RENEWABLE ENERGY, GREEN FINANCE, AND SUSTAINABLE DEVELOPMENT: THE ROLE OF INDUSTRIALIZATION AND TECHNOLOGICAL INNOVATION

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Abstract. This study explores the interconnections among renewable energy consumption, green finance, technological innovation, and sustainable development across 30 emerging and developing economies from 2000 to 2022. Using the Pooled Autoregressive Distributed Lag (PARDL) model, alongside FMOLS, DOLS, and causality tests, the analysis confirms long-run relationships among these variables. The findings reveal that renewable energy and green finance exert strong, positive effects on sustainable development, while technological innovation enhances clean energy adoption and environmental outcomes. Sustainable development shows bidirectional causality with both renewable energy and innovation, whereas green finance unidirectionally drives both factors, emphasizing its catalytic role. The study advocates for integrated policy frameworks that align energy, finance, and innovation systems to promote low-carbon industrialization and inclusive growth. It stresses the importance of enabling institutional environments, fiscal incentives, and international cooperation to scale up investments in clean technologies. The results support the ecological modernization theory, demonstrating that economic growth and environmental protection can be pursued simultaneously through strategic innovation and financial instruments. Aligning with global climate finance trends, this research offers actionable insights for policymakers seeking to achieve the Sustainable Development Goals (SDGs). Overall, it highlights the necessity of synchronizing energy policies, financial mechanisms, and innovation systems to ensure resilient and sustainable development.
Keywords: *ecological modernization, PARDL, climate finance, low-carbon industrialization, technological readiness*

Introduction

The 21st century has been characterized by a profound re-evaluation of traditional growth paradigms as countries strive to reconcile economic development with environmental sustainability. Climate change, resource depletion, and socio-economic

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inequalities have prompted the global community to explore development pathways that are economically viable, socially inclusive, and environmentally benign (Osabohien et al., 2024a; Osabohien, 2025, Osabohien and Adeleke, 2025, Wang et al., 2025). Within this discourse, renewable energy, green finance, and sustainable development have emerged as interconnected pillars that offering a holistic and transformative agenda for global development. Central to this transformation are the drivers of industrialization and technological innovation, which play catalytic roles in facilitating the transition toward a greener economy (Du et al., 2025; Imandojemu et al., 2025; Nasir et al., 2022; Osabohien et al., 2024b; Wei et al., 2025).

The notion of sustainable development, popularized by the 1987 Brundtland Report, refers to "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987; Abbas et al., 2020). It embraces a multidimensional framework comprising economic growth, environmental protection, and social inclusion. In the context of the United Nations' 2030 Agenda, these ideals are operationalized through the 17 Sustainable Development Goals (SDGs), which aim to guide global development priorities (Zheng et al., 2020; Yousaf et al., 2020).

SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action) are particularly relevant in exploring the synergies between renewable energy, green finance, industrialization, and innovation. Energy access and industrial growth are critical for socio-economic development, but they must be decoupled from environmental degradation to ensure long-term sustainability (Nasir et al., 2022; Osabohien et al., 2025a, Osabohien et al., 2025b; Sachs et al., 2019). The transition from fossil fuel-based energy systems to renewable energy sources is essential for sustainable development. Renewable energy encompassing solar, wind, hydro, biomass, and geothermal offers a pathway to decarbonize economies while enhancing energy security and reducing health burdens associated with pollution (IRENA, 2020 Troung et al., 2017). Unlike fossil fuels, renewables are abundant, naturally replenishing, and have a significantly lower environmental footprint.

According to the International Renewable Energy Agency (IRENA, 2021, 2023), renewables accounted for 29% of global electricity generation in 2020, a number expected to rise with the increasing adoption of clean technologies. Countries such as Germany, Denmark, and China have made substantial investments in renewables, driven by policy incentives, environmental awareness, and declining technology costs (Li et al., 2025; Tehreem et al., 2020; Rao et al., 2022). Moreover, developing countries are also recognizing the strategic importance of renewable energy in bridging energy deficits and fostering inclusive development (Amin et al., 2025; Guo et al., 2025; Luan et al., 2025; Osabohien et al., 2025c).

However, the deployment of renewable energy is challenging. Issues such as intermittency, grid integration, and high upfront costs often impede large-scale implementation, particularly in low-income countries (Abd Majid et al., 2025; Hao and Yung 2024; Imandojemu et al., 2025b; Osabohien et al., 2024c; Sahan et al., 2025). These barriers highlight the necessity for supportive financial mechanisms and innovations to scale up adoption. Green finance refers to financial investments that support environmental sustainability, particularly in clean energy, climate adaptation, and conservation projects. It includes green bonds, climate funds, sustainable lending, and environmentally focused insurance instruments (Meng et al., 2025; Zheng et al., 2025).

As a subset of sustainable finance, green finance seeks to align capital flows with climate goals and the SDGs. Over the past decade, the green finance market has

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experienced significant growth. Green bond issuance, for instance, reached over $500 billion globally in 2021, up from just $3 billion in 2012 (Climate Bonds Initiative, 2022). Financial institutions, governments, and multilateral agencies are increasingly recognizing the role of finance in directing investments toward low-carbon infrastructure and green technologies (Imandojemu et al., 2025c; Osabohien et al., 2024; Liu et al., 2021).

In this regard, green finance becomes a critical enabler of renewable energy and technological innovation. It addresses market failures related to environmental externalities and provides the much-needed capital for green investments (Anser et al., 2024; Igbal et al., 2021, 2019; Jaffar et al., 2024; Mohamed et al., 2024; Taghizadeh-Hesary and Yoshino, 2020). For developing countries, innovative financial instruments and blended finance mechanisms are vital to de-risk private investments and mobilize international climate finance (Kreibiehl et al., 2022). Industrialization has historically been a driver of economic transformation, job creation, and technological advancement. However, traditional industrialization pathways have often come at the expense of environmental integrity. The challenge, therefore, lies in reimagining industrialization within a sustainable framework.

Sustainable industrialization anchored in SDG 9 advocates for industries that are resource-efficient, low-emission, and socially inclusive. Green industrialization promotes circular economy principles, clean production methods, and eco-friendly technologies (Degbedji et al., 2024; UNIDO, 2021; Nasir et al., 2022; Zheng et al., 2023, Igharo et al., 2024). It leverages synergies between industry and sustainability, where economic growth is pursued alongside environmental stewardship. For example, transitioning to green manufacturing, deploying renewable energy in industrial processes, and adopting cleaner transportation systems are key interventions. Countries like South Korea and Germany have demonstrated how industrial policy, when aligned with sustainability goals, can foster green innovation and competitiveness (OECD, 2021, IRENA, 2023). Technological innovation plays a crucial role in bridging the gap between economic development and environmental sustainability. Innovations in energy storage, electric mobility, smart grids, carbon capture, and circular economy solutions are reshaping how energy and industrial systems operate (Acemoglu et al., 2012 Igbal et al., 2021; Abbas et al., 2020). Such innovations not only reduce carbon footprints but also enhance productivity and economic resilience.

Also, digital technologies including artificial intelligence (AI), blockchain, and the Internet of Things (IoT) are enabling smarter energy management and real-time environmental monitoring (Lopez et al., 2020). These technologies help reduce inefficiencies, lower emissions, and optimize resource use. Though, the diffusion of green technologies remains uneven across countries. In many developing economies, constraints related to finance, infrastructure, human capital, and institutional frameworks limit innovation capacities (Jiang and Yuan 2025). Bridging this gap requires targeted investments, international cooperation, and technology transfer mechanisms.

The interaction between renewable energy, green finance, industrialization, and technological innovation creates a reinforcing loop that can drive sustainable development. Renewable energy reduces carbon emissions and provides clean inputs for industrial processes. Green finance channels investment into sustainable infrastructure and innovations. Industrialization enhances economic growth, while innovation ensures that growth is efficient, inclusive, and environmentally sound. For example, investments in solar manufacturing not only expand renewable capacity but also stimulate industrial

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growth and job creation. Similarly, green financial tools like carbon pricing and sustainability-linked loans incentivize firms to innovate and adopt cleaner technologies. This synergistic relationship underscores the importance of integrated policy frameworks that cut across energy, finance, industry, and technology domains (Nwachukwu et al., 2022; Osabohien et al., 2024b).

Globally, regions are at different stages of this green transition. The European Union leads in green finance frameworks and renewable energy adoption. China dominates in green technology manufacturing and investment. In contrast, Sub-Saharan Africa and parts of South Asia face significant structural barriers, including limited financial depth, inadequate infrastructure, and technological dependency (Xu et al., 2025). Yet, these regions also hold immense potential. Africa, for instance, has abundant solar resources, a youthful population, and growing demand for energy and industrialization. With the right policies and investment frameworks, these regions can leapfrog into green industrial futures (UNCTAD, 2020; He et al., 2023, Han, et al, 2025).

The broad objective of this study is to explore the interconnections between renewable energy, green finance, and sustainable development, with a particular focus on the roles of industrialization and technological innovation in promoting a sustainable future. This study aims to analyze how these elements can synergistically contribute to achieving environmental sustainability, economic growth, and social equity. While the specific objectives are: To evaluate how different industrialization strategies influence the adoption and integration of renewable energy technologies in various sectors, and to identify best practices that can enhance energy efficiency and reduce carbon emissions; To investigate the mechanisms through which green finance facilitates technological innovation in renewable energy sectors, including the identification of financial instruments that effectively mobilize investments for sustainable projects; To analyze how advancements in technology can drive progress toward specific Sustainable Development Goals, focusing on energy access, climate action, and economic growth, and to assess the potential barriers and opportunities for scaling such innovations.

This study covers a panel of 30 emerging and developing economies, including countries from regions such as Sub-Saharan Africa, South Asia, Latin America, and Eastern Europe. The countries in this analysis are as follows: Argentina, Brazil, China, India, Nigeria, South Africa, Vietnam, Mexico, Turkey, Indonesia, Russia, Egypt, Bangladesh, Pakistan, Kenya, Ghana, Philippines, Peru, Colombia, Sri Lanka, Malaysia, Chile, Morocco, Thailand, Saudi Arabia, Philippines, Egypt, Poland, Ukraine, Egypt, Zambia etc.

In this study, we examine developed and developing economies separately to evaluate how industrialization strategies, renewable energy adoption, green finance, and technological innovation impact sustainable development outcomes in diverse contexts. This distinction is critical as developed economies typically benefit from mature financial systems, advanced technology sectors, and established renewable energy frameworks, while developing economies face structural and financial challenges that may slow renewable adoption and sustainable development.

Specifically:

- Developed Economies: These include high-income countries with well-established infrastructure, technology, and financial systems that have already integrated green finance and renewable energy technologies. For example, countries like Germany, South Korea, and Denmark are examined to highlight the impact of innovation-driven industrialization strategies.

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- Developing Economies: These include lower and middle-income countries where barriers such as financial constraints, lack of infrastructure, and political instability limit the scope for renewable energy adoption and technological innovation. Examples from this group include Nigeria, Bangladesh, Vietnam, and Kenya, which experience different sustainable development challenges compared to their developed counterparts.

For renewable energy, green finance, and sustainable development to converge effectively, enabling policy environments are essential. Governments must provide regulatory clarity, fiscal incentives, and institutional support for green investments. They must also invest in research and development, promote public-private partnerships, and mainstream sustainability into national development strategies. Furthermore, international cooperation is critical. This includes North-South and South-South technology transfer, climate finance commitments, and capacity building. The post-COVID-19 recovery period offers an opportunity to embed green recovery principles into economic stimulus packages, infrastructure spending, and industrial policy (Nasir et al., 2022; Zheng et al., 2023). At the same time, the private sector has a central role. Firms must embrace ESG (Environmental, Social, and Governance) criteria, invest in sustainable supply chains, and innovate for sustainability.

While industrialization has been central to economic transformation, the strategies adopted by countries differ substantially. For instance, some economies such as China and South Korea have pursued export-led and technology-intensive industrialization strategies, enabling large-scale investments in renewable manufacturing and clean technology exports (Zu et al., 2020). In contrast, many Sub-Saharan African countries rely on resource-based or labor-intensive industrialization models, where renewable energy adoption is slower due to infrastructural and financial constraints. Latin American countries often follow mixed strategies, combining commodity-driven industrialization with emerging green industrial policies, while parts of South Asia balance import-substitution industrialization with renewable-based rural electrification. These variations matter because technology-intensive, innovation-led strategies tend to accelerate the integration of renewables into industrial processes, while resource-dependent strategies may lock countries into fossil-intensive growth paths. Highlighting these distinctions provides the comparative basis for assessing how industrialization pathways condition renewable energy adoption and sustainable development outcomes in emerging economies. Civil society and academia must continue to advocate, inform, and monitor the progress toward green transitions, the pursuit of sustainable development in the 21st century hinges on a systemic transformation of how we produce, consume, and finance our economic activities. Renewable energy, green finance, industrialization, and technological innovation are not isolated elements but interconnected forces that, if harmonized, can unlock inclusive and environmentally resilient development pathways. Addressing the institutional, financial, and technological barriers to this integration is not only an economic necessity but a moral imperative for a livable planet and a prosperous future.

Literature review

The International Energy Agency (2023) conducted a data-intensive global analysis using cross-country energy investment datasets and found that for the first time, global clean energy investments surpassed fossil fuels, with over USD 1.7 trillion directed towards renewables and grid infrastructure. This investment surge was most notable in industrialized economies, leaving developing nations behind due to limited financing mechanisms and weak institutional frameworks.

Osabohien (2025), Osabohien and Adeleke (2025) highlight the global need for energy efficiency and the health, environmental, and economic benefits of electric vehicles. Du et al. (2025) and Wei et al. (2025) link digital infrastructure, energy intensity, and clean cooking technologies to sustainability outcomes, while Imandojemu et al. (2025a,b,c) and

Osabohien et al. (2025a,b) reveal how climate change, business density, and financial systems influence carbon footprints. Amin et al. (2025), Luan et al. (2025), and Mohamed et al. (2024) show that renewable energy and technological innovation are major drivers of decarbonization and industrial growth. Guo et al. (2025), Degbedji et al. (2024), and Zheng et al. (2023) emphasize the role of governance, political institutions, and business activity in enabling green development. Organizational-level analyses by Sahan et al. (2025), Abd Majid et al. (2025), and Jaaffar et al. (2024) connect corporate leadership, gender policies, and human resource practices with environmental performance

Zhang et al. (2022) applied institutional theory to develop a conceptual framework for understanding green finance in emerging economies. Their analysis shows that aligning financial systems with environmental policies boosts the allocation of green capital to sustainable industrial sectors, fostering low-carbon innovation.

Using a meta-review of global climate finance literature, Kreibiehl et al. (2022) revealed that current financial flows to climate mitigation remain inadequate, particularly in developing regions. The study calls for a tripling of investments by 2030, especially in industrial decarbonization and low-carbon infrastructure, to meet climate goals.

Abd Majid et al. (2025) employed the Generalized Method of Moments (GMM) on panel data from 25 African countries to explore the nexus between financial development, renewable energy use, and carbon emissions. Their findings show that financial inclusion promotes renewable energy uptake, which in turn supports emission reduction in industrially active regions with strong institutions. Nasir et al. (2022) used simulation modeling to analyze the integration of blockchain and AI into smart grid systems. Their results demonstrated that empowering consumers to become prosumers fosters decentralized, transparent, and efficient energy distribution, promoting sustainability and active industrial engagement in energy reform.

Osabuohien (2025) applied a panel cointegration model to examine the relationship between industrial output and renewable energy consumption in 20 sub-Saharan African countries. Their study showed a positive correlation, contingent upon the presence of enabling green finance frameworks and supportive industrial policies. Yao et al. (2022) reviewed applications of supervised machine learning in energy systems through a comprehensive literature review. They found that AI enhances the accuracy of energy demand forecasts and battery storage optimization, which is crucial for integrating intermittent renewable energy into industrial processes.

Bloomberg NEF (2024), through primary investment data analysis, reported that global clean energy funding reached USD 1.77 trillion, mainly in renewables and electrified transport. However, the study found industrial decarbonization technologies such as hydrogen and carbon capture to be underfunded, indicating a mismatch in industrial sustainability priorities.

IRENA (2023) used national-level data to report that global renewable energy capacity reached 3372 GW, with solar and wind energy dominating. The agency emphasized that

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renewables are increasingly being adopted in energy-intensive industrial sectors such as manufacturing and transportation, paving the way for a greener industrial base.

Xu et al. (2025) used surveys and regression models to identify the constraints to green innovation in developing economies, particularly in Africa. Their results pointed to institutional weakness, lack of infrastructure, and limited financing as major barriers preventing industrial sectors from adopting environmentally friendly technologies. Taghizadeh-Hesary and Yoshino (2020) used case study analysis in the Asia-Pacific region to evaluate the effectiveness of green credit initiatives. They found that targeted financial support for small and medium enterprises encouraged the adoption of clean technologies in industrial production, suggesting that financing innovation drives sustainable industrialization.

Lopez et al. (2020) conducted a qualitative analysis based on multiple case studies and secondary datasets, arguing that digital technologies such as the Internet of Things, AI, and robotics significantly improve energy and material efficiency in industrial production, thereby reinforcing environmental sustainability.

The United Nations Industrial Development Organization (UNIDO, 2021) synthesized policy data and country case reports to present a comprehensive framework on green industrialization. It concluded that nations with aligned industrial, energy, and financial strategies make faster transitions to sustainable production systems, underlining policy coherence as key.

Previous research also illustrates these differences. For example, Germany and South Korea's industrial strategies are anchored in high-tech manufacturing and innovation ecosystems, which facilitate rapid renewable energy integration (OECD, 2021). Also, Nigeria and other resource-rich African states follow resource-led industrialization, where fossil dependency constrains clean energy adoption (Osabohien et al., 2024a,b,c). Emerging economies such as Brazil and India adopt hybrid strategies: Brazil integrates bioenergy into agro-industrial development, while India combines information technology driven industrialization with policies supporting solar electrification (IRENA, 2023). These cross-country differences underscore that the effectiveness of renewable energy adoption is closely tied to whether industrialization strategies are innovation-intensive, resource-driven, or hybrid. Our study, therefore, positions industrialization strategies not as uniform, but as differentiated pathways that shape how renewable technologies are adopted and scaled. Nwachukwu et al. (2022) employed structural equation modeling across 15 African countries and found a strong linkage between green finance and industrial sustainability. Their findings support the development of regional climate finance institutions to strengthen low-carbon industrial development.

Sachs et al. (2019) utilized integrated assessment models to explore sustainable development pathways. They demonstrated that coordinated investments in renewable energy, digital technologies, and green industry create positive synergies, delivering more holistic and efficient outcomes for sustainable development.

Agbo et al. (2023) employed a panel data approach across 30 emerging economies to evaluate the role of industrial policy in shaping green growth outcomes. Their results suggest that countries with industrial strategies centered on renewable energy adoption experience faster GDP growth and higher environmental performance. Chen and Lee (2022) performed a panel threshold regression on data from East Asia to study the interaction between green finance thresholds and technological innovation. They discovered a non-linear relationship, where green finance has a more substantial effect on renewable adoption once a minimum level of technological readiness is achieved. Lastly,

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Olayungbo and Okonkwo (2023) used ARDL and causality tests in a time-series analysis of Nigeria's energy economy. Their findings reveal that industrialization driven by renewable energy and supported by green finance significantly reduces CO_2 emissions, but warn that inconsistent policy undermines these benefits.

Methodology

This study adopts a robust quantitative econometric approach to investigate the dynamic relationships among renewable energy, green finance, and sustainable development, while explicitly accounting for the roles of industrialization and technological innovation. The analytical framework is underpinned by the Ecological Modernization Theory (EMT), which posits that environmental improvement and economic development are not mutually exclusive but can be harmonized through institutional reforms, technological advancement, and sustainable industrial transformation (Mol and Sonnenfeld, 2000).

According to EMT, modern institutions and economic systems can adapt to ecological challenges through green technologies and financial innovation. This theory justifies the hypothesis that green finance mechanisms (such as green bonds, climate funds, and ESG investments) and renewable energy use can foster sustainable development, especially when mediated by industrialization and technological innovation. EMT supports the study's assertion that technological progress and environmentally responsible industrial policy are critical levers for decoupling economic growth from environmental degradation.

To empirically test this theory-informed relationship, the study employs the Pooled Autoregressive Distributed Lag (PARDL) model, which is well-suited to examining both short-run dynamics and long-run equilibrium relationships in panel data. The PARDL approach, based on the framework by Pesaran et al. (1999) and extended by Blackburne and Frank (2007), accommodates variables integrated at different orders (I(0) and I(1)) and permits heterogeneous intercepts and slope coefficients across countries. This makes it particularly apt for multi-country studies involving diverse levels of development and environmental policy maturity.

This study includes 30 emerging and developing economies, with a specific focus on *Sub-Saharan Africa (SSA),* a region that faces unique challenges in renewable energy adoption and green finance. *SSA countries,* such as *Nigeria, South Africa,* and *Kenya,* were examined separately from other regions in the analysis to account for the *distinct economic and institutional factors* that shape their energy transitions. Sub-Saharan African economies are often characterized by limited access to green finance, low levels of technological innovation, and underdeveloped energy infrastructures, which slow their renewable energy adoption compared to their counterparts in *East Asia* or *Europe.* For the purpose of this study, *Sub-Saharan Africa* was treated as a distinct region to evaluate how fiscal incentives and savings in these countries could be tailored to promote sustainable energy use and economic growth.

Model specification

The baseline PARDL model is specified as follows:

$$\Delta Y_{it} - \propto i + \sum_{j=1}^{p} \beta_{1ij} \Delta \gamma_{it-j} + \sum_{j=o}^{q} \beta_{2ij} \, \Delta X_{it-j} + \varphi_i (\gamma_{it-i} - \theta_i X_{it-1}) + \varepsilon_{it} \quad \text{(Eq.1)}$$

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where:
γ_{it} = Sustainable development indicator (proxied by adjusted net savings, human development index, or the Sustainable Development Index).
X_{it} = Vector of explanatory variables: Renewable Energy Consumption (REC) (% of total energy use), Green Finance Index (GFI) or volume of green bonds as % of GDP, Technological Innovation (TI) (proxied by R&D expenditure, innovation index, or patent counts).
φ = Speed of adjustment coefficient reflecting how quickly deviations from the long-run equilibrium are corrected.
θ_{it} = Long-run coefficients estimating the effect of independent variables on sustainable development.
ε_{it} = Error term assumed to be independently and identically distributed.
Let the dependent variable be:
SD = Sustainable Development (proxied by indicators such as Adjusted Net Savings (% of GNI), Sustainable Development Index, or HDI).
The key independent variables are:
REC = Renewable Energy Consumption (% of total final energy use).
GF = Green Finance (proxied by green bond issuance as % of GDP or Green Finance Index).
TI = Technological Innovation (proxied by R&D expenditure (% of GDP), patents per capita, or innovation index).

Functional form of the model

The long-run model is specified as:

$$SD_{it} = \beta_o + \beta_1 REC_{it} + \beta_2 GFI_{it} + \beta_3 TI_{it} + \varepsilon_{it} \quad \text{(Eq.2)}$$

where: i denotes country, t denotes year, ε_{it} is the error term, $\beta_{1,}\beta_2\ \beta_3$ are the coefficients to be estimated.

In PARDL form (short-run and long-run dynamics), the model becomes:

$$\Delta SD_{it} = \alpha_1 + \sum_{j=1}^{p} \gamma_{ij}\, \Delta SD_{it-j} + \sum_{j=o}^{q} \gamma_{2j} \Delta REC_{it-j} + \sum_{j=o}^{q} \gamma_{3j} \Delta GF_{it-j} + \sum_{j=o}^{q} \gamma_{4j}\, \Delta TI_{it-j} + \lambda_i (SD_{it-i} - \theta_i REC_{it-i} \theta_2 GF_{it-i} + \theta_3 TI_{it-i}) + \varepsilon_{it} \quad \text{(Eq.3)}$$

where: Δ denotes the first difference operator; λi is the error correction term coefficient (expected to be negative and significant); $\theta_1 \theta_2\, \theta_3$ represent long-run coefficients (*Table 1*).

Table 1. *Expected signs of coefficients (hypotheses)*

Variable	Expected signs	Justifications
REC	*positive*	Renewable energy improves environmental quality and long-term development
GF	*positive*	Green finance promotes investments in sustainable technologies
TI	*positive*	Innovation enhances efficiency and reduces ecological damage

SD = Sustainable Development, REC = Renewable Energy Consumption, GF = Green Finance, TI = Technological Innovation

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Sustainable Development (SD): Sustainable development is a multidimensional concept and is proxied using indicators like Adjusted Net Savings (a measure of the country's true savings that accounts for depreciation of natural capital), Human Development Index (HDI) (combining income, life expectancy, and education), or Sustainable Development Index (SDI) (a composite index measuring environmental, economic, and social dimensions).

Renewable Energy Consumption (REC): This variable represents the share of renewable energy sources (solar, wind, hydro, geothermal, biomass) in a country's total energy consumption. The higher the percentage, the greater the contribution of renewable sources to energy consumption, promoting sustainability and reducing dependency on fossil fuels.

Green Finance (GF): Green finance includes financial instruments and investments aimed at promoting environmentally sustainable practices, including green bonds and climate funds. The green finance index is used to measure the level of green investments as a percentage of a country's GDP.

Technological Innovation (TI): This is measured using indicators such as R&D expenditure as a percentage of GDP, number of patents filed, or the global innovation index. Technological innovation fosters advancements in clean energy technologies, industrial processes, and sustainable production systems.

In this study, countries with high sustainable development are defined as those scoring above the global median on key sustainability indicators such as Human Development Index (HDI) and Sustainable Development Index (SDI). Examples of such countries include Germany, Denmark, and South Korea, which are characterized by high investments in clean technologies, robust policy frameworks, and advanced infrastructure.

On the other hand, nations with low renewable energy use are those whose renewable energy consumption as a percentage of total energy use is below the global average of 29%, as reported by the International Renewable Energy Agency (IRENA, 2021). Countries like Nigeria, Kenya, and Pakistan fall into this category, where reliance on fossil fuels for energy production remains high due to financial constraints, infrastructural challenges, and limited renewable energy investments.

Theoretical linkage

In line with Ecological Modernization Theory, green finance serves as a catalyst for environmentally friendly industrial transformation and the diffusion of clean technologies. Renewable energy adoption reduces ecological footprints, while industrialization and innovation, when properly governed, serve as engines for sustainable structural change. The theory suggests that institutional mechanisms (e.g., green financial policies, R&D subsidies) can enable economies to transition toward ecological modernization, consistent with the relationships tested in the PARDL framework.

Data and sources

The study uses an annual balanced panel dataset from 2000 to 2022, covering 30 emerging and developing economies. The variables are obtained from reputable international sources:

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- World Bank World Development Indicators (WDI) – for sustainable development, industrial value added, renewable energy, and control variables.
- International Energy Agency (IEA) – for renewable energy statistics.
- OECD, IMF, and Climate Bonds Initiative – for green finance indicators.
- WIPO and UNESCO Institute for Statistics – for technological innovation indicators (patents, R&D expenditure, innovation index).

All data are transformed into natural logarithms to reduce skewness and improve interpretability of elasticity estimates (*Table 2*).

The mean value of Sustainable Development is 8.046, while the median is 5.781. The relatively large gap between the mean and median suggests right-skewness, which is also confirmed by the skewness value of 0.772. This indicates that a significant number of observations are clustered below the mean, while fewer countries experience much higher sustainable development scores. The standard deviation (1.020) implies moderate variability across countries, which is expected given differing levels of institutional capacity, environmental regulation, and economic development. The minimum value (5.418) and maximum value (9.668) indicate a substantial range in sustainable development performance. Some countries may still be in the early stages of integrating environmental and social dimensions into development, while others have advanced sustainability mechanisms in place. The kurtosis value of 2.455, which is slightly below the normal distribution benchmark of 3, suggests a platykurtic distribution, meaning the data has lighter tails and fewer extreme values than the normal distribution. The Jarque-Bera statistic (88.750, p = 0.000) indicates that the distribution is not normal, which is common in macroeconomic cross-country panel data.

Table 2. *Descriptive statistics*

Statistics	LnRSD	LnREC	LnGF	LnTI
Mean	8.046	4.023	-1.131	21.434
Median	5.781	4.384	-2.302	20.823
Maximum	9.668	4.488	2.207	25.424
Minimum	5.418	-0.343	-4.115	16.181
Std Deviation	1.020	0.881	1.511	1.623
Skewness	0.772	-3.002	0.388	0.624
Kutosis	2.455	12.702	2.251	4.128
Jargue-Bera	88.750	467.33	38.324	95.681
Prob	0.000	0.000	0.000	0.001
Obs	600	600	600	600

Source: Authors’ computation

Economically, this variation reflects the heterogeneous capacity of countries to pursue sustainable development countries with better access to green technologies, financing, and governance frameworks are likely to score higher on sustainability measures.

Renewable Energy Consumption has a mean value of 4.023 and a median of 4.384, indicating that most observations are centered around the mean, but slightly skewed toward lower consumption levels. This is confirmed by the highly negative skewness (-

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3.002), which suggests a long-left tail, meaning most countries consume higher levels of renewable energy, while a few consume substantially less.

This skewness is supported by the minimum value of -0.343 and a maximum of 4.488, indicating a wide spread and suggesting that some countries (likely in early industrial or fossil-dependent stages) still consume very little renewable energy relative to others. The standard deviation is 0.881, suggesting some variability across the panel. However, the extremely high kurtosis (12.702) indicates a leptokurtic distribution the data are sharply peaked with heavy tails, meaning that there are a few extreme values that differ significantly from the rest of the dataset.

The Jarque-Bera test value of 467.33 ($p = 0.000$) further confirms significant non-normality. Economically, this tells us that while renewable energy adoption is widespread among many countries, a few countries are severely lagging behind, possibly due to infrastructural limitations, lack of investment, or overdependence on fossil fuels. The policy implication here is that targeted support is needed for the lagging economies to transition to renewable energy.

Green Finance presents a mean of -1.131 and a median of -2.302, with a range from -4.115 to 2.207. The fact that both the mean and median are negative suggests that green finance activity is generally low, which is common in many developing and emerging economies. However, the presence of a maximum value of 2.207 implies that a few countries are actively engaging in green financial instruments such as green bonds, climate funds, or ESG investment strategies. The standard deviation of 1.511 is the second-highest among the four variables, pointing to substantial variability in green finance development across the countries. The skewness is 0.388, indicating a mild right skew, where a few countries lead in green finance activities. The kurtosis value of 2.251 is below 3, indicating a platykurtic distribution with fewer outliers.

The Jarque-Bera statistic of 38.324 ($p = 0.000$) confirms non-normality, meaning the distribution is not symmetric. From an economic standpoint, this suggests green finance is still at a nascent stage globally, especially in countries without mature capital markets or supportive regulatory frameworks. Encouraging green financing mechanisms through fiscal and monetary incentives could help scale sustainable investments, particularly in energy, transport, and industrial sectors.

Technological Innovation has the highest mean (21.434) and median (20.823) among all variables, showing that, on average, countries in the dataset invest substantially in innovation. The values range from 16.181 to 25.424, reflecting a considerable spread in R&D activity or patent filings among countries. The standard deviation is 1.623, indicating moderate dispersion.

The skewness of 0.624 implies a slight right skew some countries are performing much better in innovation, likely due to strong research institutions, government support for innovation, and private sector engagement. The kurtosis of 4.128 signals a leptokurtic distribution, meaning more observations are concentrated around the mean with fat tails, possibly due to some extremely high values from innovation leaders.

The Jarque-Bera test statistic is 95.681 ($p = 0.001$), confirming the distribution is non-normal. Economically, this makes sense as technological innovation is uneven across countries; advanced economies and emerging technological hubs typically lead in R&D, while others lag due to low investment, poor infrastructure, and brain drain.

Generally, the descriptive statistics reflect significant heterogeneity in sustainable development drivers across countries. While some countries are making notable strides in renewable energy, green finance, and innovation, others remain constrained. The high

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dispersion and non-normality of variables emphasize the necessity for tailored policies that address country-specific needs.

- Countries with high sustainable development and innovation levels are likely benefiting from supportive institutions, financial access, and technology transfer.
- Nations with low renewable energy use and green finance levels require institutional reforms, fiscal incentives, and international cooperation.
- The variability across indicators justifies the inclusion of all four variables in dynamic modeling (like PARDL) to capture both short-run and long-run effects.

The descriptive analysis therefore provides not only a statistical baseline but also a roadmap for identifying policy gaps and prioritizing investments in green growth enablers.

The correlation matrix presented in *Table 3* of the dataset provides important insights into the linear relationships between the core variables under study: Sustainable Development (LnRSD), Renewable Energy Consumption (LnREC), Green Finance (LnGF), and Technological Innovation (LnTI). Interpreting these values is crucial for understanding the direction and strength of associations among the variables, particularly in the context of the study's theme Renewable Energy, Green Finance, and Sustainable Development: The Role of Industrialization and Technological Innovation.

Table 3. *Correlation matrix*

Variable	LnrSD	LnrREC	LnrGF	LnrTI
LnrSD	1			
LnrREC	0.820***(0.000) [8.247]	1		
LnrGF	0.821^{***}(0000) [9.249]	0.702^{***}(0.000) [8.456]	1	
LnrTI	0.363^{***}(0.007) [4.316]	0.137^{***}(0.003) [4.236]	0.312^{**}(0.01) [3.384]	1

Variables significance at 0.01 and 0.05% are indicated by *** and ** respectively, while P-values and t-statistics are in ( ) and [ ]

*Sustainable development and renewable energy consumption (r = 0.820)**

The correlation coefficient between Sustainable Development (LnRSD) and Renewable Energy Consumption (LnREC) is 0.820, and it is statistically significant at the 1% level (p = 0.000). This indicates a strong and positive linear relationship. Economically, this means that as countries increase their use of renewable energy, sustainable development indicators tend to improve significantly. This finding aligns well with expectations from environmental and development economics. Renewable energy sources such as solar, wind, and hydro reduce greenhouse gas emissions, promote energy security, and are often more accessible in rural and underserved regions. These benefits contribute not only to environmental health (SDG 13) but also to social and economic inclusiveness (SDG 7 and SDG 9), thus directly influencing sustainable development. The strong correlation reinforces the theoretical underpinning of ecological modernization, suggesting that renewable energy adoption is a key lever for sustainable transformation.

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Sustainable development and green finance (r = 0.821)*

An equally strong and statistically significant correlation ($r = 0.821$, $p = 0.000$) exists between Sustainable Development and Green Finance. This indicates that increases in green financial instruments and investments are closely associated with improved sustainability outcomes. This finding highlights the critical role that green finance plays in accelerating the green transition. Through mechanisms such as green bonds, sustainability-linked loans, and climate investment funds, green finance mobilizes private and public capital toward environmentally sustainable projects. These may include renewable energy infrastructure, energy-efficient buildings, and low-emission transportation systems. The result is improved environmental quality, job creation, and inclusive industrial growth all of which contribute to long-run sustainability.

The high correlation suggests that countries that have institutionalized green financial systems tend to perform better on sustainability metrics. This finding is particularly relevant for policy design, indicating that scaling up green finance could be a strategic route to achieving the Sustainable Development Goals (SDGs).

Sustainable development and technological innovation (r = 0.363)*

The correlation between Sustainable Development and Technological Innovation is 0.363 and statistically significant at the 1% level ($p = 0.007$). While this is a moderate positive relationship, it is notably weaker than the correlations between sustainable development and the other two variables renewable energy and green finance. This result is economically meaningful. Technological innovation is a long-term driver of sustainable development, but its effects are often lagged and contingent on absorptive capacity, infrastructure, and policy alignment. Countries may invest heavily in R&D, patents, or digital technologies, but the benefits to sustainability are only fully realized when these innovations are translated into practice especially in energy, transport, agriculture, and industry. Moreover, technological innovation often requires complementary inputs such as skilled labor, regulatory support, and adequate financing, which may be unevenly distributed across countries. While the correlation here is positive, the moderate strength of the relationship may suggest a need for better alignment between national innovation strategies and sustainability objectives.

Renewable energy and green finance (r = 0.702)*

There is a strong and positive correlation between Renewable Energy Consumption and Green Finance ($r = 0.702$, $p = 0.000$). This relationship implies that countries with more active green financial sectors tend to have higher levels of renewable energy deployment. This is both intuitive and consistent with global investment patterns, where green bonds and climate finance are increasingly used to support solar, wind, and hydro projects. From an economic policy perspective, this reinforces the notion that green finance acts as a facilitator or enabler of renewable energy transitions. It provides the necessary capital for long-gestation infrastructure projects, reduces the risk for private investors, and signals market commitment to clean energy. The result is greater renewable energy penetration, which, as earlier noted, enhances sustainable development.

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*Technological innovation and renewable energy (r = 0.137)**

The correlation between Technological Innovation and Renewable Energy Consumption is positive but weak ($r = 0.137$, $p = 0.003$). Although statistically significant, the relationship is minimal in magnitude. This finding may indicate that while technological innovation supports the renewable energy sector (through smart grid technologies, battery storage, etc.), the adoption of these innovations is still limited in many countries especially developing economies. The weak correlation could also suggest that many innovations remain at the research or pilot stage and have yet to be fully commercialized or integrated into national energy systems. Bridging this gap between innovation and implementation may require more targeted policies that support R&D diffusion, scale-ups, and public-private partnerships.

Technological innovation and green finance (r = 0.312)

The relationship between Technological Innovation and Green Finance is moderate and statistically significant ($r = 0.312$, $p = 0.01$). This implies that green finance does play a role in stimulating innovation, particularly in clean and climate-smart technologies. In turn, technological innovation creates opportunities for new green financial products and services, establishing a feedback loop between the two.

Economically, this supports the argument that aligning green finance with innovation policy can yield significant sustainability dividends. For instance, when green bonds are earmarked for clean tech R&D, the results may enhance not only environmental quality but also economic competitiveness.

In summary, correlation matrix offers compelling preliminary evidence that renewable energy consumption and green finance are strong drivers of sustainable development, while technological innovation also plays a meaningful though more moderate supporting role. All relationships are positive and statistically significant, indicating mutual reinforcement among the variables.

These relationships are well aligned with the broader objectives of the study. They affirm the theoretical argument that sustainability is not merely a function of environmental policies, but also a product of financial innovation, technological progress, and clean industrial growth. The findings suggest that integrated strategies involving green financing instruments, renewable energy deployment, and innovation systems are crucial for advancing sustainability in emerging and developing economies (*Table 4*).

Table 4. *Result of multicollinearity test (VIF)*

Variable	Coefficient	Un-centered VIF	Centered VIF
REC	0.004	1.546	0.434
GF	0.001	1.202	0.120
TI	0.002	1.672	0.761

The coefficient values for REC, GF, and TI are 0.004, 0.001, and 0.002 respectively, indicating their estimated effects in a regression model. These values suggest relatively small contributions of each variable to the model's predicted outcome. The uncentered VIFs for REC (1.546), GF (1.202), and TI (1.672) are all below the commonly accepted threshold of 10, implying that there is no serious issue with multicollinearity in the model.

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This is further supported by the centered VIFs, which are even lower: 0.434 for REC, 0.120 for GF, and 0.761 for TI.

Low VIF values indicate that the independent variables are not strongly correlated with each other, which is beneficial for the reliability and interpretability of the regression model. Multicollinearity can distort the estimation of coefficients, increase standard errors, and reduce the statistical power of the analysis, but in this case, those concerns appear minimal.

Generally, the data suggest that the model is statistically sound with respect to multicollinearity, allowing the researcher to proceed confidently with further interpretation or hypothesis testing. This test forms an essential part of model validation in econometric or social science research, ensuring that the underlying assumptions of the regression analysis hold true.

The table above shows the stationarity of several economic variables using the Peraran-Shin Cross-Sectional Dependence Test, an essential tool in panel data econometrics. *Table 5* of the document presents the results of the non-stationarity tests for the variables: LnrSD (log of sustainable development), LnrREC (log of renewable energy consumption), LnrGF (log of green finance), and LnrTI (log of technological innovation).

Each variable is evaluated at both level and first difference, with significance levels indicated at the 1% (*), and 5% () thresholds. The test statistics are shown alongside their respective probabilities (p-values), with the stationarity decision summarized in the final column.

The results show that LnrSD is stationary at level, with a test statistic of -3.619 and a highly significant p-value (0.000), leading to the conclusion that it is integrated of order zero, I(0). This implies that LnrSD does not require differencing to become stationary, which suggests a stable time series pattern over time.

Table 5. *Cross section non-stationarity analysis results*

In Peraran-Shin analysis					
Variables	**Level Prob**	**1st Diff**	**Level Prob**	**1st Diff**	**Decision**
LnrSD	-3.619 (0.000)***	-8.273 (0.000)***	86.423 (0.006)***	181.245 (0.000)***	1(0)
LnrREC	-1.482 (0.050)	--9.832 (0.000)***	76.342 (0.034)***	202.852 (0.000)***	1(1)
LnrGF	1.602 (0.935)	-7.546 (0.000)***	43.612 (0.892)	143.224 (0.000)***	1(1)
LnrTI	1.590 (0.934)	-9.852 (0.000)***	48.876 (0.727)	181.245 (0.000)***	1(1)

*** and ** means 0.01 and 0.05 level of significance of variables respectively

Conversely, LnrREC, LnrGF, and LnrTI are non-stationary at level but become stationary after first differencing, as reflected by the strong significance of their first-difference values (e.g., -9.832 for LnrREC, -7.546 for LnrGF, and -9.852 for LnrTI, all with p-values of 0.000). This implies that these variables are integrated of order one, I(1), and must be differenced once to achieve stationarity.

The stationarity of variables is a crucial prerequisite for accurate econometric modeling, particularly in time-series and panel data contexts. Using non-stationary

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variables without differencing can lead to spurious regression results. Hence, this analysis confirms that while LnrSD can be used in levels, LnrREC, LnrGF, and LnrTI should be differenced to ensure valid inferences in further modeling stages. This systematic diagnostic supports the robustness of the study's empirical approach.

Table 6 presents the results of a panel cointegration test aimed at examining whether a long-run equilibrium relationship exists among the studied variables. The test is conducted under two hypotheses: one assuming common autoregressive coefficients and the other assuming individual autoregressive coefficients, using multiple test statistics V-stat, RHO, PP-stat, and ADF-stat.

Table 6. *Panel cointegration test results*

H_1: Common autoregressive coefficients.				
	Coefficient	**Prob value**	**Coefficient**	**Prob value**
V-stat	1.138	0.125	1.252	0.102
RHO	2.143	0.942	2.183	0.923
PP-Stat	-2.434	0.006***	-1.538	0.048**
ADF Stat	-2.490	0.008***	-1.662	0.049**

H_1: Individual autoregressive coefficients		
	Coefficient	**Prob value**
RHO	3.701	0.991
PP-Stat	-3.082	0.000***
ADF Stat	-2.801	0.003***

***, ** indicate the 0.01 and 0.05 level of significance of variables respectively. H0 is formulated under no long run relationship vector. The table indicates error cointegration analysis. The test assumes deterministic constant and trend. The SIC with 0–2 lags are used in chosen the automatic lag structure

Under the common coefficients assumption, the V-stat and RHO values are statistically insignificant, with p-values of 0.125 and 0.942 respectively, suggesting no rejection of the null hypothesis. However, the Phillips-Perron (PP-stat) and Augmented Dickey-Fuller (ADF-stat) results are statistically significant at the 1% and 5% levels (e.g., PP-stat = -2.434, p = 0.006; ADF-stat = -2.490, p = 0.008). These findings provide evidence to reject the null hypothesis of no cointegration and suggest a long-run relationship among the variables when allowing for a common trend.

Similarly, under the individual coefficient's hypothesis, the RHO value remains insignificant (p = 0.991), but both the PP-stat (-3.082, p = 0.000) and ADF-stat (-2.801, p = 0.003) are highly significant, reinforcing the evidence of cointegration.

Overall, despite some test statistics being statistically insignificant, the significance of the PP and ADF statistics across both model assumptions indicates the existence of a long-run cointegration relationship among the variables. This means that although short-run deviations may occur, the variables move together over time, supporting the theoretical expectation of economic linkage. The use of Schwarz Information Criterion (SIC) and automatic lag selection enhances the model's robustness (*Table 7*).

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Table 7. *Long run and short run PARDL*

Variable	PMG estimate	MG estimates	DFE estimates
Long run parameter estimates of LnrSD			
LnrREC	0.202^{***} (0.000)	0.06^{***} (0.000)	0.082^{***} (0.000)
LnrGF	0.226^{***} (0.000)	0.130^{***} (0.000)	0.143^{***} (0.000)
Short run parameter estimates of LnrSD			
ECM(-1)	-0.143^{***} (0.000)	-0.048^{**} (0.000)	-0.103^{***} (0.000)
ΔLnrREC	0.060 (0.252)	0.052(0.43)	0.030(0.029)
ΔLnrGF	$0.0520.202^{***}$ (0.002)	0.014(0.283)	0.016(0.052)
ΔLnrTI	0.0032*** (0.0003)	0.0343(0.000)	0.0623(0000)
Long run parameter estimates of LnrREC model			
LnGI	-0.414^{***} (0.006)	0.212^{***} (0.036)	-0.324^{***} (0.000)
LnSD	2.142^{***} (0.000)	1.421^{**} (0.042)	2.023^{***} (0.026)
LnTI	-0.232^{***} (0.000)	-0.120^{***} (0.048)	-0.167^{***} (0.000)
Short run parameter estimates of LnrREC model			
ECM(-1)	-0.179^{***} (0.003)	0.112^{***} (0.000)	-0.141^{***} (0.000)
ΔLnrGF	-0.691^{*} (0.076)	-0.342^{***} (0.871)	-0.432^{*} (0.072)
ΔLnrSD	0.051(0.099)	0.045(0.872)	0.499(0.854)
ΔLnrTI	0.021(0.117)	0.022(0.464)	0.022(0.268)
Num of Obs	592	592	592
Num of SSA	24	24	24
Hausman Taylor test	MG vs PMG		MG vs DFE
X^2 (3)	2.384		2.665
P-value > X^2	0.895		0.996

Sample size reduces to 592. This is as a result of initial lag order of the independent variables included in the RHS of the rGDP model formulated in model (6). Probability values are reported in (). ***, ** indicate the 0.01 and 0.05 level of significance of variables respectively

The table presents results from ARDL (1,1) model estimations using Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE) approaches to analyze the long- and short-run effects of renewable energy consumption (REC), green finance (GF), technological innovation (TI), sustainable development (SD) on real (SD) and REC.

In the long run, REC and GF have significant positive effects on SD across all models, suggesting that increased renewable energy use and public spending foster economic growth. For instance, REC coefficients range from 0.06 (MG) to 0.202 (PMG), all statistically significant. Similarly, GF is strongly positive in all models. The error correction term (ECM) is negative and significant in all short-run models, indicating stable long-run relationships.

For the REC model, green finance (GI) shows mixed effects: negatively related in PMG and DFE but positive in MG. Sustainable development (SD) has a strong positive effect across models, implying that increased savings boost renewable energy consumption. Technological innovation (TI) negatively influences REC in all models.

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The Hausman test results show no significant differences between MG, PMG, and DFE (p-values > 0.89), indicating that PMG or DFE models are appropriate. Overall, the findings underscore the importance of fiscal support and savings in promoting economic growth and renewable energy usage in Sub-Saharan Africa (*Table 8*).

Table 8. *Long run robustness check using FMOLS and DOLS result*

Dependent variables SD		Independent variables REC		
Variables	**FMOLS**	**DOLS**	**FMOLS**	**DOLS**
LnrGF	0.024^{**} (0.013) [3.624]	0.011 $(0.014)^{**}$ [3.415]	-0.024^{**} (0.028) [3.367]	-0.026 $(0.026)^{**}$ [3.328]
LnrTI	0.168^{***} (0.000) [11.208]	0.162^{***} (0.000) [7.816]	0.162^{***} (0.000) [11.068]	0.148^{***} (0.000) [8.728]
LnrSD			0.0202^{***} (0.000) [9.052]	0.288^{***} (0.000) [8.286]
R^2	0.92	0.96	0.95	0.98
LR variance	0.039	0.016	0.037	0.017
N	600	600	600	600

***, ** indicate the 0.01 and 0.05 level of significance of variables respectively while probability values and t-statistic are reported in () and [] respectively

The table presents the results of Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) regressions examining the long-run relationships between sustainable development (SD), renewable energy consumption (REC), green financing (GF), and technological innovation (TI).

Green financing (GF) positively and significantly influences sustainable development in both models (FMOLS: 0.024, DOLS: 0.011), indicating that increased green financial investments promote long-term sustainability. However, GF negatively impacts renewable energy consumption in both models, though still statistically significant. This suggests that while green financing supports broader sustainable goals, its direct effect on renewable energy uptake may be constrained by allocation inefficiencies or competing priorities.

Technological innovation (TI) strongly and positively affects both SD and REC across all models (coefficients ranging from 0.148 to 0.168, $p < 0.01$). This highlights technology's critical role in enhancing environmental outcomes and facilitating clean energy adoption.

Additionally, sustainable development significantly promotes renewable energy consumption (FMOLS: 0.0202, DOLS: 0.288), suggesting a feedback mechanism where progress in sustainability encourages cleaner energy choices.

Also, the models exhibit high explanatory power (R^2 ranging from 0.92 to 0.98), indicating robust relationships. The findings underscore the importance of targeted green financing and innovation in fostering both sustainable development and renewable energy use in the long term (*Table 9*).

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Table 9. *Pannel causality test results*

H_o	W- Stat	Z-stat	P value	Causality	Decision
REC → SD SD → REC	3.302 *** 5.406 ***	2.213*** 6.618***	0.028 0.000	Yes Yes	Bidirectional feedback
GF→ SD SD → GFI	1.624 6.330***	1.212 8.632***	0.162 0.000	Yes Yes	Unidirectional
TI → SD SD → TI	6.047*** 8.432***	8.062*** 11.000***	0.000 0.000	Yes Yes	Bidirectional feedback
REC → GF GF → REC	3.094 3.743***	1.802 3.168***	0.062 0.000	No Yes	Unidirectional
GF → TI TI → GF	7.001*** 3.013	11.123*** 1.635	0.000 0.103	Yes No	Unidirectional
REC → TI TI → REC	5.301*** 5.673***	6.351*** 2.018***	0.000 0.003	Yes Yes	Unidirectional

*** & *** Indicate the 0.01 & 0.05 level of significance of variables respectively

The causality test results reveal dynamic interrelationships among sustainable development (SD), renewable energy consumption (REC), green financing (GF), and technological innovation (TI).

A bidirectional causality exists between REC and SD, indicating that each variable significantly influences the other. This suggests a reinforcing loop where sustainable development promotes renewable energy use, and vice versa. Similarly, SD and TI also exhibit bidirectional causality, emphasizing that innovation is both a driver and a product of sustainability efforts.

Unidirectional causality is observed from SD to GF, meaning sustainable development leads to increased green financing, but not the reverse. The same pattern holds between GF and TI, where green financing drives innovation, but innovation does not significantly influence financing flows.

Interestingly, REC and GF show a unidirectional link from GF to REC, highlighting that financial support enhances renewable energy adoption. A similar unidirectional causality exists between REC and TI, suggesting renewable energy consumption promotes technological advancement, but not vice versa.

In summary, the results emphasize the central role of sustainable development as both an influencer and a recipient of key policy variables, while green financing and innovation emerge as instrumental tools in achieving long-term sustainability.

Discussion of findings

The empirical findings from this study shed light on the intricate interconnections between renewable energy consumption (REC), green finance (GF), technological innovation (TI), and sustainable development (SD) across 30 emerging and developing economies. Our results resonate with the findings from prior studies while also contributing novel insights into the role these variables play in shaping long-term sustainability outcomes.

Renewable energy and sustainable development

The positive relationship between renewable energy consumption and sustainable development is well documented in the literature (Sachs et al., 2019; Abd Majid, et al

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2025). Our study strengthens these claims by revealing that renewable energy adoption is a crucial factor in driving sustainable outcomes. For instance, countries that increased their renewable energy share saw significant improvements in SD indicators, aligning with Ecological Modernization Theory, which posits that environmental protection and economic growth can coexist through strategic innovation (Mol and Sonnenfeld, 2000). Our finding of a robust correlation between REC and SD across different regions supports the views of IRENA (2023) and Osabohien (2025), who argue that renewable energy deployment is a cornerstone of sustainable economic growth.

Green finance and technological innovation

Green finance emerges as a key enabler of both renewable energy adoption and technological innovation. This supports the work of Kreibiehl et al. (2022), who emphasize the importance of aligning financial flows with environmental goals to achieve sustainability. Our findings confirm that green finance not only catalyzes clean energy investments but also facilitates innovation by providing capital for R&D, as demonstrated by Zhang et al. (2022). The impact of green finance on technological innovation further resonates with Taghizadeh-Hesary and Yoshino (2020), who argue that targeted financial instruments, such as green bonds and climate funds, play an essential role in accelerating technological advancements in the clean energy sector.

Interestingly, the unidirectional causality from green finance to renewable energy consumption, as identified in our study, complements the findings of Osabohien et al. (2024b), which suggest that financial systems in developing economies remain underdeveloped and often fail to mobilize adequate capital for renewable energy projects. The results underscore the need for improved financial mechanisms, such as green bonds, which can unlock private investments into sustainable infrastructure.

Technological innovation and sustainable development

Our study’s findings regarding the role of technological innovation in promoting sustainable development are consistent with the broader literature on innovation’s role in achieving environmental goals (Yao et al., 2022; Zhang et al., 2022). While the relationship between TI and SD is weaker than that of REC and SD, the correlation is still significant, indicating that technological innovation remains a crucial driver of sustainable development, albeit with a lag. This is in line with the findings of Sachs et al. (2019), who argue that while technological advancements are critical for improving energy efficiency and decarbonizing industries, their full impact is often realized over the long term, contingent on factors such as infrastructure, policy alignment, and market readiness.

Our study also highlights the role of digital technologies in enabling more efficient energy systems, as pointed out by Lopez et al. (2020), where innovations in smart grids, AI, and IoT help optimize resource use and reduce emissions. These technologies play a significant part in reshaping industrial energy consumption and, when paired with green finance, can accelerate the transition to a low-carbon economy.

While *technological innovation* is often associated with *green-energy innovations* (e.g., solar panels, wind turbines, battery storage), it also encompasses a broader spectrum of advancements in *industrial processes, digital technologies,* and *energy-efficient innovations*. Innovations in fields such as *artificial intelligence (AI), automation,* and *digitalization* significantly contribute to energy management, resource optimization, and *smart grid technologies,* all of which indirectly support *renewable energy integration* and

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sustainable development. Therefore, the correlation between technological innovation and renewable energy or green finance does not imply that all innovations are explicitly *green-oriented,* but rather that technological progress, in general, aids the *sustainable transformation* of industries and energy systems.

Comparative insights

In examining developed vs developing economies, our study builds on the literature that shows developed countries typically have stronger financial systems, advanced technological sectors, and established policies that support green energy and innovation (Osabuohien et al., 2024a). Our study finds that developed economies like Germany and South Korea benefit from integrated industrial policies that promote clean energy innovation and financial mechanisms, whereas developing economies such as Nigeria and Vietnam face barriers like poor infrastructure, limited access to green finance, and low innovation capacities, limiting their potential for large-scale renewable energy adoption. These results echo the challenges highlighted by Abass et al. (2020) and Kreibiehl et al. (2022), who call for enhanced international cooperation and financial support to help developing nations leapfrog to cleaner industrialization pathways.

Our research suggests that resource-driven industrialization in developing regions can hinder clean energy adoption, aligning with the findings of Osabohien (2025), Osabohien et al., 2024a, c and Nasir et al. (2022), who stress that technology-driven industrialization strategies accelerate the integration of renewable energy. We emphasize that targeted policies are required to align industrial strategies with sustainability goals, particularly in resource-rich economies that depend heavily on fossil fuels.

Sub-Saharan and other regions

The results underscore the importance of fiscal support and savings in fostering economic growth and renewable energy adoption. However, the impact of fiscal incentives varies considerably across regions. In Sub-Saharan Africa, the relationship between fiscal support and renewable energy consumption is more pronounced, reflecting the region’s dependence on external financial flows and the need for policy interventions to catalyze clean energy investments. Countries in SSA face significant barriers, such as limited domestic savings, infrastructure challenges, and political instability, which impede the scaling of renewable energy projects. In contrast, in more advanced economies like South Korea and Germany, the connection between fiscal support and renewable energy adoption is facilitated by robust financial markets, technological capacity, and stable institutional frameworks. Thus, SSA nations need tailored financial mechanisms to overcome these challenges and foster green energy transitions effectively.

Conclusions and recommendations

The study concludes that renewable energy consumption and green finance have strong, positive long-term effects on sustainable development in emerging and developing economies. Technological innovation also significantly contributes, primarily by enhancing renewable energy adoption and improving environmental outcomes. The existence of long-run cointegration and bidirectional causality between sustainable development and both renewable energy and innovation underscores their dynamic

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interdependence. Green finance emerges as a unidirectional driver of renewable energy and technological innovation, emphasizing its catalytic role. The research validates the Ecological Modernization Theory, affirming that economic growth and environmental sustainability can be harmonized through targeted financial instruments and innovation-led policies. Based on these findings, the study recommends integrated policy frameworks that simultaneously advance renewable energy, green finance, and innovation. Governments should establish enabling environments with regulatory clarity, fiscal incentives, and investments in R&D. Tailored financial instruments especially in resource-constrained countries are essential for de-risking investments and mobilizing private capital. The private sector must align with environmental, social, and governance (ESG) criteria, while international cooperation is crucial for technology transfer and climate finance. Also, harmonizing energy policy, finance, and innovation is vital for achieving inclusive and resilient sustainable development.

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