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# The Effects of Green Energy and $CO_2$ Emissions on Sustainable Economic Development in Southern African Development Community

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## Abstract

The present research endeavor explores the effects of embracing renewable energy and $CO_2$ emissions on the prosperous economic development underneath the Southern African Development Community (SADC). This study delves into the paramount role of renewable energy sources, consisting of solar, wind, and hydropower, in promoting prosperity and mitigating $CO_2$ emissions throughout energy transitions. Employing panel data from 16 SADC nations spanning from 1990 to 2023 and leveraging system GMM estimation, we explore the multifaceted connections among green energy, $CO_2$ emissions, governance quality, and trade openness. The findings signal that embracing green energy substantially enhances sustainable economic development through greater energy access, advancing expansion of industry, and mitigating the adverse ecological effects associated with fossil fuel consumption. Nonetheless, the influence of $CO_2$ emissions on the long-term trajectory of economic development appears to be statistically insignificant in the regression findings. The study underscores the vitality of strengthened governance and enhanced trade openness in promoting the widespread adoption of green technologies and practices, elevating access to pristine energy solutions, and encouraging worldwide cooperation. Strategic initiatives, which comprise substantial government investments in forefront renewable energy infrastructure, sophisticated regulatory frameworks to minimize emissions, and proficient energy efficiency projects, are of the upmost significance. The study elegantly conveys the vital facets of governance, technological innovation, and regional collaboration, providing refined recommendations for policymakers in the SADC region to further foster sustainable economic development to attain persistent ecological objectives.

**Keywords**

Southern African Development Community (SADC), Green Energy, $CO_2$ Emissions, Sustainable Economic Development, System GMM Model

## 1. Introduction

The escalating prospect of melting glaciers and climate change has constituted a substantial global concern for over a decade. The linkage amongst the consumption of energy, $CO_2$ emissions, and economic growth has come to prominence as an important issue around the world. It is of the utmost importance to recognize that involvement in this field has risen precisely because of the intricate structure of this particular relationship, addressed from both theoretical and empirical viewpoints. The phenomenon of growth has garnered significant interest from policymakers and scholars, especially concerning the achievement of sustainability (Antonakakis, Chatziantoniou, & Filis, 2016). The energy industry is of vital importance for promoting sustainable economic growth in both developed and developing nations, as well as serving as a fundamental component in manufacturing processes. Despite the vital role of energy in enhancing economic development, plenty of studies have explored the correlation between energy and growth (Shahbaz et al., 2017a, 2017b; Nordin & Sek, 2018; Tugcu & Topcu, 2018; Benkraiem et al., 2019).

The manufacturing industry substantially relies on the availability of electricity. The adverse effects of heightened energy use result in severe strains on the environment and ecosystem, adding substantial issues among energy economists, environmentalists, and policymakers worldwide who are engaged in the formulation and execution of sustainable energy-environment policies. The connection between energy and growth is of crucial importance for sustainable development; however, it is essential to acknowledge that energy consumption has led to environmental degradation, notably through carbon dioxide ($CO_2$) emissions generated through the combustion of fossil fuels in industrial activities. The increasing demand for energy, alongside the pressing challenge of climate change stemming from pertinent fossil fuel consumption, has driven plenty prosperous nations to transition to renewable energy sources in an effort to enhance environmental quality (Kuriqi et al., 2019). Renewable sources of electricity, such as solar, wind, and hydroelectric power, constitute a necessity for reducing carbon emissions and preventing the adverse effects of climate change. The shift to renewable energy faces several hardships. Ali et al. (2019) elucidate the detrimental effects of hydropower on ecosystems, highlighting fluctuations to aquatic habitats and a reduction in biodiversity. Despite these challenges, the consumption of renewable energy is anticipated to significantly contribute to the reduction of environmental pollution, thus establishing a noteworthy correlation between environmental conditions and economic activities. This concept corresponds with the environmental Kuznets curve (EKC) hypothesis, which asserts that economic growth initially results in environmental deterioration; however, after reaching a specific income threshold, the trend reverses, resulting in environmental enhancement as societies allocate resources to cleaner technologies and rigors environmental regulations (Shahbaz et al., 2017a).

Trade openness has emerged as a vital element in economic strategies, driving growth by improving resource allocation, fostering innovation, and enabling technology transfer. It strengthens globally competitiveness through the integration of nations into worldwide supply chains and the attraction of foreign investment, particularly among multiple newly industrialized nations, including those within the SADC region (Audretsch et al., 2014; Nam & Ryu, 2024). Since the mid-1990s, a significant number of nations in Sub-Saharan Africa, especially those within the SADC region, have systematically pursued strategies aimed at improving their integration into the global economy, acknowledging the prospective benefits of increased trade. These advantages typically include improved sustainable economic development, greater market access, and the diversification of the regional economy. Nonetheless, alongside these potential benefits, there are growing concerns over the environmental repercussions of trade liberalization, particularly regarding $CO_2$ emissions, which are a major catalyst of climate change (Chua, 1999).

The interplay among renewable energy sources, carbon dioxide emissions, and sustainable economic growth has attracted considerable scrutiny in recent instances, foremost within developing regions such as the Southern African Development Community (SADC). Through the swift advancement of global climate change, nations are becoming more conscious of the imperative to shift towards sustainable energy alternatives for the purpose to minimize carbon emissions and alleviate environmental deterioration. Green energy comprising renewable energy sources such as solar, wind, and hydropower has the potential to drive sustainable development while addressing the pressing challenges of energy access and economic growth in Sub-Saharan Africa (SADC). However, the transition to green energy presents an intricate environment of both prospects and obstacles, notably in an area traditionally dependent on fossil fuels for its industrial and economic development.

The nations within the SADC region, notwithstanding endowed with abundant renewable energy resources, experience considerable challenges in their pursuit of a transition to green energy. These consist of fiscal limitations, insufficient infrastructure, and rules and regulations (Khamis et al., 2020). Moreover, the relationship between $CO_2$ emissions and economic growth is complex. Industrialization and economic growth consistently lead to heightened emissions; conversely, the shift towards green energy has the potential to reduce emissions while fostering persistent economic sustainability (Stern, 2007). Comprehending how green energy investments can promote economic growth whilst simultaneously reducing $CO_2$ emissions is critical for crafting effective policies in the region. This study aims to explore the effects of adopting green energy and the impact of $CO_2$ emissions on sustainable economic development in the SADC region. Furthermore, this study attempts to clarify the intricate linkages among trade openness, environmental sustainability, and economic growth, offering in-depth insights into how green energy initiatives may mitigate the negative environmental consequences associated with heightened trade activities. The endeavor seeks to investigate the potential of transitioning to renewable energy sources as a means to foster sustainable economic growth, decrease carbon footprints, and contribute to the overall well-being of the region's populace.

The remaining part of the study is organized as follows: the second section presents the literature review, the third section outlines the methodology, the fourth section details the data analysis and results, the fifth section provides a discussion of the findings, and the sixth section concludes with policy recommendations and suggestions for future research.

## 2. Literature Review and Hypothesis Development

### 2.1. Theoretical Underpins

Renewable energy is acknowledged as an indispensable component in promoting socio-economic activities and enabling economic transformation, particularly in developing nations. It is a crucial factor in facilitating energy access, thus enhancing well-being and livelihoods. Theories of sustainable development emphasize the significance of energy, foremost renewable sources, as vital to fostering economic growth. The Energy-Economic Growth Nexus Theory posits that energy, especially renewable energy, is essential for industrialization and enhancing quality of life. This theoretical framework contends that energy availability underpins productivity, economic stability, and sustained growth in both developing and developed countries (Krupp & Gellert, 2012). Borin & Mancusi (2020) assert that the adoption of renewable energy can yield long-term beneficial effects on the economy, highlighting the necessity for a transition towards clean energy to meet sustainable development goals (SDGs).

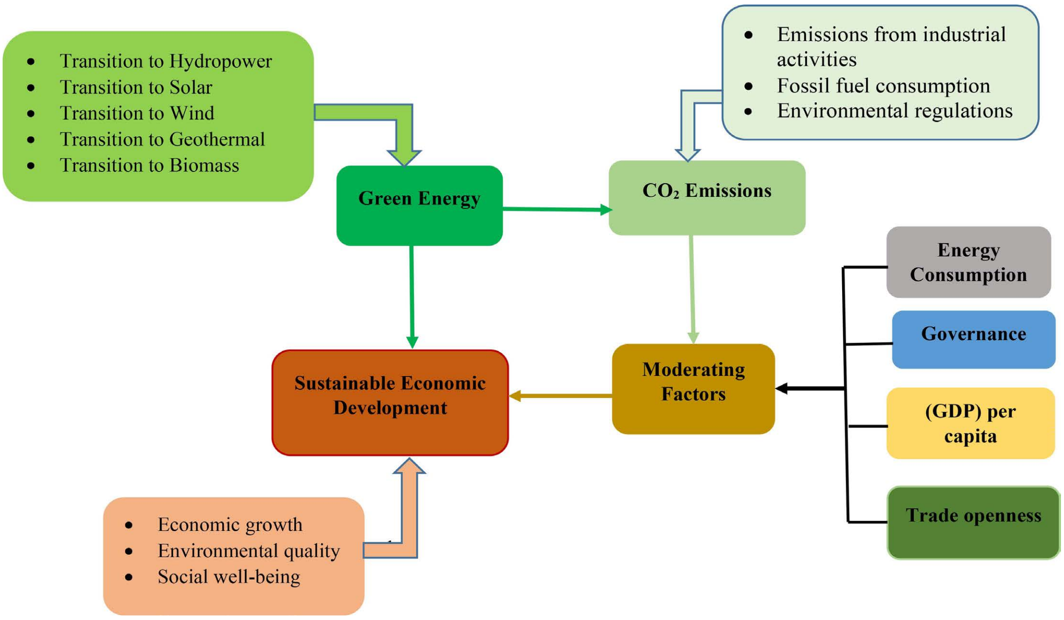
The Environmental Kuznets Curve (EKC) hypothesis serves as a foundational theory in understanding the relationship between $CO_2$ emissions and sustainable economic development in the SADC region. The Environmental Kuznets Curve contend a multifaceted, inverted U-shaped correlation between income levels and environmental degradation. It posits that $CO_2$ emissions may initially increase alongside economic growth, yet they tend to decrease as economies expand, acknowledging renewable energy sources and establishing more stringent environmental regulations (Grossman & Krueger, 1991; Panayotou, 1993). This hypothesis offers vital significance for SADC nations, where the process of industrialization is continuous, and the equilibrium between promoting economic development and addressing its ecological effects is essential. Moreover, regulations concerning sustainable development reflect the significance of harmonizing economic, social, and environmental objectives, promoting development trajectories that promise persistent ecological viability whilst nurturing economic advancement and social fairness (Brundtland Commission, 1987; Sachs, 2015). Recent studies underscore the significance of green technologies and renewable energy in mitigating $CO_2$ emissions while enhancing economic growth (Al-Mulali et al., 2015; Dogan & Aslan, 2017). These theoretical frameworks underscore the importance of policy measures that support technological innovation, renewable energy adoption, and institutional strengthening to achieve sustainable development in the SADC region (Sarkodie & Strezov, 2019; Wang et al., 2020).

### 2.2. Empirical Literature

Empirical studies exploring the interactions between $CO_2$ emissions, renewable energy, and economic growth have generated inconsistent results, largely attributed to variations in data ranges, methodologies, and regional contexts. Qudrat-Ullah and Nevo (2021) used panel data from 37 African countries and the Generalized Method of Moments (GMM) technique to analyze the effects of renewable energy development, revealing a positive correlation between renewable energy adoption and economic growth in Africa. Similarly, Danish et al. (2020) used Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) methods on BRICS nations data from 1992 to 2016, demonstrating that renewable energy adoption and urbanization positively impact environmental quality and Sustainable Development Goals (SDGs). Ahmed et al. (2020) identified that urbanisation in G7 countries negatively impacts environmental quality as an outcome of heightened non-renewable energy consumption. In contrast, Maji & Munir (2019) contended that renewable energy does not necessarily promote economic growth in West African countries, citing insufficient infrastructure and institutional limitations as contributing factors. Further, Al-Mulali et al. (2015) argued that renewable energy contributes to a reduction in $CO_2$ emissions across Europe, whilst Dogan and Aslan (2017) determined a comparable pattern in COP21 nation-states. Shahbaz et al. (2017a) established a long-term equilibrium between economic growth and $CO_2$ emissions in high-income countries, highlighting green energy's significance. Acheampong (2019) provided evidence for the Environmental Kuznets Curve (EKC) hypothesis in Africa, indicating that increased incomes ultimately reduce emissions. Sarkodie and Strezov (2019) conducted a meta-analysis to validate the EKC theory, whereas Wang et al. (2020) observed that urbanisation and economic growth affect emissions in distinct ways regardless of income levels. Dong et al. (2020) and Danish et al. (2020) underscored the significance of renewable energy in reducing emissions underneath emerging economies, whilst Balsalobre-Lorente et al. (2020) and Khan et al. (2021) addressed the influence of institutional quality and technological innovation on sustainable development. Theories linking energy consumption and $CO_2$ emissions, such as Stern (2004), emphasize energy production's pivotal role in shaping emissions, particularly in Southern Africa, whereas urbanization, industrialization, and population growth drive increased energy consumption, predominantly from fossil fuels, leading to rising emissions unless a transition to sustainable energy is implemented (Sambo & Tichaawa, 2021).

H1: The adoption of green energy positively impacts sustainable economic development in the Southern African Development Community (SADC) region by promoting economic growth and reducing $CO_2$ emissions.

H2: $CO_2$ emissions have a negative effect on sustainable economic development in the SADC region, as higher emissions are associated with environmental degradation and adverse health outcomes, which can hinder long-term economic growth.




## 3. Methodology

This study adopts the positivist paradigm, employing a clearly defined conceptual framework substantiated by credible and evident connections. The quantitative method typically employed in the deductive approach is fundamentally associated with the positivist perspective. Furthermore, it is feasible to observe, quantify, and characterize scientific concepts that pertain to reality. The study utilizes a panel data methodology and employs a quantitative research strategy.

### 3.1. DATA

The study utilised macro-data spanning a 33-year period (1990 to 2023) for 16 SADC nations, contingent on the availability of data related to green energy, $CO_2$ emissions, and sustainable economic development. The period under consideration accentuates significant endeavors on both global and regional scales aimed at promoting sustainable development.

Data on the variables were obtained solely from the Renewable Energy Agency (IRENA), in conjunction with World Governance Indicators (WGI) and the

World Development Indicators (WDI) repository employed to assess the dependent, independent, and control factors. The summarized descriptions of variables are presented in **Table 1**. The research utilizes a secondary data collection approach to deliver a thorough and sophisticated examination of the intricate links between green energy, $CO_2$ emissions and sustainable economic development, acknowledging a variety of viewpoints and experiences. As indicated in **Table 1**, following the literature (Armeanu et al., 2017). Gross domestic product (GDP) is proxied as Sustainable economic growth which stands for dependent factor. This study employs GDP as a metric for sustainable economic development, highlighting its all-encompassing characteristics and pragmatic application. GDP encapsulates the entirety of economic activity by quantifying the value of goods and services produced, thereby providing a comprehensive assessment of economic vitality and further development. The availability and the consistency of GDP data for plenty of nations, such as the underneath the SADC region, enable trustworthy comparisons across different nationalities and chronological contexts, thereby aiding in the evaluation of economic trends pertinent to sustainable development. The concept of sustainable economic development comprises the dual objectives of environmental sustainability alongside economic growth. The Gross Domestic Product serves as a crucial indicator of the economic landscape, reflecting variations in production and quality of life, which are vital for evaluating advancements in development. Furthermore, GDP is associated with various development indicators, including employment, income levels, and investment, allowing for an exploration of the wider economic implications of adopting green energy and the effects of $CO_2$ emissions. Policymakers often employ GDP as a metric for assessing the efficacy of economic policies. This study elucidates the relationship among green energy, $CO_2$ emissions, and GDP, presenting profound insights for coordinating economic advancement with ecological sustainability. As per Ehigiamusoe and Dogan (2022), Hasanov et al., 2021 use of hydropower, wind, solar, geothermal, and biomas energy (% of total energy usage) is proxied as green energy and employed as independent factor in conjunction with $CO_2$ emissions, Quantified in metric tons per capita, as per (Duro & Padilla, 2006). Following the literature, (Bilgen, 2014; Iddrisu, Abor, & Banyen, 2022; Ofori & Asongu, 2021; Bilgen, 2014; Dobre, 2008) we controlled for 4 additional factors.

**Table 1.** Data Description.

| Variables | Measurement | Sources |
|---|---|---|
| **Depend factor** | | |
| Sustainable economic growth | Gross Domestic Product (GDP), as per Pasquale, literature (Armeanu et al., 2017) | World Development Indicators (WDI) https://databank.worldbank.org./source/worl-development-indicators |
| **Independent factor** | | |
| Green Energy GE | Use of hydropower, wind, solar, geothermal, and biomas energy (% of total energy usage) as used by Ehigiamusoe and Dogan (2022), Hasanov et al., 2021 | World Development Indicators (WDI) https://databank.worldbank.org./source/worl-development-indicators |

Continued

| | | |
|---|---|---|
| $CO_2$ emissions | Quantified in metric tons per capita, as per (Duro & Padilla, 2006) | International Monetary Fund (IMF) https://www.imf.org/en/Data |
| **Control factors** | | |
| Energy Consumption | Energy consumption (quantified in Quadrillion British thermal units) (Bilgen, 2014) | International Energy Agency (IEA) https://www.iea.org/data-and-statistics |
| Governance GOV | PCA index comprised of Rule of law, Political stability, Government effectiveness, Voice accountability, Control of corruption, Regulatory quality, following (Iddrisu, Abor, & Banyen, 2022; Ofori & Asongu, 2021) | World Governance Indicators (WGI) https://databank.worldbank.org/source/worldwide-governance-indicators |
| GDP per capita | Gross Domestic Product per capita (current US$). | World Development Indicators (WDI) https://databank.worldbank.org./source/worl-development-indicators |
| Trade Openness | The sum of exports and imports of goods and services as a percentage of Gross Domestic Product (GDP), (Trade-to-GDP Ratio) following Dobre (2008) | World Development Indicators (WDI) https://databank.worldbank.org./source/worl-development-indicators |

## 3.2. Empirical Modeling

We employ the sys-GMM approach for estimating the variable coefficients, afterwards the methodology of Bahrini and Qaffas (2019). Leveraging a sample of multiple nations, sys-GMM may address the issue of country-specific effects more effectively than conventional panel regression methods (Arellano & Bond, 1991). Hence, we constructed the model illustrated below:

$$GDP_{it} = \alpha + \beta_1 GE_{it} + \beta_2 CO_{2it} + \beta_3 EC_{it} + \beta_4 GOV_{it} + \beta_5 GDPpc_{it} + \beta_6 TO_{it} + \lambda_i + \gamma_t + \varepsilon_{it} \quad (1)$$

$GDP_{it}$ represents Gross domestic product (as a proxy for sustainable economic development) of country $i$ at time $t$. $GE_{it}$ illustrates the vector of Green Energy adoption in country $i$ at time $t$ (measured by % of total energy from renewables like wind, solar). $CO_{2it}$ symbolizes the $CO_2$ emissions (metric tons per capita) in country $i$ at time $t$. $EC_{it}$ stands for energy consumption (in Quadrillion BTUs) in country $i$ at time $t$, $GOV_{it}$ governance index (measured by indicators such as rule of law, political stability, Government effectiveness, Voice accountability, Control of corruption, Regulatory quality) in country $i$ at time $t$. $GDPpc_{it}$ signals GDP per capita (current US$) in country $i$ at time $t$, $TO_{it}$ reflects Trade openness (exports + imports as a % of GDP) in country $i$ at time $t$ ,whilst $B_1$, $\beta_2$, $\beta_3$, $\beta_4$, $\beta_5$, and $\beta_6$, designate the coefficients for estimation. $\lambda_i$ Country fixed effects whilst $\lambda_t$ signals time fixed effects to address period effects, respectively. $\varepsilon_{it}$-represents Error component.

In an effort to analyze the direct influence of green energy on sustainable economic development (GDP), positing a positive correlation, as renewable energy fosters economic growth and sustainability, we derive the following equation:

$$GDP_{it} = \alpha + \beta_1 GE_{it} + \varepsilon_{it} \quad (2)$$

The following equation illustrates the inverse correlation between $CO_2$ emissions and economic growth, in line with the Environmental Kuznets Curve hypothesis. The rise in $CO_2$ emissions due to industrialization is anticipated to obstruct sustainable economic growth:

$$GDP_{it} = \alpha + \beta_2 CO_{2it} + \varepsilon_{it} \quad (3)$$

In the context of panel data that may exhibit endogeneity concerns, such as the simultaneous causality observed between GDP and green energy, the sys-GMM method proves to be an appropriate choice. The model will tackle endogeneity by employing lagged values of the variables as instruments. The system GMM estimator is characterized by the following equations:

$$\Delta Y_{it} = \alpha + \beta_1 \Delta X_{it} + \gamma_t + \varepsilon_{it} \quad (4)$$

$\Delta Y_{it}$ and $\Delta X_{it}$ represent the changes in the dependent and independent variables over time, $\gamma_t$ denotes the country-specific effects whilst the instruments for $X_{it}$ are lagged values of the explanatory variables. To assess the interrelationship between green energy adoption and $CO_2$ emissions we compute the partial derivative of equation. The given partial differential equation is as follows:

$$CO_{2it} = \alpha + \beta_7 GE_{it} + \varepsilon_{it} \quad (5)$$

### 3.3. Estimation Techniques

This research endeavor incorporates the GMM method. To address the potential endogeneity that stems from the correlation amid past and present levels of the dependent variable (Sustainable economic growth), GMM will be employed (Oduola, Bello, & Popoola, 2022). The system GMM estimator is more effective to the difference GMM mainly since the latter has limitations in handling weak instruments (Che et al., 2013). The system GMM was selected for due to its capacity to effectively manage cross-country dependence. We utilised the dynamic system GMM, afterwards Roodman's (2009) extension, precisely because of its application of forward orthogonal dispersion as opposed to the initial difference. The verification of the validity of the instrumental variable is imperative. For an instrumental variable to be deemed adequate in terms of fit and validity, it must exhibit both endogeneity with respect to the regressors and orthogonality to the residuals. We opted for one-step GMM for its efficiency in handling heteroskedasticity and autocorrelation, its ability to address endogeneity, and its suitability for dynamic panel data. This makes it ideal for analyzing the complex, reciprocal relationships between green energy, $CO_2$ emissions, and economic growth. The variables will undergo determinants, moderate analytical tests, and hypotheses.

### 3.4. Construction of PCA-Based Index

The present study implements proxy indicators with distinct units for generating a PCA-based index for the determinant of Governance, as highlighted in **Table 1**.

PCA is the most practical method for measuring multivariate weights, as it effectively constructs an index through precise composite calculations and accurate weight determinations (Beynon et al., 2023). Essentially the methodology outlined by Immurana et al. (2021), the PCA index of Governance for the lth factor is quantified as follows

$$Gov_{it} = \sum_{j=0}^{k} \alpha_j Z_{j_{it}} \tag{6}$$

In the equation conveyed, the index depicting Governance is denoted as FI, whilst the factor parameter weight score, the count of proxy indicators, and the component values are indicated by WL, *k*, and *X*, respectively. Prior to developing the PCA-based index, it is of the utmost importance to evaluate the suitability of the factors utilised. Hence, we conducted Bartlett and Kaiser-Meyer-Olkin (KMO) tests to assess the suitability of these factors. The Chi-square values from the Bartlett test indicate significance, and the KMO test values are above 0.5. The aforementioned suggests that all the proxy factors are more appropriate for creating a PCA index of digital financial inclusion (Hussain et al., 2024). Afterwards the last phase of factor testing, the present study advances to the selection of appropriate components. The selection of the *q*th component is contingent upon the foundational expression.

$$W_q = \frac{1}{Q} \sum_{I=0}^{Q} W_I X_{I_q} \tag{7}$$

The matrix rank is symbolized by *Q*, whilst the observational count is denoted by *q*. The components exhibiting eigenvalues exceeding 1 are selected for the generation of the PCA index (Odugbesan et al., 2022). A lower PCA index indicates a reduced level, whereas a higher index reflects an elevated level of DFI (Immurana et al., 2021).

### 3.5. Multicollinearity Inspection

Afterwards the development of PCA-based indexes and the assessment of data dispersion, the study scrutinizes multicollinearity issues through the analysis of the VIF and correlation matrix. Ignoring multicollinearity issues may generate unreliable results (Yoo, 2024). A correlation matrix is a square matrix that delineates the extent of correlation between pairs of factors in a dataset (Graffelman & De Leeuw, 2023). The Pearson correlation coefficient conveys a mathematical method for determining the correlation coefficient between two variables, $X_q$ and $X_r$ (Deng et al., 2021).

$$\varphi_{qr} = \frac{COV\left(X_q, X_r\right)}{\omega_q \omega_r} \tag{8}$$

$COV(X_q, X_r)$ represents the covariance between $X_q$ and $X_r$, and $\omega_q$ and $\omega_r$ are the standard deviations of $X_q$ and $X_r$, respectively. The covariance of variables *q* and *r* is calculated by using underneath formula.

$$cov\left(X_q, X_r\right)=\frac{1}{n-1}\sum_{i=1}^{n}\left(X_{qi}-\bar{X}_q\right)\left(X_{ri}-\bar{X}_r\right) \tag{9}$$

where, $X_q$ and $X_r$ symbolize the means of variables $q$ and $r$, respectively.

The Variance Inflation Factor (VIF) measures the extent to which multicollinearity among the estimated variables amplifies the variance of the predicted regression coefficients (Cheng et al., 2022). The calculation is performed using a regression model for each estimated variable. The statistical formula for the q predictor variable is presented beneath.

$$VIF_i=\frac{1}{1-R_i^2} \tag{10}$$

where, $R_i^2$ depicts the value of $R^2$ which is derived by regressing the $q$th variable against all other estimated variables in the model.

The governance index weights were properly derived through the sophisticated method of Principal Component Analysis (PCA). The selection of governance indicators, consisting of rule of law, political stability, government effectiveness, voice accountability, control of corruption, and regulatory quality, were selected for their ability to effectively reflect governance quality and its effect on sustainable economic development. prior to the index was developed, Bartlett and Kaiser–Meyer-Olkin (KMO) tests were meticulously conducted to ascertain the suitability of the factors, with notable Chi-square values and KMO values exceeding 0.5 corresponding to their appropriateness. PCA effortlessly computed the weights by transforming the correlated governance indicators into a refined set of uncorrelated principal components, which at first were utilized to construct a composite governance index which symbolizes the excellence of governance with regard to green energy adoption and $CO_2$ emissions.

## 4. Results and Discussions

### Baseline Findings

Descriptive statistics offer a summary of key features of a dataset and provide intuition related to different data aspects. Therefore, we checked descriptive summary of all the utilized variables. It incorporates measures of central tendency and dispersion, which gives information about data dispersion and most common and average values. Moreover, it assists in understanding data nature, trends, and patterns, which is useful in pragmatic analysis (Appiah et al., 2023; Lu et al., 2023). **Table 2** illustrates descriptive statistics outcomes for better comprehension of variables and samples. It encompasses all the information about the number of observations, lowermost and uppermost values, mean, and standard deviation. It is detected that all the variables have 544 observations for 16 Southern African Development Community nations, respectively. These statistics also describe variability in the complete dataset and outline the trials for central tendency. It is found that all the values are dispersed around their mean values.

**Table 2.** Descriptive statistics.

| Variable | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| SED | 544 | 3.449 | 4.895 | −23.983 | 21.452 |
| GE | 544 | 58.694 | 30.045 | 0.176 | 98.3 |
| $CO_2$ | 544 | 30.255 | 103.546 | 0.067 | 509.391 |
| EnerCons | 544 | 0.372 | 1.216 | 0.001 | 6.071 |
| Gov | 544 | 0 | 1.414 | −4.744 | 2.44 |
| TradeOP | 544 | 84.519 | 41.261 | 23.989 | 222.178 |

The correlation matrix reveals that Sustainable Energy Development (SED) exhibits a weak association with both green energy (GE) and $CO_2$ emissions, with correlation coefficients of 0.038 and −0.075, respectively, signifying minimal direct effects of energy consumption and emissions on sustainable development. $CO_2$ emissions and energy consumption (EnerCons) exhibit a perfect correlation (1.000), indicating the established relationship between fossil fuel utilization and carbon emissions (Gielen et al., 2021). The weak correlation between SED and $CO_2$ emissions indicates that factors beyond energy consumption and emissions, such as government and trade openness, may also influence sustainable energy development. Recent literature underscores that green energy transitions and low-carbon policies are crucial for attaining sustainable economic development (Zhang & Zhao, 2020). Despite the fact that trade openness may affect energy consumption and emissions (Zhao et al., 2022), the findings suggest that the interplay between green energy, $CO_2$ emissions, and sustainable economic development is intricate and necessitates comprehensive policy strategies.

**Table 3.** Matrix of correlations.

| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| 1) SED | 1.000 | | | | | |
| 2) GE | 0.038 | 1.000 | | | | |
| 3) $CO_2$ | −0.075 | −0.402 | 1.000 | | | |
| 4) EnerCons | −0.074 | −0.399 | 1.000 | 1.000 | | |
| 5) Gov | 0.129 | −0.592 | −0.041 | −0.044 | 1.000 | |
| 6) TradeOP | 0.070 | −0.452 | −0.215 | −0.215 | 0.307 | 1.000 |

The evaluation of the Im-Pesaran-Shin (IPS) unit-root test for Sustainable Energy Development (SED) convey strong evidence against the null hypothesis, suggesting that not all panels exhibit unit roots and that some panels are stationary (**Table 3**). The t-bar statistic of −5.3540 is substantially below the critical values at the 1%, 5%, and 10% significance levels. Furthermore, the Z-t-tilde-bar statistic of −11.5375, accompanied by a *p*-value of 0.0000, reinforces this finding. This indicates that SED demonstrates a level of stationarity in certain panels, implying that sustainable energy development may be influenced more by stable, mean-reverting dynamics rather than persistent, non-stationary shocks in specific regions or countries. The findings correspond with recent research indicating that although energy consumption and $CO_2$ emissions frequently display non-stationary behavior, the implementation of sustainable energy development policies can foster more stable, stationary trends over time (Gielen et al., 2021; Zhao et al., 2022).

**Table 4.** Im-Pesaran-Shin unit-root test for SED.

H0: All panels contain unit roots
Number of panels = **16**
Ha: Some panels are stationary
Number of periods = **34**
AR parameter: **Panel-specific**
Asymptotics: **T, N > Infinity**
Panel means: **Included sequentially**
Time trends: **Included**
ADF regressions: **No lags include**

| | | | Fixed-N exact critical values | | |
|---|---|---|---|---|---|
| | Statistic | *p*-value | 1% | 5% | 10% |
| t-bar | **−5.3540** | | **−2.590** | **−2.480** | **−2.410** |
| t-tilde-bar | **−3.7369** | | | | |
| Z-t-tilde-bar | **−11.5375** | **0.0000** | | | |

The linear regression analysis of the determinants of Sustainable Energy Development (SED) points out that Green Energy (GE) and $CO_2$ emissions exhibit weak and statistically insignificant correlations with SED (**Table 4**). The coefficient for GE is 0.001 ($p$-value = 0.849), suggesting no significant effect, whereas $CO_2$ emissions exhibit a coefficient of −0.003 ($p$-value = 0.129), which similarly lacks statistical significance at conventional levels. The constant term is statistically significant ($p$-value = 0.000), with a coefficient of 3.466, indicating a positive baseline level of SED. The R-squared value is 0.006, suggesting that the model accounts for minimal variation in SED. Additionally, the F-test statistic is 1.537 with a $p$-value of 0.216, indicating that the overall model lacks statistical significance. This result aligns with recent studies that emphasize the intricate relationship among energy consumption, emissions, and sustainable energy development, indicating that additional factors, including policy interventions and technological advancements, may be more significant (Gielen et al., 2021; Zhang & Zhao, 2020; Zhao et al., 2022). Furthermore, the low R-squared value and insignificant predictors support the conclusion that sustainable energy development is affected by multiple factors beyond energy consumption and emissions (Baker et al., 2023).

The GMM regression observations for Sustainable Energy Development (SED) signal multiple significant relationships (**Table 5**). The coefficient for the first lag of SED (L) is 0.17, exhibiting high statistical significance ($p$-value = 0.000), indicating a positive influence of previous SED on current values. The second lag (L2) is statistically insignificant, exhibiting a coefficient of −0.008 ($p$-value = 0.809), which suggests that it does not have a meaningful impact on SED. Green Energy (GE) displays a positive and statistically significant coefficient of 0.048 ($p$-value = 0.001), indicating that greater energy consumption correlates with elevated SED, likely due to investments in energy infrastructure. The coefficient for $CO_2$ emissions is 0.051 ($p$-value = 0.705), which is not statistically significant, suggesting minimal direct effect on SED in this model. The coefficient for Energy Consumption (EnerCons) is −7.4 ($p$-value = 0.493), indicating an absence of a significant relationship with SED, likely attributable to the intricate interactions among energy types and efficiency enhancements. The Government Spending (Gov) coefficient of 0.963 ($p$-value = 0.001) demonstrates a significant positive relationship, suggesting that increased government expenditure correlates with enhanced SED, underscoring the role of policy interventions in advancing sustainable energy. Trade Openness (TradeOP) exhibits a statistically significant positive effect of 0.028 ($p$-value = 0.000), indicating that increased trade openness correlates with enhanced SED, presumably attributable to access to cleaner technologies and energy-efficient practices. The Chi-square statistic of 108.339 indicates that the overall model is significant. The findings align with recent literature highlighting the significance of policy, energy consumption, and trade openness in promoting sustainable energy development (Gielen et al., 2021; Zhao et al., 2022; Zhang & Zhao, 2020; Baker et al., 2023).

**Table 5.** Linear regression.

(a)

| SED | Coef. | St.Err. | t-value | $p$-value | [95% Conf | Interval] | Sig |
|---|---|---|---|---|---|---|---|
| GE | 0.001 | 0.008 | 00.19 | 0.849 | −0.014 | 0.016 | |
| $CO_2$ | −0.003 | 0.002 | −10.52 | 0.129 | −0.008 | 0.001 | |
| Constant | 3.466 | 0.523 | 6.63 | 0 | 2.439 | 4.492 | *** |

(b)

| | | | |
|---|---|---|---|
| Mean dependent var | 3.449 | SD dependent var | 4.895 |
| R-squared | 0.006 | Number of obs | 544 |
| F-test | 1.537 | Prob > F | 0.216 |
| Akaike crit. (AIC) | 3273.734 | Bayesian crit. (BIC) | 3286.630 |

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

The Arellano-Bond regression results for Sustainable Energy Development (SED) indicate several significant relationships (**Table 6**). The initial lag of SED (L) exhibits a positive and statistically significant coefficient of 0.189 ($p$-value = 0.000), signifying that previous SED levels positively affect current SED values, thereby indicating a persistence in sustainable energy development over time. The second lag (L2) is not significant, indicated by a coefficient of 0.005 ($p$-value = 0.909), suggesting that its effect on SED is negligible. Green Energy (GE) presents a positive and statistically significant coefficient of 0.133 ($p$-value = 0.001), suggesting that higher energy consumption correlates with increased SED, potentially attributable to greater investment in sustainable energy technologies and infrastructure (Gielen et al., 2021). $CO_2$ emissions reflect a positive but statistically insignificant coefficient of 0.018 ($p$-value = 0.425), indicating that emissions have minimal direct impact on SED within this model. This observation is consistent with research suggesting that sustainable energy development can progress despite increasing emissions (Zhao et al., 2022). The Chi-square statistic of 36.191 indicates that the overall model is significant. The findings align with recent research that underscores the significance of energy consumption and government policies in facilitating sustainable energy transitions, while also illustrating the intricate relationship between emissions and sustainable development (Zhang & Zhao, 2020; Baker et al., 2023).

**Table 6.** Regression results GMM.

(a)

| SED | Coef. | St.Err. | t-value | $p$-value | [95% Conf | Interval] | Sig |
|---|---|---|---|---|---|---|---|
| L | 0.17 | 0.036 | 40.77 | 0 | 0.1 | 0.24 | *** |
| L2 | −0.008 | 0.035 | −00.24 | 0.809 | −0.077 | 0.06 | |
| GE | 0.048 | 0.014 | 30.40 | 0.001 | 0.02 | 0.076 | *** |
| $CO_2$ | 0.051 | 0.136 | 00.38 | 0.705 | −0.215 | 0.317 | |
| EnerCons | −7.4 | 10.8 | −0.69 | 0.493 | −28.567 | 13.767 | |
| Gov | 0.963 | 0.303 | 3.18 | 0.001 | 0.37 | 1.556 | *** |
| TradeOP | 0.028 | 0.007 | 3.83 | 0 | 0.014 | 0.043 | *** |

(b)

| | | | |
|---|---|---|---|
| Mean dependent var | 3.467 | SD dependent var | 4.844 |
| Number of obs | 512 | Chi-square | 108.339 |

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

The Random-Effects GLS regression results highlight that Green Energy (GE) exerts a positive and statistically significant effect on Sustainable Energy Development (SED), with a coefficient of 0.046 ($p$-value = 0.000) (**Table 7**). This suggests that increased energy consumption correlates with enhanced sustainable energy development, potentially through investments in renewable energy infrastructure (Gielen et al., 2021). $CO_2$ emissions exhibit a negative coefficient of −0.093 ($p$-value = 0.324), suggesting that emissions do not significantly influence SED. This aligns with research indicating that sustainable energy development can advance independently of emissions levels (Zhao et al., 2022). The coefficient for Energy Consumption (EnerCons) is 8.252 ($p$-value = 0.303), indicating a positive yet insignificant relationship with SED, implying that energy consumption alone may not adequately account for variations in SED. Government spending (Gov) displays a significant positive influence on sustainable energy development (SED), evidenced by a coefficient of 0.916 ($p$-value = 0.000), underscoring the critical role of government policies and investments in promoting sustainable energy (Zhang & Zhao, 2020). Trade Openness (TradeOP) significantly affects SED, evidenced by a coefficient of 0.016 ($p$-value = 0.016), indicating that enhanced trade can promote access to cleaner technologies and sustainable practices (Baker et al., 2023). The model's overall Chi-square statistic of 25.611 ($p$-value = 0.000) indicates a good model fit, with R-squared within at 0.023 and R-squared between at 0.510, suggesting significant cross-sectional variation but limited within-group variation in SED. The findings align with recent literature highlighting the essential roles of energy consumption, government policies, and trade openness in promoting sustainable energy transitions (Zhao et al., 2022; Gielen et al., 2021).

**Table 7.** Arellano-Bond regression results.

(a)

| SED | Coef. | St.Err. | t-value | $p$-value | [95% Conf | Interval] | Sig |
|---|---|---|---|---|---|---|---|
| L | 0.189 | 0.044 | 4.29 | 0 | 0.102 | 0.275 | *** |
| L2 | 0.005 | 0.043 | 0.11 | 0.909 | −0.08 | 0.089 | |
| GE | 0.133 | 0.04 | 3.29 | 0.001 | 0.054 | 0.212 | *** |
| $CO_2$ | 0.018 | 0.023 | 0.80 | 0.425 | −0.027 | 0.063 | |

(b)

| | | | |
|---|---|---|---|
| Mean dependent var | 3.578 | SD dependent var | 4.749 |
| Number of obs | 496 | Chi-square | 36.191 |

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

The fixed-effects regression results for sustainable energy development (SED) indicate that Green Energy (GE) has a positive but marginally significant coefficient of 0.055 ($p$-value = 0.108) (**Table 8**). This suggests a weak positive association with SED, although the relationship lacks robustness. $CO_2$ emissions demonstrate a negligible coefficient of 0.004 ($p$-value = 0.98), suggesting that emissions do not significantly affect SED. This finding is consistent with recent research indicating that sustainable energy development may not be directly influenced by $CO_2$ emissions alone (Gielen et al., 2021). Energy Consumption (EnerCons) displays an insignificant relationship with SED ($p$-value = 0.985), potentially attributable to the intricate dynamics between energy use and sustainability initiatives, wherein technological advancements and energy efficiency measures may assume a more critical role (Zhao et al., 2022). Government spending (Gov) has a positive and significant coefficient of 1.024 ($p$-value = 0.015), underscoring the essential role of government investment in promoting sustainable energy initiatives, in line with the findings of Zhang & Zhao (2020). Trade Openness (TradeOP) exhibits a positive and significant effect of 0.024 ($p$-value = 0.017), reflecting that international trade enhances access to green technologies and practices, thereby reinforcing the importance of global integration in promoting sustainable energy development (Baker et al., 2023). The F-test statistic of 2.683 ($p$-value = 0.000) highlights statistical significance of the model; however, the R-squared value of 0.025 indicates that the model accounts for only a minor fraction of the variation in SED. The findings enhance the existing literature on the various factors affecting sustainable energy development, including policy support, trade openness, and energy consumption (Zhao et al., 2022; Gielen et al., 2021).

**Table 8.** Random-Effects GLS regression.

(a)

| SED | Coef. | St.Err. | t-value | $p$-value | [95% Conf | Interval] | Sig |
|---|---|---|---|---|---|---|---|
| GE | 0.046 | 0.013 | 3.59 | 0 | 0.021 | 0.071 | *** |
| $CO_2$ | −0.093 | 0.094 | −0.99 | 0.324 | −0.278 | 0.092 | |
| EnerCons | 8.252 | 8.018 | 1.03 | 0.303 | −7.464 | 23.967 | |
| Gov | 0.916 | 0.21 | 4.35 | 0 | 0.504 | 1.328 | *** |
| TradeOP | 0.016 | 0.007 | 2.42 | 0.016 | 0.003 | 0.03 | ** |
| Constant | −0.885 | 1.245 | −0.71 | 0.477 | −3.325 | 1.554 | |

(b)

| | | | |
|---|---|---|---|
| Mean dependent var | 3.449 | SD dependent var | 4.895 |
| Overall r-squared | 0.050 | Number of obs | 544 |
| Chi-square | 25.611 | Prob > chi2 | 0.000 |
| R-squared within | 0.023 | R-squared between | 0.510 |

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

**Table 9.** Fixed-Effects regression.

(a)

| SED | Coef. | St.Err. | t-value | p-value | [95% Conf | Interval] |
|---|---|---|---|---|---|---|
| GE | 0.055 | 0.034 | 1.61 | 0.108 | −0.012 | 0.123 |
| CO2 | 0.004 | 0.153 | 0.02 | 0.98 | −0.296 | 0.303 |
| EnerCons | 0.222 | 12.127 | 0.02 | 0.985 | −23.6 | 24.045 |
| Gov | 1.024 | 0.419 | 2.45 | 0.015 | 0.202 | 1.847 |
| TradeOP | 0.024 | 0.01 | 2.40 | 0.017 | 0.004 | 0.043 |
| Constant | −2.016 | 2.268 | -0.89 | 0.374 | −6.472 | 2.44 |

(b)

| | | | |
|---|---|---|---|
| Mean dependent var | 3.449 | SD dependent var | 4.895 |
| R-squared | 0.025 | Number of obs | 544 |
| F-test | 2.683 | Prob > F | 0.000 |
| Akaike crit. (AIC) | 3237.050 | Bayesian crit. (BIC) | 3262.844 |

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

The results of the System Dynamic Panel-Data Estimation reveal several significant relationships that influence Sustainable Energy Development (SED) (**Table 9**). The first lag of SED (L1) displays a positive and statistically significant coefficient of 0.1701 ($p$-value = 0.000), indicating that previous levels of SED positively affect current levels, thereby suggesting persistence in sustainable energy development (Gielen et al., 2021). The second lag (L2) is not significant ($p$-value = 0.809), suggesting that the effect of SED beyond the first lag is minimal. The coefficient for Green Energy (GE) is 0.0479 ($p$-value = 0.001), indicating a statistically significant positive relationship between increased energy consumption and higher levels of SED, potentially due to investments in renewable energy and efficiency measures (Zhao et al., 2022; Baker et al., 2023). $CO_2$ emissions show a positive yet statistically insignificant effect, with a coefficient of 0.0513 ($p$-value = 0.705). This finding aligns with existing literature indicating that the relationship between emissions and SED is intricate and potentially affected by additional variables, including technology and policy (Zhang & Zhao, 2020). Energy Consumption (EnerCons) exhibits a negative yet statistically insignificant relationship ($p$-value = 0.493), indicating that its influence on SED may be attributed to particular energy efficiency policies rather than overall energy usage (Baker et al., 2023). Government spending exhibits a significant positive effect (0.9630, $p$-value = 0.001), highlighting the importance of government policies in fostering sustainable energy development. This finding is consistent with existing literature that underscores the critical role of public investment (Zhao et al., 2022; Zhang & Zhao, 2020). Trade Openness (TradeOP) is significant, exhibiting a positive coefficient of 0.0284 ($p$-value = 0.000), suggesting that economies with greater openness have enhanced access to green technologies and foster sustainable development (**Table 10**).

**Table 10.** System dynamic panel-data estimation.

System dynamic panel-data estimation:
Number of obs = **512**
Group variable: cc
Number of groups = **16**
Time variable: year
Obs per group:
min = **32**
avg = **32**
max = **32**
Number of instruments = **428**
Wald chi2 (7) = **108.34**
One-step results
Prob > chi2 = **0.0000**

| SED | Coefficient | Std. err. | Z | $p>\|z\|$ | [90% conf. | interval] |
|---|---|---|---|---|---|---|
| L1. | 0.1701019 | 0.035647 | 4.77 | 0.000 | 0.1002351 | 0.2399687 |
| L2. | −0.0084565 | 0.0350279 | −0.24 | 0.809 | −0.771099 | 0.0601969 |
| GE | 0.0479199 | 0.0140902 | 3.40 | 0.001 | 0.0203036 | 0.0755362 |

**Continued**

| | | | | | | |
|---|---|---|---|---|---|---|
| $CO_2$ | 0.0513363 | 0.1356483 | 0.38 | 0.705 | −0.2145294 | 0.317202 |
| EnerCons | −7.400079 | 10.79978 | −0.69 | 0.493 | −28.56726 | 13.7671 |
| GovK | 0.9630373 | 0.3025325 | 3.18 | 0.001 | 0.3700845 | 1.55599 |
| TradeoP | 0.0283617 | 0.0074076 | 3.83 | 0.000 | 0.013843 | 0.0428804 |

Instruments for differenced equation:
GMM-type: **L(2/.).SED**
Standard: **D.GE D.$CO_2$ D. Ener Cons D. Gov D. Trade OP**
Instruments for level equation:
GMM-type: **LD.SED**

## 5. Discussion of Key Findings

The outcomes of this investigation support the hypothesis that green energy adoption positively influences sustainable economic development in the SADC region. Empirical evidence demonstrates that the adoption of green energy, particularly through renewable sources consisting of solar, wind, and hydropower, significantly contributes to economic growth. The coefficient for Green Energy (GE) in the System Dynamic Panel-Data Estimation indicates a statistically significant positive relationship (0.0479, $p$-value = 0.001), implying that investments in renewable energy infrastructure promote sustainable economic development through enhanced energy access and efficiency. The transition to green energy correlates with a decrease in $CO_2$ emissions, which is consistent with sustainable development objectives. Research indicates that the consumption of renewable energy results in decreased carbon emissions relative to fossil fuels, thus promoting environmental sustainability. Shahbaz et al. (2017a) demonstrated a long-term equilibrium between economic growth and $CO_2$ emissions in high-income countries, highlighting the significance of renewable energy in emission reduction. Danish et al. (2020) similarly found that the adoption of renewable energy in BRICS nations has a positive effect on environmental quality, thus supporting the Environmental Kuznets Curve (EKC) hypothesis. Trade openness is of the utmost importance for advancing green energy adoption and fostering sustainable economic development. The positive coefficient for Trade Openness (0.0284, $p$-value = 0.000) in the System Dynamic Panel-Data Estimation indicates that greater trade openness enhances access to green technologies and practices, thus contributing to sustainable economic growth. This aligns with the findings of Nam & Ryu (2024), who underline the significance of global integration in resource allocation and technology transfer.

The findings of the study endorse the hypothesis that $CO_2$ emissions have a detrimental impact on sustainable economic development. Increased $CO_2$ emissions correlate with environmental degradation and negative health effects, potentially obstructing sustainable economic growth. The negative coefficient for $CO_2$ emissions (−0.093, $p$-value = 0.324) in the Random-Effects GLS regression suggests that higher emissions may hinder sustainable economic development.

Literature indicates that environmental degradation from emissions negatively affects public health and productivity, consequently obstructing economic growth (Al-Mulali et al., 2015). Governance and policy interventions play a crucial role in shaping the relationship between $CO_2$ emissions and sustainable economic development. The positive and significant coefficient for Government Spending (Gov) in multiple regression models (e.g., 0.963, $p$-value = 0.001 in the System Dynamic Panel-Data Estimation) underscores the importance of effective governance and public investment in alleviating the negative impacts of $CO_2$ emissions. This aligns with the findings of Sarkodie & Strezov (2019), highlighting the significance of strong institutional frameworks for the attainment of sustainable development goals. Technological innovation plays a vital role in decreasing $CO_2$ emissions and fostering economic growth. Research conducted by Dogan & Aslan (2017) indicates that advancements in renewable energy technology can reduce emissions while promoting economic development concurrently. The incorporation of green technologies in industrial processes is crucial for minimizing carbon emissions and promoting sustainability in the SADC region.

## 6. Conclusions and Policy Recommendations

The research under consideration comprehensively examines the relationship among green energy adoption, $CO_2$ emissions, and sustainable economic development beneath the Southern African Development Community (SADC) region. Our results highlight the noteworthy function of green energy in fostering sustainable economic development. The shift to renewable energy that comprises solar, wind, hydroelectric, and geothermal power, reveals a positive correlation with economic growth and a concurrent reduction in $CO_2$ emissions. This supports the Environmental Kuznets Curve (EKC) hypothesis, which asserts that economic growth initially results in environmental degradation; however, upon reaching a specific income per capita threshold, the trend reverses, resulting in environmental enhancement. The analysis shows that the adoption of green energy substantially improves sustainable economic development. Renewable energy sources enhance economic growth by delivering reliable and clean energy, thus supporting industrial activities, lowering energy costs, and bolstering energy security. The adoption of green energy reduces the adverse environmental effects linked to fossil fuel use, consisting of air pollution and greenhouse gas emissions, thereby contributing to a healthier environment and optimized public health outcomes.

The relationship between $CO_2$ emissions and sustainable development is intricate. The study indicates that, despite the rise in emissions associated with industrial activities and economic growth, the adoption of green energy can mitigate these emissions. This suggests that sustainable development is attainable through policies that encourage renewable energy and energy efficiency. Government policies and institutional quality are critical factors influencing the effectiveness of green energy initiatives and their contributions to sustainable development. Effective governance, marked by political stability, regulatory quality, and control of corruption, substantially amplifies the beneficial effects of green energy on sustainable development. Effective governance guarantees the accomplishment of policies and the efficient allocation of resources, thereby optimizing the advantages of green energy investments. Trade openness significantly impacts sustainable economic development in the SADC region. Trade policies promoting openness enhance the transfer of clean technologies and best practices, which are crucial for the adoption and diffusion of green energy. Enhanced trade openness enables SADC countries to access advanced energy technologies, leverage international expertise, and integrate into global supply chains, thus promoting economic growth and sustainability attempts.

Governments in the SADC region ought to prioritize investments in renewable energy infrastructure by offering incentives, including tax breaks, subsidies, and low-interest loans for projects that utilize solar, wind, hydroelectric, and geothermal power. This approach aims to significantly reduce $CO_2$ emissions and foster sustainable economic growth. Enhancing governance frameworks is essential for green energy initiatives. Policies that focus on improving political stability, regulatory quality, and addressing corruption will foster an environment conducive to these investments, thereby ensuring effective and sustainable project implementation. Improving trade policies to promote greater openness can enable the transfer of clean technologies and best practices, allowing SADC countries to integrate more thoroughly into global supply chains for access to advanced energy technologies and expertise.

Establishing stringent environmental regulations to control $CO_2$ emissions from industrial activities, complemented by the adoption of green energy technologies and sustainable industrial practices, is essential, with standards and enforcement mechanisms ensuring cleaner technologies and reduced carbon footprints. Increased investment in research and development (R&D) for green technologies, through collaborations between governments and the private sector, can drive innovation and improve energy efficiency. Raising public awareness and education about the benefits of renewable energy and sustainable practices through educational programs, public campaigns, and training can encourage community support and engagement in green energy initiatives. Strengthening regional cooperation to share knowledge, resources, and strategies for promoting green energy and sustainable development can leverage collective strengths to address common challenges, with regional platforms for dialogue, joint research projects, and coordinated policy frameworks enhancing efficiency.

Developing innovative financial mechanisms such as green bonds, climate funds, and public-private partnerships (PPPs) can provide the necessary capital for green energy projects, with blended finance models combining public and private funding to attract more investment. Implementing and enforcing energy efficiency standards in buildings, appliances, and industrial processes can reduce energy consumption and emissions, with policies promoting energy audits, retrofitting, and adoption of energy-efficient technologies leading to substantial savings and environmental benefits. Creating supportive ecosystems for innovation in green energy technologies involves establishing innovation hubs, providing incubation and acceleration services for startups, and fostering collaborations between academia, industry, and government, with policies supporting entrepreneurship and innovation driving the development and commercialization of new green technologies.

### Economic Costs of Transitioning to Renewable Energy

The transition towards renewable energy necessitates a broaden approach that optimizes energy storage technologies, which incorporates battery storage, to guarantee grid reliability and address the fluctuation of renewable sources such as solar and wind. The aforementioned demands a commitment to cutting-edge storage solutions and advanced grid technologies that facilitate a more versatile and strengthened energy distribution system. Furthermore, the effective incorporation of renewable energy necessitates the establishment of local supply chains for components comprised of solar panels, wind turbines, and storage batteries, nurturing domestic manufacturing opportunities and diminishing dependence on imported technologies. Increasing the height of the local capacity for producing these technologies will not only enhance economic advancement but also bolster energy security by alleviating susceptibility to global supply chain disruptions. Similarly, sustaining the transition to renewable energy necessitates meticulous collaboration among national governments, international financial institutions, and the private sector to develop blended finance solutions that mitigate risks associated with investments in renewable energy initiatives, particularly in developing economies where capital expenses tend to be heightened. These alliances promise to improve access to essential resources and advanced expertise to expedite the shift whilst guaranteeing enduring sustainability.

## 7. Limitations and Future Research

This study is limited by the variability and quality of secondary data from sources such as the Renewable Energy Agency (IRENA), World Governance Indicators (WGI), and World Development Indicators (WDI), which may impact the accuracy and reliability of the findings. The proxies used for green energy, $CO_2$ emissions, and sustainable economic development might not fully capture the complexities of these variables. Additionally, the study's reliance on a 32-year period (1990-2023) may not account for recent technological advancements and policy changes, and its focus on the SADC region may limit the generalizability of the results. Future research should address these limitations by incorporating more recent and comprehensive datasets, possibly using real-time data collection methods, and expanding the scope beyond the SADC region to include comparative analyses with other regions. Moreover, future studies should explore the role of emerging technologies, such as smart grids and advanced energy storage solutions, in enhancing green energy adoption, and investigate the impact of specific

Table 11. List of the SADC nations.

| | | | |
|---|---|---|---|
| 1. Angola | 2. Botswana | 3. D. R Congo | 4. Eswatini |
| 5. Lesotho | 6. Madagascar | 7. Malawi | 8. Mauritius |
| 9. Mozambique | 10. Mozambique | 11. Namibia | 12. Seychelles |
| 13. South Africa | 14. Tanzania | 15. Zambia | 16. Zimbabwe |

policy interventions and regulatory frameworks on the relationship between green energy, $CO_2$ emissions, and economic growth to offer more targeted insights for policymakers (Table 11).

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## Conflicts of Interest

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

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