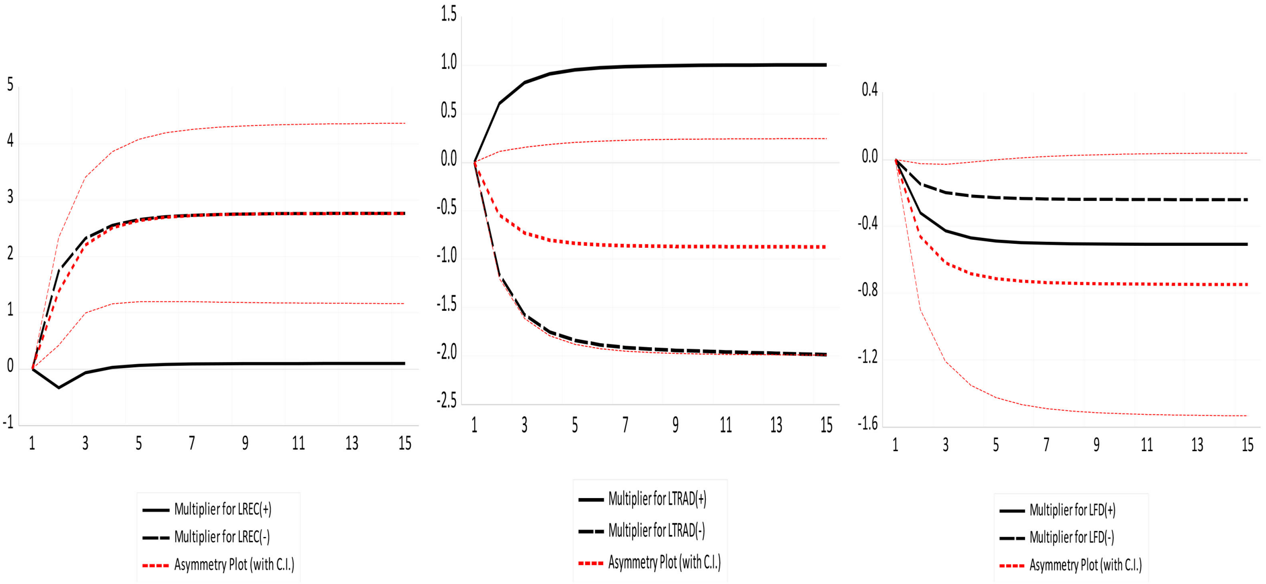
Moreover, a positive shock to financial development affects positively and significantly CO_2 emissions in Zimbabwe at 1% level and negatively affect Botswana and Comoros both at 5% level of significance. The adverse shock e.g., a negative shock to financial development increase CO_2 emissions in Botswana and Seychelles respectively at 5% and 1% level of significance. Only in Zimbabwe, carbon emissions react significantly and negatively to a negative financial development shock. Hence negative shock decrease CO_2 emissions in Zimbabwe. The response of CO_2 emissions to financial development in the short-term is also symmetric significant and positive (for Botswana, Madagascar, Mauritius, Mozambique and Tanzania all at 1% level except for Madagascar at 5% level) and significantly negative (for Lesotho and South Africa both at 5% level). Ozturk and Acaravci (2013) and Islam et al. (2013) argue that increased trade openness lead to increased CO_2 emissions.

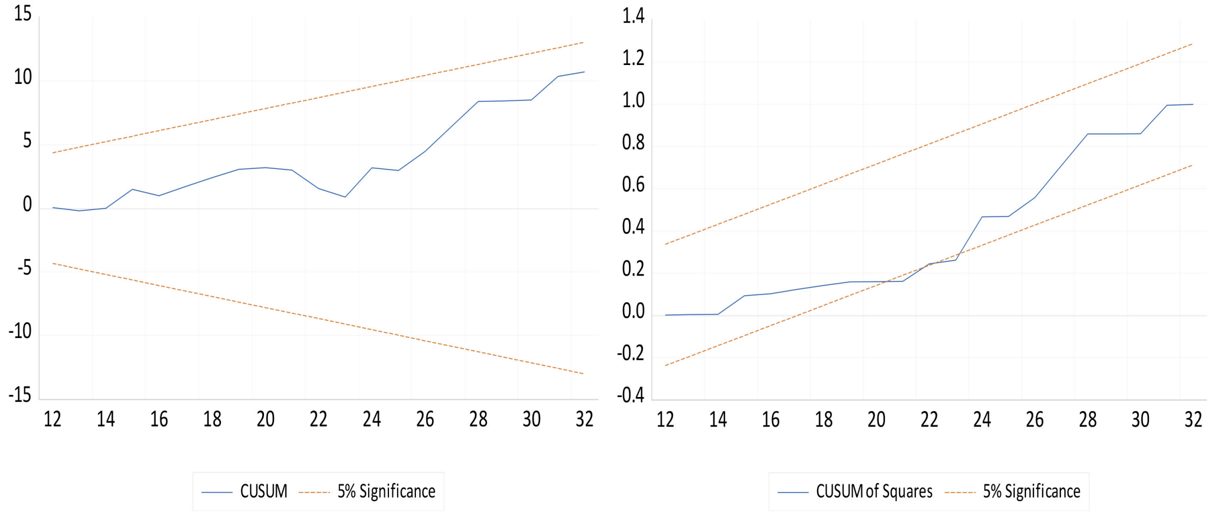
Finally, all coefficients of ECM (−1) representing the speed of adjustment are significantly negative. **Figure 1** depicts the plots of dynamic multipliers, illustrating the asymmetrical effects in the relationship among renewable energy consumption, trade openness, financial development and atmospheric pollution in eleven SADC countries. These cumulative plots demonstrate the adjustment pattern of carbon emissions towards its new long-term equilibrium in response to either a negative or positive unitary shock in renewable energy consumption, trade openness and financial development. The continuous black line and the dashed black line represent the positive and negative curves, respectively, capturing the adjustment of CO_2 emissions to positive and negative shocks in the mentioned variables. The asymmetric line portrays the disparity between negative and positive shocks to the variables.



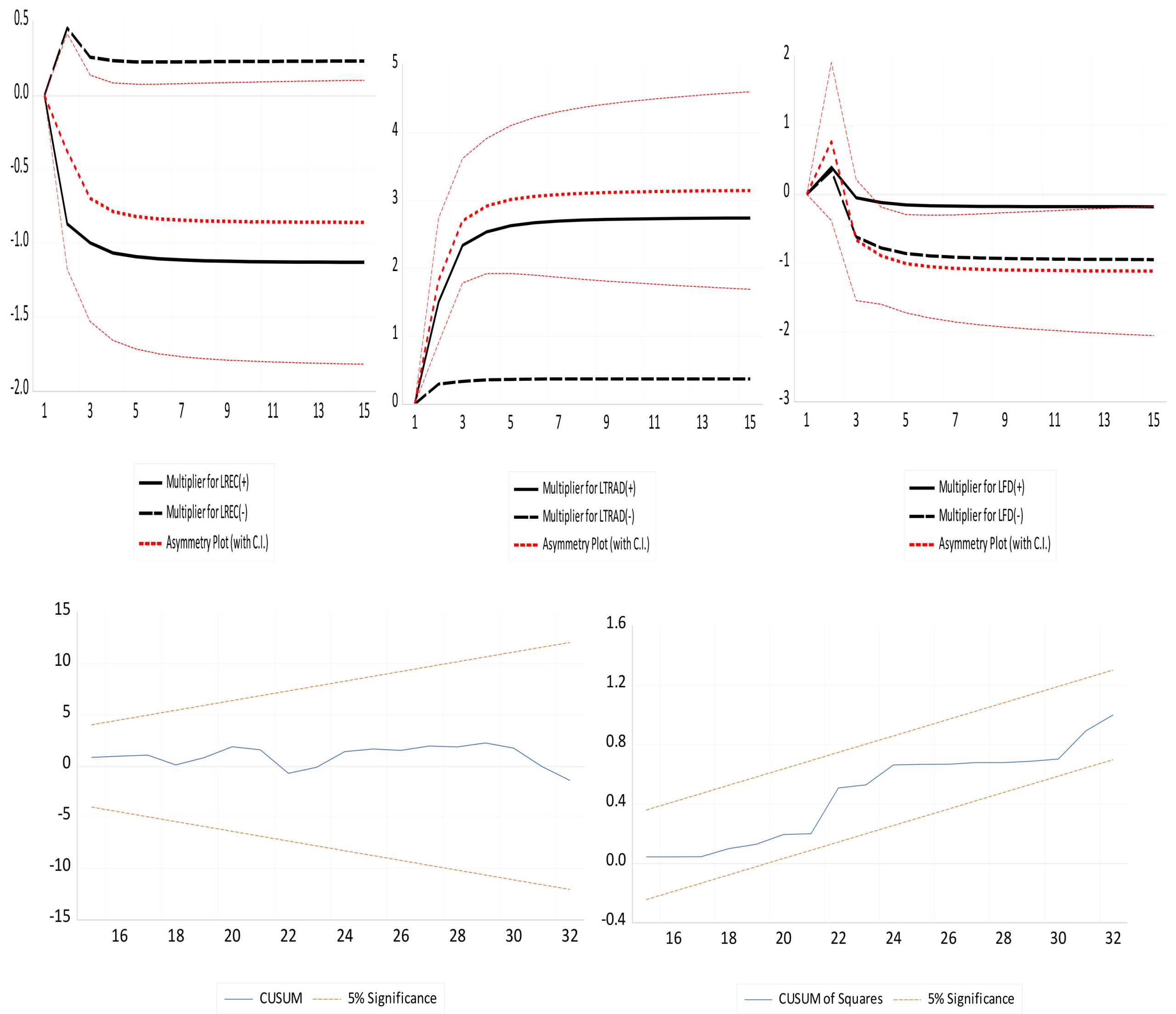


Botswana

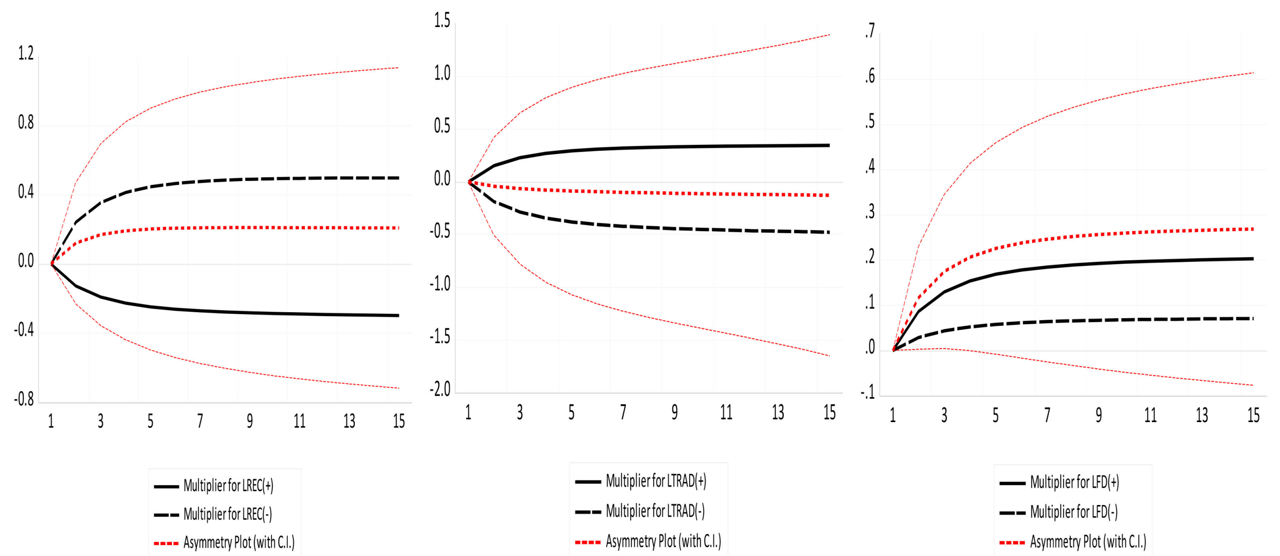


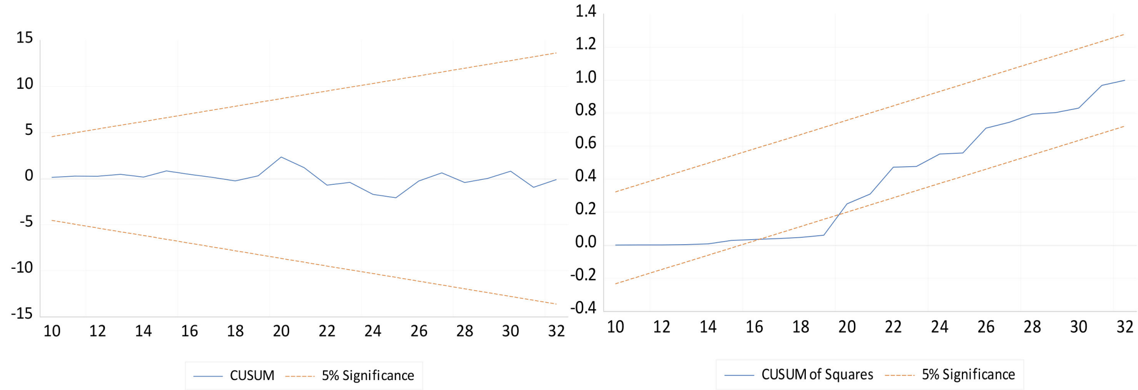


COMOROS

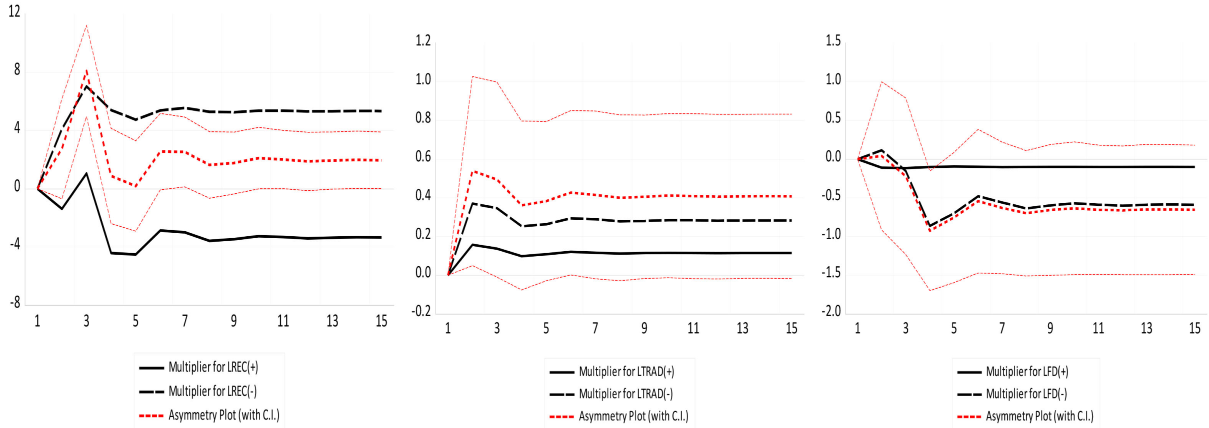

Multiplier for LREC(+)
Multiplier for LREC(-)
Asymmetry Plot (with C.I.)
Multiplier for LTRAD(+)
Multiplier for LTRAD(-)
Asymmetry Plot (with C.I.)
Multiplier for LFD(+)
Multiplier for LFD(-)
Asymmetry Plot (with C.I.)
CUSUM
5% Significance
CUSUM of Squares
5% Significance

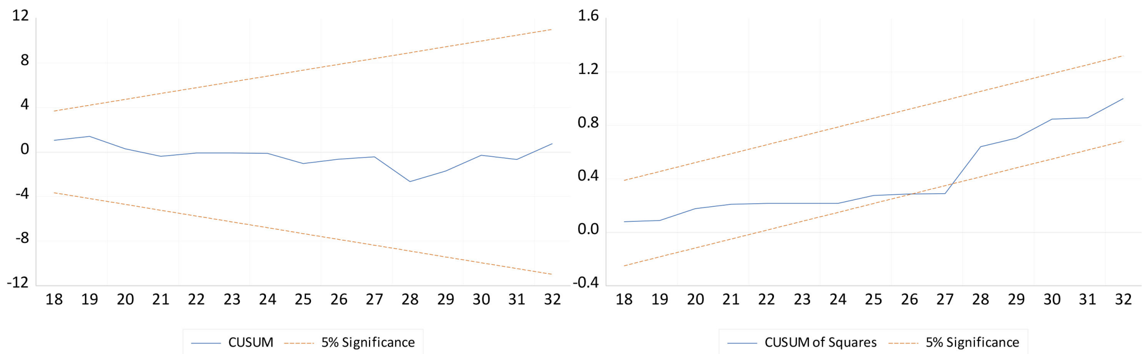
Eswatini


Multiplier for LREC(+)
Multiplier for LREC(-)
Asymmetry Plot (with C.I.)
Multiplier for LTRAD(+)
Multiplier for LTRAD(-)
Asymmetry Plot (with C.I.)
Multiplier for LFD(+)
Multiplier for LFD(-)
Asymmetry Plot (with C.I.)

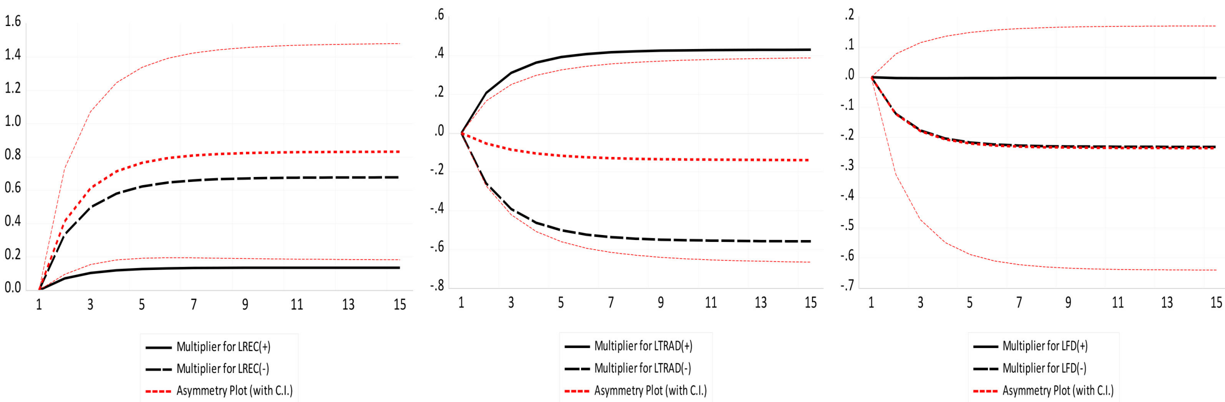


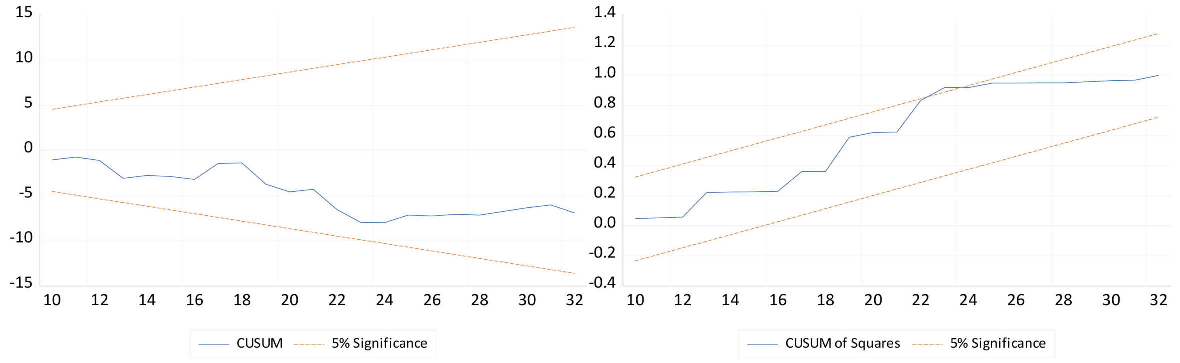
Lesotho



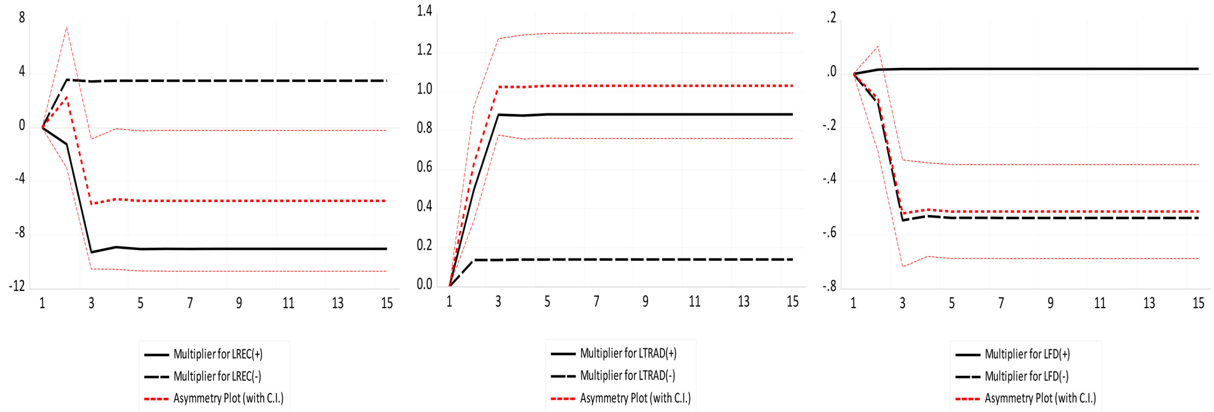


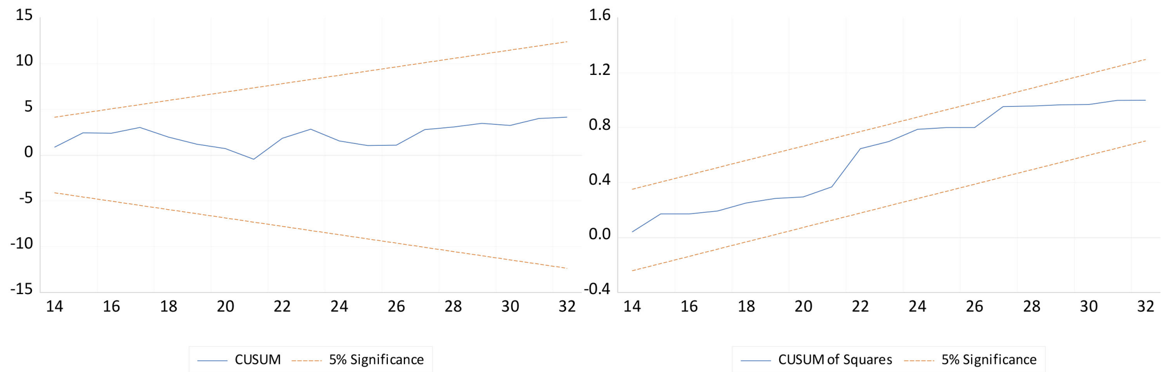
Madagascar



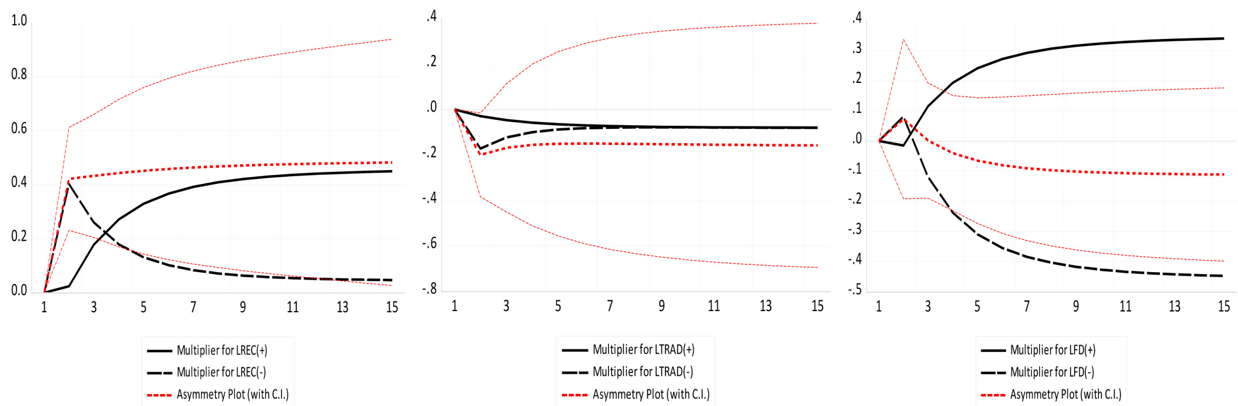


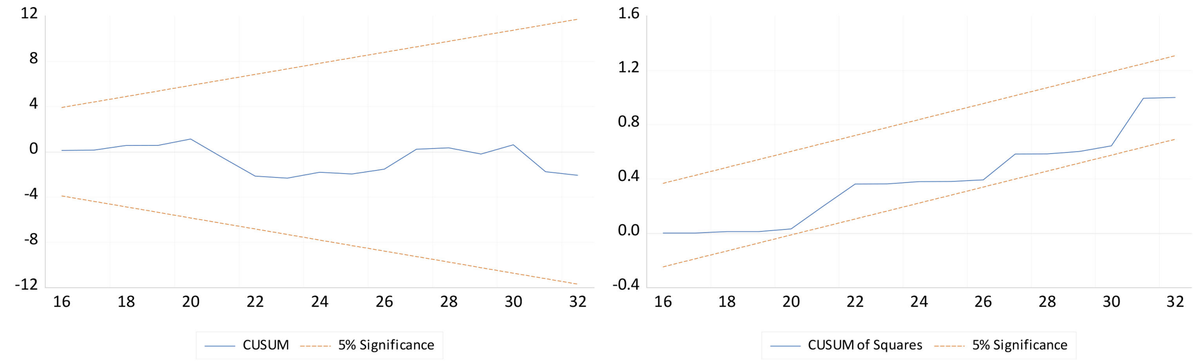
Mauritius



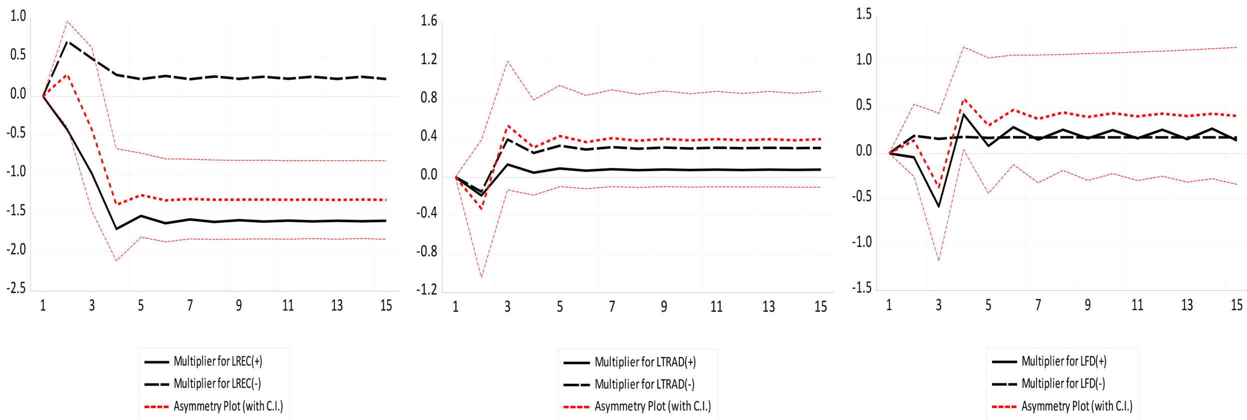


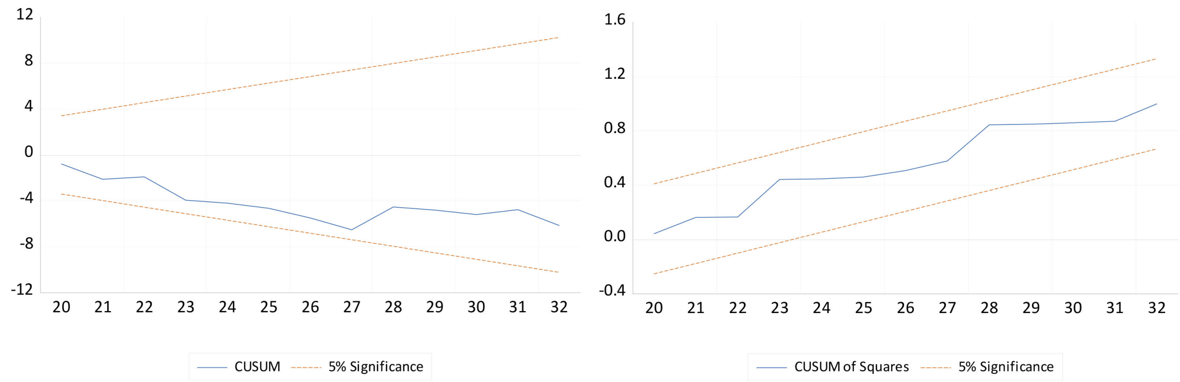
Mozambique



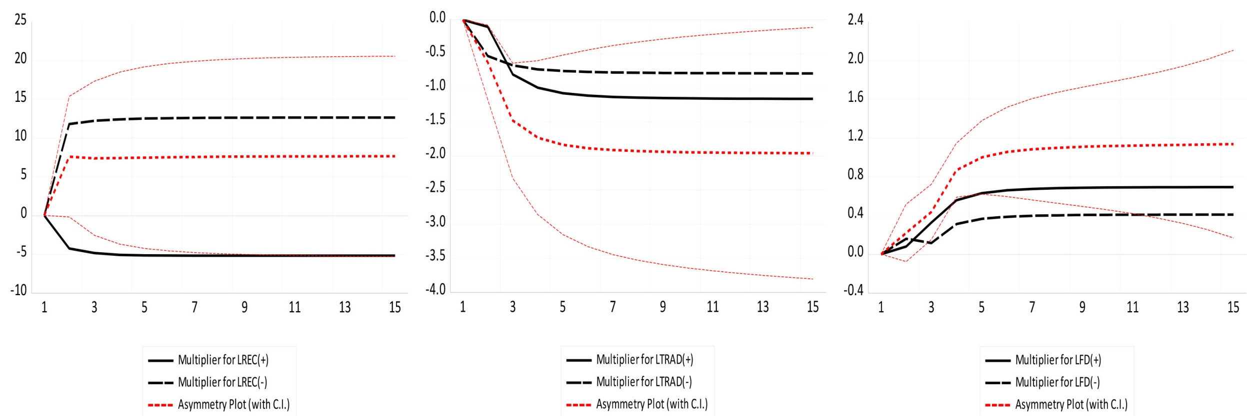


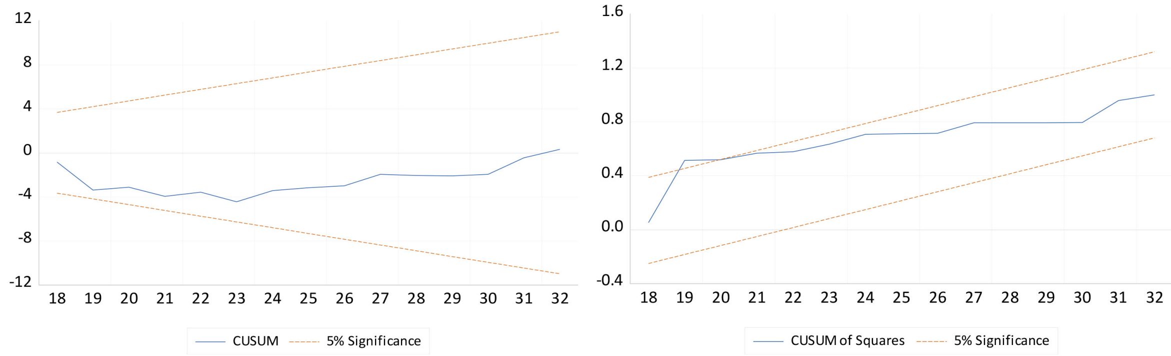
Seychelles



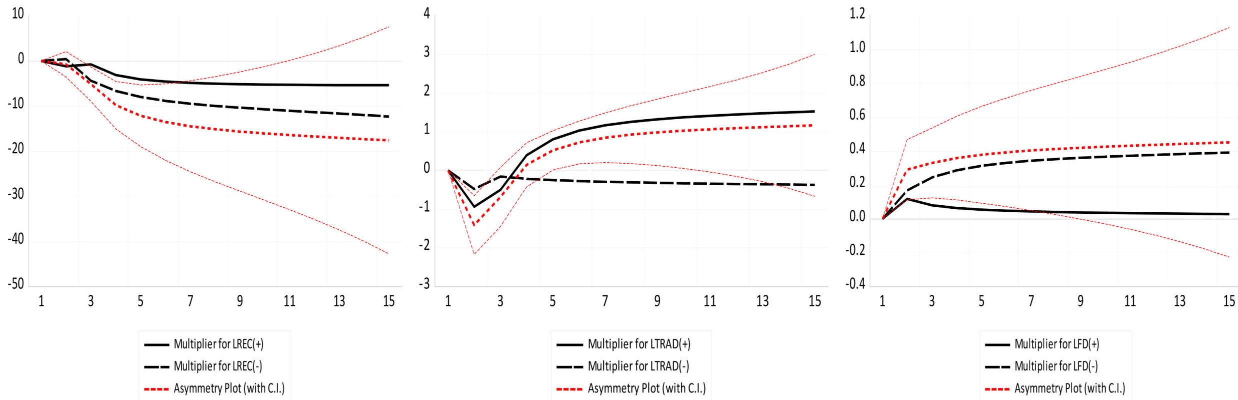


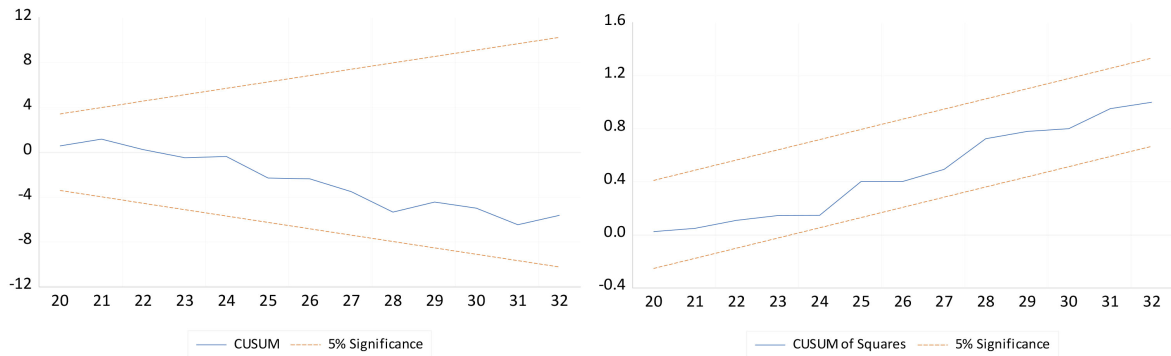
South Africa





Tanzania





Zimbabwe

Figure 1. Dynamic cumulative impact of renewable energy, financial development, and trade openness on selected SADC's countries with CUSUM and CUSUM of squares.

Table 6 displays the diagnostic results. It provides some assumption that must be verified in order to use the NARDL model. The F_{stat} denoting the F statistic is significant at 1% level for all countries showing that the model is globally significant. The adjusted R squared shows the percentage of explanation of CO_2 emissions by renewable energy consumption, trade openness and financial development. The results of Breusch-Godfrey autocorrelation test (LM) and the ARCH test of heteroskedasticity indicate the absence of autocorrelation and heteroscedasticity in the residuals, the assumption of normality is also proved by Jarque-Bera test.

Table 6. Diagnostic tests.

	Diagnostics tests				
	F_{stat}	$\bar{R}^2$	BP	ARCH (I)	JB
Botswana	11.937***	0.772	3.337	0.867	0.542
Comoros	34.094***	0.901	10.817*	6.041	1.823
Eswatini	7.561***	0.713	3.638	1.159	4.098
Lesotho	227.738***	0.981	7.316*	0.592	0.189
Madagascar	7.357***	0.746	14.794	0.214	0.930
Mauritius	741.832***	0.994	3.052	0.022	1.225
Mozambique	343.323***	0.991	4.006	0.014	0678
Seychelles	212.362***	0.988	12.154	0.643	2.939
South Africa	45.683***	0.959	14.698	0.449	0.061
Tanzania	214.608***	0.990	5.119*	1.315	0.468
Zimbabwe	42.883***	0.957	20.444	0.382	0.167

Note: ***, ** and * indicate significance at 1%, 5% and 10% level, respectively. Standard errors are in brackets. J-B, ARCH (.) and BG are Jarque-Bera, heteroscedasticity and Breusch-Godfrey test.

5. Conclusion and Policy Implications

This study examines the relationship between carbon emissions, renewable energy consumption by incorporating trade openness and financial development. The study uses eleven SADC countries annual data spanning from 1990 to 2022 and depending on their availability.

A descriptive statistic was firstly presented followed by unit root tests. The unit root tests used to investigate the stationarity of series are Augmented Dickey-Fuller (ADF) and Zivot-Andrews (ZA) tests. Then, the NARDL method of Shin et al. (2014) was used to analyze the co-integration relationship between series. The NARDL approach allows to analyze the co-integration relationship between variables with different degrees of integration.

The results showed that renewable energy consumption, trade openness and financial development have asymmetrical effects on carbon dioxide emissions respectively in nine (9), nine (9) and eight (8) countries in the long-term. The asymmetrical effects of the same variables on CO_2 emissions are observed on six (6), seven (7) and four (4) countries respectively in the short-term.

In the long-term, a positive shock on renewable energy consumption decrease (reduce) CO_2 emissions in Lesotho, Madagascar, Mozambique, South Africa, Tanzania and Zimbabwe (due to the adoption of new energy sources with respect to the quality of the environment) except for Seychelles. A positive change in trade openness also decreases CO_2 emissions only in Tanzania (import of clean energy technologies and reduction of taxes on imports of these technologies) and increase it in Eswatini and Mozambique (imports of new technologies are low). In the case of financial development, positive shock increase carbon dioxide emissions in Tanzania (financial development makes it possible to finance the development of a dense industrial body, increased production, responsible for pollution emissions).

A negative shock on renewable energy uses also decrease CO_2 emissions in large number of countries namely Comoros, Lesotho, Madagascar, Mauritius, Mozambique, and Tanzania. The same shock on trade openness reduces CO_2 emissions in South Africa, and adversely rise CO_2 emissions in Mauritius and Tanzania. Negative changes in financial development have also mixed effect. In one hand it contributes to reduce carbon emissions in Tanzania and Zimbabwe and in the other hand, to promote atmospheric pollution in Madagascar, Mauritius, Mozambique and Seychelles.

In the short-term, a positive and negative change in renewable energy use reduces CO_2 emissions in Comoros, Madagascar, Mauritius and Seychelles. The trade openness plays a catalyst role in CO_2 emissions in Eswatini and Mozambique due to a positive change and reduces them in Tanzania and Zimbabwe. By contrast, a negative shock to trade openness leads to a positive and increasing effect on carbon emissions in Seychelles, Tanzania and Zimbabwe. A positive shock on financial development increase CO_2 emissions in Zimbabwe and decrease it in Botswana and Comoros. By contrast, a negative change in financial development leads to a rising effect on atmospheric pollution in Botswana and Seychelles and reducing this pollution in Zimbabwe.

Policy Implications

Promotion of renewable energy and green technologies.

Long-term strategy: it is imperative that governments direct their attention towards the promotion and investment in renewable energy sources as a means to mitigate carbon emissions. The implementation of policies, such as tax benefits and research grants, which serve to incentivize the utilization of clean energy technologies, can effectively foster the development and utilization of renewable energy. In the short-term, it is to ensure the swift integration of renewable energy sources, it is essential to employ specific measures. Countries that have witnessed a positive impact on carbon emissions through the adoption of renewable energy should prioritize initiatives aimed at expediting the incorporation of these technologies. This may involve streamlining regulatory procedures, offering immediate financial incentives, and fostering collaborations between the public and private sectors.

For the purpose of trade openness policies for sustainable development: in the context of a long-term strategy, it is imperative for countries to evaluate their trade policies in order to guarantee their alignment with sustainable development objectives. In cases where enhanced trade openness leads to heightened carbon emissions, it is crucial to prioritize approaches that encourage the implementation of cleaner production methods and the adoption of environmentally friendly technologies through imports. Additionally, it may be worthwhile to explore trade agreements that facilitate the exchange of green technologies and facilitate the reduction of tariffs on clean energy imports.

Financial development for sustainable practices: long-term strategic approach involves fostering the advancement and execution of eco-friendly monetary endeavors, exemplified by green bonds or funds specifically designated for projects that are environmentally conscious. Financial establishments may be motivated to allocate resources towards ventures that endorse sustainability and diminish carbon emissions. Conversely, short-term measures encompass providing immediate incentives, such as tax advantages or decreased interest rates, to financial institutions that partake in investments that align with initiatives promoting low-carbon or carbon-neutral practices.

Author Contributions

Kifory Ouattara and Konan Auguste KOUAKOU conceptualized the study idea, drafted the paper, and fill all parts of the study.

Availability of Data and Materials

The data is publicly available from World Development Indicators or can be obtained from the authors by a request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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