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Financial Development and the Renewable Energy Transition in South Africa: Uncovering the Causal Dynamics

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ABSTRACT

This study examines the causal relationship between financial development and renewable energy consumption in South Africa using annual data from 1990 to 2024. The analysis employs a vector error correction model (VECM) Granger causality framework to distinguish between short-run dynamics and long-run equilibrium relationships. Unit root tests confirm that the variables are integrated of order one, while the Johansen cointegration test indicates the existence of a long-run relationship among renewable energy consumption, financial development, economic growth, inflation, and capital formation. The VECM Granger-causality results reveal strong long-run unidirectional causality running from financial development, economic growth, inflation, and capital formation to renewable energy consumption. In the short run, credit extension and economic growth are found to Granger-cause renewable energy consumption. The findings highlight the importance of financial sector development in facilitating renewable energy expansion. Strengthening financial systems may therefore support South Africa's transition toward a more sustainable energy system.

Keywords: Renewable Energy Transition, Financial Development, Vecm-Granger Causality, South Africa
JEL Classifications: D04, C32, Q47, Q42, Q01

1. INTRODUCTION

Global warming and widening developmental disparities have intensified the need to understand the drivers of sustainable growth, particularly in emerging economies that are simultaneously energy-intensive and environmentally vulnerable. Evidence shows that poorer countries are disproportionately affected by climate change due to limited adaptive capacity, weaker health systems, and constrained fiscal resources (McMichael et al., 2003). Energy remains central to economic development, industrial production, and improvements in living standards (Kaygusuz, 2012). However, the continued dominance of fossil fuels in the global energy mix has significantly contributed to rising CO_2 emissions and environmental degradation. The growing urgency to decarbonise has therefore shifted attention toward renewable energy sources (RES) as a mechanism to reconcile economic growth with environmental sustainability (Rifkin, 2011; Mukhtarov et al., 2020).

South Africa represents a particularly compelling case within this global transition. Despite possessing substantial renewable energy potential, the country remains heavily dependent on coal. Coal accounted for approximately 85% of electricity generation in 2016 and still represented about 81.8% of the national energy mix in the first half of 2021 (CSIR, 2021). South Africa is Africa's largest CO_2 emitter, contributing nearly 34% of the continent's total emissions and ranking among the top global emitters (Ndoricimpa, 2017; Akinbami et al., 2021). At the same time, the country receives an average of approximately 220 W/m^2 of global solar radiation per year, significantly higher than many regions in Europe and the United States and enjoys more than 2,500 hours of sunshine annually, with average solar radiation levels between 4.5 and 6.5 kWh/m^2/day (Edkins et al., 2010; Khobai et al., 2020). Wind resources along the Western and Eastern Cape further strengthen its renewable energy prospects. Projections suggest that renewable energy could contribute up to 70% of electricity generation by 2050 (Banks and Schaffler, 2005).

Despite this potential, South Africa's energy system has faced persistent structural challenges. Following rapid post-apartheid economic expansion, electricity demand began to outstrip supply, culminating in recurring power shortages and load-shedding initiated in late 2007 (Khobai et al., 2016). Electricity sales volumes declined by approximately 4.7% between 2009 and 2019, further straining the financial position of Eskom, the national electricity utility. Projections indicated a potential 4,000 MW capacity shortfall in 2021 under a 70% energy availability factor (The Conversation, 2020). These inefficiencies, combined with environmental pressures, underscore the urgency of diversifying the energy mix and strengthening renewable energy deployment.

Within this context, financial development emerges as a potentially critical determinant of renewable energy expansion. Theoretically, financial development through banking sector deepening, capital market expansion, and increased foreign direct investment facilitates capital mobilisation, lowers transaction costs, and enhances resource allocation efficiency. One strand of literature argues that financial deepening stimulates energy demand by expanding credit availability for households and firms, thereby increasing consumption of energy-intensive goods and capital equipment (Chang, 2015; Sadorsky, 2010). Conversely, another perspective suggests that sophisticated financial systems can channel funds toward renewable energy projects, green technologies, and environmentally friendly investments at lower financing costs, thereby promoting sustainable energy transitions (Mahalik et al., 2017; Kassi, 2020). These competing theoretical channels imply that the direction of influence between financial development and renewable energy consumption is not unidirectional and must be empirically determined.

While international studies provide evidence of a relationship between financial development and energy consumption, most focus on aggregate energy use or rely on panel data frameworks that obscure country-specific dynamics. For South Africa, empirical work has largely concentrated on growth-energy or emissions-energy linkages, with limited attention to renewable energy specifically and even less emphasis on establishing the direction of causality. Many studies identify long-run associations but do not disentangle short-run from long-run causal dynamics within a cointegration framework. Consequently, it remains unclear whether financial development drives renewable energy consumption, whether renewable energy expansion stimulates financial sector development, or whether a bidirectional feedback mechanism exists.

The problem statement therefore centres on the absence of country-specific time-series evidence that rigorously examines the causal relationship between financial development and renewable energy consumption in South Africa. Without clarity on causality, policymakers cannot determine whether financial sector reforms should precede renewable energy policies or whether renewable energy expansion itself can strengthen financial development through investment flows and market innovation.

This study addresses this gap by applying a Vector Error Correction Model (VECM) and Granger causality framework to annual data for the period 1990-2024. By focusing explicitly on causality tests within a cointegrated system, the study distinguishes between short-run dynamics and long-run equilibrium adjustments. The VECM approach enables the identification of long-run causality through the error correction term and short-run causality through lagged differenced variables, thereby clarifying the direction of influence between financial development and renewable energy consumption.

The contribution of this study lies in providing robust country-specific evidence on the causal structure of the finance-renewable energy nexus in South Africa. By moving beyond correlation to establish both short- and long-run causality, the study offers policy-relevant insights for sequencing financial and energy reforms within the country's broader transition strategy. In doing so, it contributes to the literature on sustainable finance and energy transition by highlighting the institutional conditions under which financial development can effectively support renewable energy expansion in an energy-constrained emerging economy

2. LITERATURE REVIEW

Electricity consumption has expanded alongside the modernisation of production systems and rising industrial potential, and it is widely recognised as a core infrastructure input underpinning living standards and economic activity (Masuduzzaman, 2012). This recognition explains why the causal linkage between energy use and economic growth has dominated the literature since Kraft and Kraft (1978) provided early evidence that energy use precedes growth. Subsequent empirical studies have continued to explore this nexus across countries and methodologies, yet the results remain persistently ambiguous with respect to causal direction because energy-growth interactions are not structurally invariant across countries, time periods, or energy systems. Recent studies continue to document this heterogeneity. For example, Acheampong et al. (2022), Wang et al. (2023), and Khan et al. (2024) show that the direction of causality between energy consumption and economic growth varies significantly across developed and developing economies, largely reflecting differences in industrial structures, technological adoption, and energy policies. The canonical four-hypothesis framework; conservation, growth, feedback, and neutrality, therefore remains useful as a policy map, but it also exposes a key limitation in much of the subsequent work: energy is often treated as a homogeneous aggregate when the contemporary policy challenge increasingly involves a compositional transition from fossil-based energy toward renewable sources. When empirical models aggregate energy sources, neutrality or conservation findings may conceal offsetting dynamics in which fossil energy declines while renewable energy expands, producing weak net effects that are then misinterpreted as the absence of a relationship. Recent transition-focused studies emphasise that disaggregating energy sources is critical for identifying the structural drivers of the energy transition (Sadorsky, 2022; Shahbaz et al., 2023; Usman et al., 2024).

Building on the energy-growth tradition, the finance-energy and finance-renewables literature shifts attention to how financial development shapes the energy system through credit allocation, capital-market functioning, and broader intermediation efficiency. This literature typically motivates two competing views: financial deepening can raise energy demand by expanding consumption and investment, while it can also facilitate the transition toward cleaner energy systems by lowering the cost of capital and easing access to long-term financing for renewable projects (Chang, 2015; Sadorsky, 2010). Recent empirical work increasingly supports the latter argument by highlighting the role of green finance and sustainable investment instruments in accelerating renewable energy deployment (Shahbaz et al., 2022; Razzaq et al., 2023; Nguyen and Su, 2024). Conceptually, the literature often groups the transmission mechanisms into four channels: The direct effect, the business effect, the wealth effect, and EKC-style nonlinearities. However, a closer examination reveals a persistent mismatch between the theoretical narratives presented and the empirical variables used to test them. The direct effect emphasises that a more efficient financial system expands household and firm credit, enabling purchases of energy-using durables and capital equipment and therefore raising energy consumption (Furuoka, 2015; Sadorsky, 2011). This channel is compelling for aggregate energy demand, but it does not necessarily imply higher renewable energy consumption unless the energy supply mix and relative prices allow incremental demand to be met through renewable sources rather than fossil fuels. Recent work confirms that financial development may stimulate overall energy consumption without necessarily increasing renewable energy use unless supportive policy frameworks and investment incentives exist (Adebayo et al., 2022; Baloch et al., 2023). Without explicitly modelling renewable energy consumption or renewable energy shares, the direct effect may generate empirical results suggesting that finance increases energy use while providing little evidence about renewable transition dynamics.

The business-cycle channel rooted in Minsky's financial instability hypothesis (Minsky, 1982) and extended by Kregel (2004, 2010) similarly explains how credit conditions propagate investment cycles that translate into energy demand. Yet, as with the direct effect, this mechanism primarily explains fluctuations in aggregate energy consumption rather than renewable adoption unless financial flows are directed toward renewable infrastructure or clean-energy projects. Recent research on green financial markets highlights that renewable energy expansion often depends on specialised financing mechanisms such as green bonds, climate funds, and sustainable banking practices (Flammer, 2021; Zhang et al., 2023; Taghizadeh-Hesary and Yoshino, 2024). The wealth effect, drawing on behavioural perspectives linking asset-price increases to higher spending (Yang et al., 2020), also offers a plausible explanation for increased energy demand, particularly in economies where housing and equity markets influence consumption patterns (Haider and Adil, 2019; Sadorsky, 2011). However, the transition from wealth-induced consumption to renewable energy adoption is not automatic and requires intermediate financial mechanisms that channel savings toward green investment and renewable technologies. Finally, EKC-type reasoning (Grossman and Krueger, 1991; Piketty, 2013; Nkalu et al., 2020) is frequently invoked to justify nonlinear relationships between development and environmental outcomes, yet recent studies emphasise that financial development should not be treated as a simple proxy for income or modernisation because its different dimensions; depth, efficiency, and access, can affect energy systems through distinct channels (Shahbaz et al., 2022; Ahmed et al., 2024).

These conceptual tensions help explain why empirical evidence continues to fragment across the four causality hypotheses. One strand reports unidirectional causality running from financial development to energy consumption (Ozturk and Acaravci, 2013; Mudakkar et al., 2013; Sadorsky, 2010), which is broadly consistent with credit-driven expansion in investment and consumption. Recent studies such as Shahbaz et al. (2022) and Usman et al. (2024) reinforce this view by showing that financial deepening stimulates energy demand in emerging economies. A second strand finds reverse causality, suggesting that energy consumption can stimulate financial development by supporting industrial expansion and economic activity (Yandan and Zhang, 2009; Al-Mulali and Sab, 2012; Islam et al., 2013). More recent work confirms that energy infrastructure investment can expand financial intermediation and capital markets (Acheampong et al., 2022; Khan et al., 2024). A third strand supports feedback causality (Khan et al., 2014; Shahbaz and Lean, 2012; Abosedra et al., 2015), implying mutually reinforcing interactions between financial systems and energy markets. Recent panel studies also find bidirectional relationships between financial development, renewable energy adoption, and economic growth in several emerging economies (Razzaq et al., 2023; Nguyen and Su, 2024). Finally, the neutrality hypothesis remains evident in some studies (Shahbaz et al., 2013), although more recent work suggests that neutrality results may arise from model misspecification, structural breaks, or aggregation bias rather than genuine independence between finance and energy systems (Sadorsky, 2022; Wang et al., 2023).

Country-specific evidence illustrates this heterogeneity clearly. Mukhtarov et al. (2018) for Azerbaijan and Mukhtarov et al. (2020) for Kazakhstan show that financial development and economic growth exert a positive long-run influence on energy consumption, while energy prices can dampen consumption in the short run. More recent studies extend these findings by showing that financial sector development also promotes renewable energy deployment in resource-dependent economies when supportive policies and investment incentives are present (Adebayo et al., 2022; Taghizadeh-Hesary and Yoshino, 2024). In developed contexts, Farhani and Solarin (2017) demonstrate that finance, trade, and FDI increase US energy demand in the long run while also revealing asymmetric causal relationships. Similar asymmetric dynamics are reported by Baloch et al. (2023), who show that positive and negative financial shocks affect renewable energy investment differently across advanced economies. Denisova (2020) finds that in Germany, urbanisation and economic growth increase energy consumption while financial market development has an insignificant effect, suggesting that structural and technological factors may dominate financial influences in mature economies. Cross-country evidence further reinforces this heterogeneity. Ma and Fu (2020) find a positive effect of financial development on energy consumption globally and in developing countries but not in developed ones, while Coban and Topcu (2013) show that financial development has limited effects across the EU27 but stronger impacts in older member states. More recent global panel studies confirm that financial development plays a stronger role in shaping renewable energy transitions in developing economies where capital constraints are more binding (Shahbaz et al., 2023; Usman et al., 2024).

When the focus shifts specifically to renewable energy consumption, the role of financial development becomes even more pronounced. Evidence that financial development increases renewable energy consumption has been reported in Azerbaijan (Mukhtarov et al., 2020) and Nigeria (Dimnwobi et al., 2022), supporting the argument that financial systems can relax investment constraints in renewable energy deployment. Similar conclusions are reported by Adebayo et al. (2022) and Razzaq et al. (2023), who find that financial development and green finance significantly stimulate renewable energy adoption in emerging economies. Conversely, Zhe et al. (2021) find that renewable energy consumption positively influences financial development in Turkey, highlighting the possibility of reverse causality through investment flows and financial innovation. Burakov and Freidin (2017) demonstrate that different econometric approaches may yield contrasting causal interpretations, reinforcing the need for methodological robustness when analysing finance-energy relationships. More recent nonlinear and asymmetric analyses further show that the relationship between financial development and renewable energy consumption can differ depending on positive or negative financial shocks (Shahbaz et al., 2023; Baloch et al., 2023). Regional heterogeneity within countries also remains important. For example, Wang et al. (2021) find that the causal relationship between finance and renewable energy varies across Chinese provinces depending on differences in industrial development, financial market depth, and renewable resource endowments.

Across this literature, two persistent methodological limitations weaken inference and limit comparability. First, financial development is operationalised using diverse proxies such as money supply (M2), private sector credit, stock market capitalisation, and composite financial development indices. These proxies correspond to different theoretical mechanisms, yet many studies interpret them interchangeably. Recent literature emphasises that bank-based and market-based financial systems influence renewable energy investment through different channels (Taghizadeh-Hesary and Yoshino, 2024; Nguyen and Su, 2024). Second, many studies fail to align the dependent variable with the theoretical claim, often using total energy consumption to infer renewable energy transition dynamics. Recent transition-focused studies emphasise that renewable energy consumption, renewable energy capacity, or renewable energy shares provide more accurate indicators of clean-energy transition processes (Sadorsky, 2022; Shahbaz et al., 2023; Usman et al., 2024).

The South African evidence further illustrates these issues and highlights the need for a more transition-focused empirical design. Lefatsa et al. (2021) report unidirectional Granger causality running from financial development to energy consumption, while Odhiambo (2019) finds a positive long-run relationship between financial development and energy use. More recent studies focusing on South Africa confirm that financial development can facilitate renewable energy investment through improved capital allocation and financial innovation, although the strength of this relationship depends heavily on policy frameworks and energy market reforms (Adebayo et al., 2022; Shahbaz et al., 2023). In a coal-dominant energy system such as South Africa's, electricity supply constraints and structural inefficiencies may weaken the transmission from financial development to realised energy consumption, even when financial systems increase latent investment demand. At the same time, renewable deployment remains dependent on policy implementation, grid infrastructure, and procurement systems such as renewable energy independent power producer programmes. Consequently, finance may be a necessary but not sufficient condition for renewable energy expansion. An empirical framework that distinguishes short-run and long-run causal dynamics and that focuses specifically on renewable energy consumption is therefore essential for generating policy-relevant insights.

Overall, the literature provides strong motivation for examining the causal relationship between financial development and renewable energy consumption, yet it also demonstrates that empirical results remain highly context-dependent. Recent studies increasingly emphasise the importance of aligning theoretical mechanisms with empirical proxies and distinguishing between aggregate energy demand and renewable energy transition dynamics (Shahbaz et al., 2023; Usman et al., 2024; Nguyen and Su, 2024). By focusing specifically on renewable energy consumption and by employing econometric techniques capable of distinguishing short-run from long-run dynamics, this study contributes to the literature by providing more precise evidence on the role of financial development in facilitating the renewable energy transition within the South African context.

3. METHODOLOGY

3.1. Data Collection

The study uses annual time series data covering the period from 1990 to 2024. These data will be collected from diverse and reputable data sources to examine the interconnectedness between the variables. Renewable energy consumption will be sourced from the International Energy Agency (IEA) and will be treated as the dependent variable. It is measured by renewable energy consumption as a percentage of total final energy consumption. FD and GDP are sourced from the South African Reserve Bank database while capital formation is obtained from the World Development Indicators of the World Bank. Three proxies are used for FD and include: Monetary aggregate (M3), Exchange rate transportation and Credit extension. The measure of economic growth (GDP) is real GDP per capita (2010 USD) and capital formation is measured as Gross fixed capital formation. Finally, inflation was sourced from SARB and proxied by consumer price index (CPI) as illustrated in Table 1.

3.2. Model Specification

The study's main objective is to determine the nexus between renewable energy consumption and financial development.

Table 1: Data description

Regressand variable	Source	Description
Renewable energy consumption	IEA	Renewable energy consumption as percentage of total final energy consumption
Regressor variables		
FD	World Bank	Monetary aggregate (M3), exchange rate transportation and credit extension.
GDP	World Bank	Real GDP (using constant prices of 2010)
Inflation	SARB	Inflation rate
Capital formation	World Bank	Gross fixed capital formation is taken as capital formation of South Africa

Source: Own calculation

Drawing from this main objective and from the previous literature (Mahalik and Mallick, 2014; Burakov and Freidin, 2017 and Mukhtarov et al., 2020), the study specifies a partial model depending on the relevance of the variables. The following model expresses the link between renewable energy consumption, financial development, Gross Domestic Product, Inflation, and gross fixed capital formation. The study adopts the following model specification:

$$LRE_t = \alpha + \beta_1 LFD_t + \beta_2 LGDP_t + \beta_3 LCPI_t + \beta_4 LK_t + \propto_t \quad (1)$$

Where RE_t represents renewable energy consumption, FD_t denotes financial development, GPD_t refers to gross domestic product per capita, CPI_t represents the consumer price index, and K_t denotes capital formation, while η_t captures the stochastic error term. For the purposes of this analysis, the model is estimated using the logarithmic transformation of the variables.

3.3. Unit Root

The initial step in examining the existence of a long-run cointegrating relationship among the variables is to determine whether the series are stationary or non-stationary. To assess the stationarity properties of the variables at both levels and first differences, this study employs three widely used unit root tests: the Augmented Dickey-Fuller (ADF) test developed by Dickey and Fuller (1979), the Phillips-Perron (PP) test proposed by Phillips and Perron (1988), and the Dickey-Fuller Generalized Least Squares (DF-GLS) test introduced by Elliott et al. (1996). Employing these three tests jointly enhances the robustness and reliability of the unit root analysis, as each test is based on different assumptions and addresses econometric issues such as serial correlation, heteroskedasticity, and small-sample bias in distinct ways. Consequently, applying multiple unit root tests ensures that the stationarity results are not driven by the limitations of a single testing procedure.

3.4. Co-integration Test

The next step is to detect a long run relationship between the variables given that both series are integrated of the same order. We apply the Johansen test for cointegration developed by Johansen (1988). This is a multivariate econometric technique used to determine the existence and number of long-run equilibrium relationships among non-stationary time-series variables that are integrated of the same order, typically I(1). Unlike the Engle-Granger approach, which is limited to a single cointegrating relationship, the Johansen procedure allows for the identification of multiple cointegrating vectors within a system of equations estimated through a Vector Autoregressive (VAR) framework. The method relies on two likelihood ratio statistics; the trace statistic and the maximum eigenvalue statistic, to test the null hypothesis of no cointegration against the alternative of one or more cointegrating relationships. When testing for the null hypothesis that r = 0, both the trace test and the maximum Eigen value test have statistics that are below the critical values at the 5% level of significance (Johansen, 1991). This implies that the null hypothesis of no cointegration cannot be rejected at the 5% level of significance. Therefore, both tests verify that the series do not have a long run relationship.

3.5. VECM Granger-causality

3.5.1. Granger causality test

The Granger-causality is employed to detect the direction of causality between the variables after evaluating the long-term linkage between the variables. The Vector Error Correction Model is used to evaluate the direction of causality if the results detect the existence of a long run relationship. The VECM can detects sources of causality and measures the long and short run relationship between variables. Equations 2-6 are responsible for the formation of the VECM. The dependent variable, independent variables, and error correction term are all explained in each equation:

$$\begin{aligned}\Delta LRE_t &= \alpha_{10} + \sum\nolimits_{i=1}^{q} \alpha_{11}\Delta LRE_{t-i} + \sum\nolimits_{i=1}^{r} \alpha_{12}\Delta LFD_{t-i} \\ &+ \sum\nolimits_{i=1}^{s} \alpha_{13}\Delta LGDP_{t-i} + \sum\nolimits_{i=1}^{t} \alpha_{14}\Delta LCPI_{t-i} \\ &+ \sum\nolimits_{i=1}^{u} \alpha_{15}\Delta LK_{t-i} + \psi_1 ECT_{t-1} + \varepsilon_{1t}\end{aligned} \quad (2)$$

$$\begin{aligned}\Delta LFD_t &= \alpha_{10} + \sum\nolimits_{i=1}^{q} \alpha_{11}\Delta LFD_{t-i} + \sum\nolimits_{i=1}^{r} \alpha_{12}\Delta LRE_{t-i} \\ &+ \sum\nolimits_{i=1}^{s} \alpha_{13}\Delta LGDP_{t-i} + \sum\nolimits_{i=1}^{t} \alpha_{14}\Delta LCPI_{t-i} \\ &+ \sum\nolimits_{i=1}^{u} \alpha_{15}\Delta LK_{t-i} + \psi_1 ECT_{t-1} + \varepsilon_{2t}\end{aligned} \quad (3)$$

$$\begin{aligned}\Delta LGDP_t &= \alpha_{10} + \sum\nolimits_{i=1}^{q} \alpha_{11}\Delta LGDP_{t-i} + \sum\nolimits_{i=1}^{r} \alpha_{12}\Delta LFD_{t-i} \\ &+ \sum\nolimits_{i=1}^{s} \alpha_{13}\Delta LRE_{t-i} + \sum\nolimits_{i=1}^{t} \alpha_{14}\Delta LCPI_{t-i} \\ &+ \sum\nolimits_{i=1}^{u} \alpha_{15}\Delta LK_{t-i} + \psi_1 ECT_{t-1} + \varepsilon_{3t}\end{aligned} \quad (4)$$

$$\begin{aligned}\Delta LCPI_t &= \alpha_{10} + \sum\nolimits_{i=1}^{q} \alpha_{11}\Delta LCPI_{t-i} + \sum\nolimits_{i=1}^{r} \alpha_{12}\Delta LFD_{t-i} \\ &+ \sum\nolimits_{i=1}^{s} \alpha_{13}\Delta LGDP_{t-i} + \sum\nolimits_{i=1}^{t} \alpha_{14}\Delta LRE_{t-i} \\ &+ \sum\nolimits_{i=1}^{u} \alpha_{15}\Delta LK_{t-i} + \psi_1 ECT_{t-1} + \varepsilon_{4t}\end{aligned} \quad (5)$$

$$LK_t = \alpha_{10} + \sum_{i=1}^{q} \alpha_{11} \Delta LK_{t-i} + \sum_{i=1}^{r} \alpha_{12} \Delta LFD_{t-i} + \sum_{i=1}^{s} \alpha_{13} \Delta LGDP_{t-i} + \sum_{i=1}^{t} \alpha_{14} \Delta LCPI_{t-i} + \sum_{i=1}^{u} \alpha_{15} \Delta LRE_{t-i} + \psi_1 ECT_{t-1} + \varepsilon_{5t} \quad (6)$$

The difference operator is Δ, the constant term is α_{it}, and the error correction term is ECT, which is generated from the long run cointegrating links. The coefficients of the independent variables capture the short-term causal linkages. A typical Wald test is used to establish this. The error correction terms serve as the foundation for long-term causal linkages. To determine the significance of the speed of adjustment in ECT terms, the t-statistics is used. If the error correction term's coefficients are both negative and significant, there is evidence of a long-term causal relationship.

4. RESULTS

4.1. Unit Root Tests

Prior to examining the existence of a long-run relationship among the variables, it is essential to determine their order of integration by testing for stationarity. Table 2 reports the results of the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Dickey-Fuller Generalised Least Squares (DF-GLS) unit root tests. The outcomes of the ADF and PP tests indicate that the variables are non-stationary in levels but become stationary after first differencing. The DF-GLS test was also employed to enhance the robustness of the analysis, and its results are consistent with those obtained from the ADF and PP tests, confirming that the variables are non-stationary at levels but attain stationarity when differenced once.

4.2. Co-integration

The results of the Johansen cointegration analysis, based on both the Trace statistic and the Maximum Eigenvalue statistic, are reported in Table 3. These tests are employed to determine whether a long-run equilibrium relationship exists among the variables included in the model. The empirical findings indicate the presence of at least one cointegrating vector, suggesting that renewable energy consumption, financial development, capital formation, economic growth, and inflation move together in the long run in the context of South Africa. These findings are consistent with previous empirical studies. For instance, Zhe et al. (2021) report evidence of a long-run relationship between renewable energy consumption and macroeconomic variables in Turkey, while Wu and Broadstock (2015) identify similar cointegration relationships among energy consumption, economic growth, and financial development across 22 emerging market economies.

4.3. Granger Causality

The findings under co-integration proved that there is existence of long run relationship between renewable energy consumption, financial development, capital formation, inflation, and economic growth. This confirms that there is an existence of either a unidirectional and or bidirectional causality among the variables. Therefore, the next step is to determine the direction of causality among the variables. The results presented in Tables 4 and 5. Table 4 presents the findings for the long run causality while Table 5 illustrates the results for the short run causality.

The findings in Table 4 show the coefficient of the lagged error term, which is used to assess if there is long-term causation between the variables. The existence of a long run causality among the variables will be confirmed if the coefficient of the lagged error term is negative and significant.

4.3.1. Renewable energy consumption model

The analysis commences the long run causality with the renewable energy consumption being the dependent variable under the Credit extension model. The results report that the coefficient of the lagged error term (−7.111) is negative and significant at 1% level of significance. This implies that there is a unidirectional causality flowing from economic growth, inflation, capital formation and credit extension to renewable energy consumption.

The study continues to assess the existence of a long run causality when renewable energy consumption is the dependent variable using monetary aggregate (M3) as the proxy for financial development. The results confirmed a strong one-way causality running from monetary aggregate (M3), capital formation, inflation, and economic growth to renewable energy consumption. This is ascribed by the coefficient of the lagged error term (−7.189) is negative and significant at 1% level of significance. Finally, the existence of a long run causality was performed when renewable energy consumption is the dependent variable under the stock exchange transportation model. The coefficient of the lagged error term (−8.583) is found to be negative and significant at 1% level of significance. This implies that there is a unidirectional causality flowing from stock exchange transportation, capital formation, inflation, and economic growth to renewable energy

Table 2: Unit root tests

Variable	Levels			First difference		
	ADF	PP	DF-GLS	ADF	PP	DF-GLS
LRE	−0.5357	−0.6911	−0.2261	−4.0410*	−4.0145*	−2.1232**
LCRE	−1.8339	−2.4774	−0.2512	−2.7300**	−2.2.6930**	−2.7581*
LMS	2.1645	4.2750	0.6691	−3.5782**	−3.1254**	−2.5529**
LSET	−2.4360	−2.5388	−0.5823	−4.1054*	−4.0957*	−3.7176*
LK	−1.7811	−1.4776	−1.0218	−2.7674***	−2.7225***	−2.1937**
LCPI	−2.9811**	−2.5333	−1.7842***	−6.4660*	−7.4937*	−6.2485*
LGDP	−1.707	−0.9785	−1.7154***	−3.5228**	−3.1967**	−2.2529**

*,**,***represent 1%, 5% and 10% significance levels, respectively. Source: Own calculation

Table 3: Johansen cointegration test results

Trace test	0.05 critical value	Probability value	Cointegration number
160.1784	124.7970	0.0001	None*
107.1118	97.8166	0.0041	At most one*
41.3743	48.8421	0.2376	At most two
21.0134	29.4942	0.4372	At most three
Max-eigen test	**0.05 critical value**	**Probability value**	**Cointegration number**
54.2661	47.2341	0.0214	None*
41.2127	43.0775	0.0044	At most one*
25.1365	32.5843	0.1553	At most two
20.5415	27.8764	0.3622	At most three

Source: Own calculation

Table 4: VECM Granger-causality results

Dependent variable	Type of causality	
	Long run	
	Error correction term	Sign of ECT
Renewable energy consumption	7.111*	Negative
Credit extension	4.724**	Negative
Capital formation	1.405	Positive
Inflation	17.113	Positive
Economic growth	0.324**	Negative
Renewable energy consumption	7.189*	Negative
Monetary aggregate (M3)	5.238**	Negative
Capital formation	0.182	Negative
Inflation	7.485	Negative
Economic growth	0.161***	Negative
Renewable energy consumption	8.583*	Negative
Stock exchange transportation	9.267*	Negative
Capital formation	0.914	Negative
Inflation	14.803	Negative
Economic growth	0.145***	Negative

Source: Researcher's own calculation

Table 5: Vector error correction model (VECM)

Dependent variable	Type of causality				
	Short run				
	∑ΔLRE	∑ΔlCRE	∑ΔlK	∑ΔlCPI	∑ΔlGDP
ΔlRE	-	0.343*	0.465	0.370	0.967**
ΔLCRE	16.501*	-	2.107	7.59**	4.474
ΔlK	7.55**	6.011**	-	1.333	6.605**
ΔlCPI	3.081	3.21	4.029	-	1.554
ΔlGDP	3.022	0.161	2.161	0.096	-
	∑ΔLRE	∑ΔlMS	∑ΔlK	∑ΔlCPI	∑ΔlGDP
ΔlRE	-	12.420*	4.904	3.452	4.518**
ΔLMS	4.195	-	0.155	4.52	0.357
ΔlK	6.722**	7.343**	-	1.10	9.733*
ΔlCPI	1.090	8.803**	4.263	-	8.671**
ΔlGDP	4.753	1.66	1.279**	1.601	-
	∑ΔLRE	∑ΔlSET	∑ΔlK	∑ΔlCPI	∑ΔlGDP
ΔlRE	-	1.407	0.381	1.909	1.325
ΔLSET	15.516*	-	6.204**	32.373*	1.999
ΔlK	1.043	0.537	-	0.762	9.092**
ΔlCPI	2.146	2.555	6.599**	-	13.219*
ΔlGDP	2.233	0.518	3.295	0.078	-

Source: Researcher's own calculation

consumption in the long run. It has been realised that for all the proxies of financial development show that financial development Granger-causes renewable energy consumption in the long run. These results support the findings of Qamruzzaman and Jianguo (2020) and Wang et al. (2021).

The results for short run causality were also tested and the findings were illustrated in Table 5. This was executed by testing the null hypothesis that there is no short run causality flowing between renewable energy consumption and the other variables. The results rejected the null hypothesis that there is no short run causality flowing from credit extension and economic growth to renewable energy consumption. This implies that credit extension and economic growth Granger-cause renewable energy consumption in the short run. These findings are consistent with the findings of Eren et al. (2019) for India. The rest of the variables, the results failed to reject the null hypothesis which indicates that they do not Granger-cause renewable energy consumption in the short run. Under monetary aggregate (M3) model, the results rejected the null hypothesis that monetary aggregate (M3) and economic growth do not Granger-cause renewable energy consumption. The remaining variables were found not to Granger-cause renewable energy consumption. This is on account that the results failed to reject the null hypothesis that there is no short run causality flowing from inflation and capital formation to renewable energy consumption. Lastly, for the stock exchange transportation model, the results failed to reject the null hypothesis for all the variables which means that there is not short run causality flowing from stock exchange transportation, capital formation, inflation, and economic growth to renewable energy consumption.

4.3.2. Financial development model

Table 4 further reports the results where financial development (under different proxies) is taken as the dependent variable. The long run results depicts that the coefficients of the lagged error term (4.724 and 5.238) are negative and significant at 5% level of significance under monetary aggregate (M3) and Credit extension proxies, respectively. The results further showed that the coefficient of the lagged error term (9.267) is negative and significant at 5% level of significance under the stock exchange transportation model. The results posit that there is a unidirectional causality flowing from renewable energy consumption, capital formation, inflation, and economic growth to financial development (under all the proxies) in the long run. These finding are in line with the results found by Ari and Cergibozen (2018) for India.

Table 5 reported the short run causality where financial development (under different measures) is utilised as the dependent variable. The findings for the credit extension model reported that there is a short run causality flowing from renewable energy consumption to inflation to credit extension. This is on account that the results rejected the null hypothesis no short run causality flowing from renewable energy consumption and inflation to credit extension. These results confirm the findings of Ari and Cergibozen (2018) for India. The results further showed that capital and economic growth do not Granger-cause credit extension in the short run.

4.3.3. Inflation model

Furthermore, the results for the long run causality are illustrated in Table 4 when inflation is the dependent variable. Commencing with the credit extension model, the results show a positive and non-significant coefficient of the lagged error term. This implies that there is no causality found running from renewable energy consumption, credit extension, capital formation and economic growth to inflation. Under the Monetary aggregate (M3) model, the coefficients of the lagged error term is negative but not significant. The same findings were established under the stock exchange transportation model. It can be deduced from these findings that there is no causality flowing from renewable energy consumption, financial development (under all the different proxies), capital formation and economic growth to inflation in the long run.

When inflation is used as the dependent variable, the short run results failed to reject the null hypothesis of no causality flowing from all the variables to inflation under the credit extension model. Under the monetary aggregate (M3), the results rejected the null hypothesis of no short run causality flowing from credit extension and economic growth to inflation. This implies that credit extension and economic growth Granger-cause inflation in the short run. No short run causality was established for the other variables.

4.3.4. Capital formation model

Table 4 further shows the results where capital formation is used as the dependent variable under the different proxies of financial development. The results posited that there is no causality flowing from renewable energy consumption, financial development (under all the different proxies), inflation and economic growth to capital formation in the long run. This is on account that under the credit extension model, the coefficient of the lagged error term is positive and not significant while under the Monetary aggregate (M3) and Stock exchange transportation models, the coefficients of the lagged error term are negative but not significant.

The short run results when capital formation is used as the dependent variables detected a short run causality flowing from renewable energy consumption, credit extension and economic growth to capital formation under the credit extension model. This is on account that the results failed to reject the null hypothesis that renewable energy consumption, credit extension and economic growth Granger-cause capital formation in the short run. Similar results were established under the monetary aggregate (M3) model. Under the stock exchange transportation, the results established a short run causality flowing from economic growth to capital formation in the short run.

4.3.5. Economic growth model

Table 4 further presents the findings when economic growth is utilised as the dependent variable under the three different proxies of financial development. The findings under the credit extension posits that there is a one-way causality flowing from renewable energy consumption, credit extension, inflation, and capital formation to economic growth in the long run. This is depicted by the coefficient of the lagged error term (−0.324) is negative and significant at 5% level of significance. These results are consistent with the findings of Khobai and Le Roux (2018) for South Africa. There is also a weak causality found flowing from renewable energy) consumption, financial development (Monetary aggregate M3 and stock exchange transportation), inflation and capital formation to economic growth in the long run. This is supported by the fact that by the coefficients of the lagged error term (0.161 and 0.145) are negative and significant at 10% level of significance for Monetary aggregate (M3) model and stock exchange transportation model, respectively.

The results from Table 5 show that when economic growth is employed as the dependent variable, there is no short run causality flowing from renewable energy consumption, financial development, capital formation and inflation under both credit extension model and stock exchange transportation. These results are consistent with the results of Azeakpono and Lloyd (2020) for Nigeria. The short run results were only established under the monetary aggregate (M3) model where it was detected that capital formation Granger-causes economic growth.

5. CONCLUSION

This study examined the causal relationship between financial development and renewable energy consumption in South Africa using annual time-series data covering the period 1990-2024. The analysis incorporated economic growth, capital formation, and inflation as additional macroeconomic variables in order to capture broader economic dynamics influencing renewable energy consumption. By applying unit root tests, the Johansen cointegration approach, and a Vector Error Correction Model (VECM) with Granger causality tests, the study distinguished between long-run equilibrium relationships and short-run causal dynamics among the variables. The results confirmed that all variables are integrated of order one and that a stable long-run relationship exists among renewable energy consumption, financial development, economic growth, capital formation, and inflation in South Africa.

The long-run causality results reveal strong unidirectional causality running from financial development, economic growth, inflation, and capital formation to renewable energy consumption across all financial development proxies considered in the study. This finding suggests that improvements in financial sector depth and efficiency can play a crucial role in facilitating the expansion of renewable energy by mobilising capital, reducing financing constraints, and supporting investment in clean energy technologies. In addition, the results show that renewable energy consumption also contributes to financial development in the long run, indicating the presence of feedback mechanisms whereby the expansion of renewable energy projects stimulates financial market activity through increased investment opportunities and financial innovation.

The short-run results provide further insight into the dynamic interactions among the variables. Specifically, credit extension and economic growth were found to Granger-cause renewable energy consumption in the short run, highlighting the importance of access to finance and economic expansion in driving immediate changes in renewable energy demand. However, other variables such as inflation and capital formation were not found to exert significant short-run causal effects on renewable energy consumption, suggesting that their influence is more pronounced over longer adjustment periods.

Overall, the findings highlight the critical role of financial development in supporting South Africa's transition toward a more sustainable energy system. Strengthening financial institutions, improving access to credit, and deepening capital markets can facilitate the mobilisation of resources required for renewable energy investments. As South Africa seeks to reduce its dependence on fossil fuels and address persistent energy supply constraints, policies aimed at enhancing financial sector development and promoting investment in renewable energy technologies will be essential for achieving long-term energy security, economic growth, and environmental sustainability

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