Impact of Renewable Energy Indicators on Sustainable Development in Nigeria

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ABSTRACT

This study investigated the impact of renewable energy indicators on sustainable development in Nigeria over the period 1990 to 2024. The main objective was to examine how solar energy consumption, total biomass consumption, and hydroelectric production influenced sustainable development as measured by the Human Development Index. The motivation for the study was rooted in Nigeria's persistent energy challenges, its growing reliance on renewable sources, and the urgent need to understand how these transitions translate into human development outcomes. The methodology combined descriptive statistics, unit root tests, bounds testing for cointegration, and the Auto-Regressive Distributed Lag model to analyze both short-run and long-run dynamics. The statistical techniques ensured that the relationships were rigorously examined despite the mix of integration orders among the variables. The findings revealed three distinct outcomes. First, total biomass consumption had a positive but statistically insignificant effect on human development, implying that its dominant traditional use limited its developmental contribution. Second, solar energy consumption had a negative and significant effect, suggesting that despite its rapid growth, structural and institutional challenges such as high costs, weak policy frameworks, and poor integration constrained its ability to improve welfare outcomes. Third, hydroelectric production had a positive and significant effect, confirming its role as the most stable and impactful renewable source for long-term improvements in education, health, and income levels. The error correction mechanism further confirmed a strong speed of adjustment, indicating that the system quickly returned to equilibrium after short-term shocks. The study recommended that the Federal Ministry of Environment and the Energy Commission of Nigeria should lead efforts to modernize biomass through clean technologies. The Rural Electrification Agency and the Nigerian Electricity Regulatory Commission should strengthen financing and grid integration to enhance solar's developmental impact, while the Federal Ministry of Power and the Transmission Company of Nigeria should prioritize the expansion and climate resilience of hydroelectric infrastructure. Collectively, these actions were necessary to maximize the developmental benefits of renewable energy in Nigeria.

Keywords: Renewable energy, solar energy consumption, biomass consumption, hydroelectric production, sustainable development

JEL Codes: Q20, Q42, Q56, O13, O44

INTRODUCTION

The growing urgency to mitigate climate change and foster inclusive development has placed renewable energy at the core of the global sustainability agenda. Across the world, renewable energy indicators, such as solar energy consumption, total biomass consumption, and hydroelectric power generation, are increasingly used to track and evaluate the role of clean energy sources in achieving sustainable outcomes (Pata et al., 2024). These indicators not only reflect the energy mix of a country but also provide insight into its transition from fossilbased systems toward more environmentally friendly and socially inclusive energy solutions. Globally, solar energy has seen exponential growth in deployment due to its scalability, decreasing costs, and potential for decentralized energy provision. Biomass, a more traditional form of renewable energy, remains vital in both developed and developing contexts, particularly in rural areas. Hydroelectric power, often the most established form of renewable energy in many countries, continues to provide substantial shares of electricity in several economies, though it faces challenges related to environmental impacts and water resource variability (International Energy Agency [IEA], 2024).

In Sub-Saharan Africa, the renewable energy transition is marked by both promise and constraint. The region holds immense potential for solar energy given its abundant irradiation, and many countries have begun to harness this potential through mini-grid systems, solar home systems, and grid-scale photovoltaic (PV) installations. Biomass remains the dominant energy source for cooking and heating, although its use is often inefficient and unsustainable. Hydropower contributes significantly to electricity generation in countries like Ethiopia, Zambia, and Ghana, yet its role is limited by climate-induced water stress and infrastructural gaps. According to the International Renewable Energy Agency (IRENA, 2023), renewable energy represented about 23% of total energy generation in Sub-Saharan Africa in 2022, with hydropower accounting for over half of that share. However, the actual impact of these renewable energy sources on socio-economic development remains uneven across the region (Saud et al., 2024).

Focusing specifically on Nigeria, the country presents a compelling case for examining the relationship between renewable energy indicators and sustainable development. Nigeria, the most populous country in Africa, is grappling with the dual challenge of expanding energy access while curbing environmental degradation. A closer look at Nigeria's renewable energy data from 1990 to 2024 reveals a dynamic but gradual transition. Solar energy consumption in Nigeria rose from just 0.25 GWh in 1990 to 319.23 GWh in 2024, representing a dramatic increase and signaling a growing interest in solar technology as a viable energy source (Rural Electrification Agency [REA], 2024). Similarly, total biomass consumption has grown from 2,135.20 PJ in 1990 to 10,598.70 PJ in 2024, reflecting its sustained relevance, particularly in household energy use and informal economic sectors (International Energy Agency [IEA], 2024). Hydroelectric production, on the other hand, has experienced a more fluctuating trend: peaking at 41.86% of total electricity production in 1991, dipping significantly to 13.01% in 2014, and modestly recovering to 25.50% by 2024 (World Development Indicators [WDI], 2024). These trends underscore the varying degrees of integration and reliance on different renewable energy sources over time.

Parallel to these energy trends, Nigeria's Human Development Index (HDI), a measure for sustainable development encompassing life expectancy, education, and per capita income, has shown a gradual improvement. Starting at 0.411 in 1990, HDI peaked at 0.539 in 2019 before experiencing a slight decline to 0.522 in 2024 (United Nations Development Programme [UNDP], 2024). This upward trajectory, despite recent stagnation, suggests that some progress has been made in the key dimensions of development. However, Nigeria still lags behind global averages, indicating that while development is occurring, it remains slow and uneven, particularly when contrasted with the scale of renewable energy expansion. Globally, countries that have integrated renewable energy into their development strategies, such as Germany, Denmark, and Costa Rica, have often seen concurrent improvements in human development metrics, largely due to increased energy access, job creation, and environmental health benefits (IEA, 2024).

Sustainable development has evolved to encapsulate a holistic approach to growth, balancing economic advancement, environmental protection, and social inclusion. While developed countries have made significant strides by investing in green technologies and low-carbon infrastructure, developing countries like Nigeria are still navigating the complexities of energy poverty, limited institutional capacity, and financial constraints. Nonetheless, renewable energy provides an opportunity to bridge development gaps in a sustainable manner. In Nigeria, the link between access to renewable energy and human development is becoming increasingly relevant, particularly in rural areas where energy access is lowest (Global Alliance for Clean Cookstoves, 2024).

Given that renewable energy sources are critical drivers of sustainable development through their roles in enhancing energy access, promoting environmental sustainability, and supporting socio-economic growth, it is imperative to examine how key renewable energy indicators, represented by Solar Energy Consumption, Total Biomass Consumption, and Hydroelectric Production, have influenced sustainable development outcomes in

Nigeria. Therefore, it is in the interest of this study to conduct an analysis of how these components of renewable energy have impacted the country's Human Development Index over the period 1990 to 2024.

LITERATURE REVIEW

Conceptual Review

Renewable energy indicators

Renewable energy indicators have been widely recognized in literature as key measurable variables that help to assess the progress, effectiveness, and sustainability of renewable energy adoption within an economy. These indicators serve as proxies to evaluate not only the quantity but also the quality of renewable energy integration across sectors. In recent years, researchers have emphasized the growing importance of renewable energy in shaping socio-economic and environmental outcomes, particularly in developing countries. According to ObengDarko and Aboagye (2023), renewable energy indicators are vital tools for tracking the evolution of energy systems and understanding their contribution to development goals such as poverty reduction, improved health outcomes, and environmental conservation. These indicators reflect how various renewable energy sources are utilized, and they provide essential data for policy analysis, investment decisions, and development planning.

Solar energy consumption has been one of the most prominently used indicators in recent literature, due to the rapid advancement and scalability of solar technologies. Scholars such as Eboh et al. (2022) defined solar energy consumption as the amount of energy harnessed from the sun and utilized in electricity generation, heating, or other energy services within a given time frame. They noted that solar energy consumption is often expressed in gigawatt-hours (GWh) and is indicative of the level of investment in solar infrastructure, technological adaptation, and energy accessibility. Solar energy has been highlighted for its decentralized nature, which allows for rural electrification, and for its alignment with global efforts to reduce carbon emissions (Akintunde & Bello, 2023). The relevance of solar energy as an indicator stems from its potential to transform energy-poor communities and contribute to sustainable development through clean, affordable, and reliable energy access.

Total biomass consumption is another critical indicator of renewable energy, particularly in the context of developing economies where traditional biomass remains a dominant energy source. According to the International Energy Agency (2024), biomass consumption includes all forms of organic materials used to produce energy, including wood, agricultural residues, dung, and increasingly, modern bioenergy products such as biogas and biofuels. Scholars such as Nwachukwu and Uzochukwu (2023) conceptualized total biomass consumption as the total amount of bio-based energy utilized across sectors including household cooking, industrial processes, and electricity generation, usually measured in petajoules (PJ). They further emphasized the dual character of biomass consumption: while it is renewable, its unsustainable use can lead to deforestation, land degradation, and negative health effects from indoor air pollution. Hence, the indicator not only reflects energy usage but also the sustainability and efficiency of bioenergy systems in a given context.

Hydroelectric production, often measured as the percentage of total electricity generated from hydropower sources, has also featured prominently in recent conceptual discussions of renewable energy indicators. Researchers such as Ahmed and Dangana (2022) defined hydroelectric production as the generation of electricity using the gravitational force of falling or flowing water, commonly from dams or river-based systems. They noted that hydroelectric power has been one of the earliest and most stable sources of renewable electricity, particularly in Sub-Saharan Africa, due to its relatively low operating costs and large-scale output potential. However, it has also been critiqued for its vulnerability to climate change, particularly droughts and water scarcity, which can significantly affect electricity production levels. Hydroelectric production as an indicator, therefore, encapsulates not only the level of renewable energy utilization but also the resilience and sustainability of the energy infrastructure.

Sustainable Development

Sustainable development has remained a pivotal concept in global policy and academic discourse, especially in the face of increasing environmental degradation, poverty, and inequality. Conceptually, sustainable development has evolved to encapsulate a multidimensional framework that integrates economic growth, environmental protection, and social inclusion. The foundational definition was provided by the Brundtland Commission in 1987, which described sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition has continued to shape contemporary interpretations, including those offered in recent literature that emphasize measurable indicators and context-specific applications. According to Musa and Ojo (2023), sustainable development entails a harmonized progression in human well-being, ecological sustainability, and institutional governance, all aimed at long-term societal resilience.

Recent scholars have increasingly adopted the Human Development Index (HDI) as a reliable proxy for measuring sustainable development outcomes. HDI captures three critical dimensions: health (measured by life expectancy at birth), education (measured by mean years of schooling and expected years of schooling), and standard of living (measured by gross national income per capita). According to Bakare and Hassan (2022), the HDI provides a composite measure that goes beyond income to reflect the actual quality of life and access to basic services in a given country. They argued that sustainable development, in practical terms, is reflected in improvements in HDI scores over time, particularly when such improvements are accompanied by environmentally responsible and socially inclusive policies. Similarly, Olatunji et al. (2024) emphasized that HDI is an essential tool for assessing the human-centered impact of development interventions, including energy access, healthcare, and education.

Global frameworks such as the United Nations Sustainable Development Goals (SDGs) have further strengthened the conceptual understanding of sustainable development by providing 17 goals and 169 targets aimed at achieving inclusive and environmentally sound development by 2030. Goal 7, which focuses on affordable and clean energy, and Goal 13, which addresses climate action, are directly relevant to the energydevelopment nexus. According to the United Nations Development Programme (2024), progress in these areas has direct implications for other goals related to education, health, and poverty reduction. Therefore, the pursuit of sustainable development has become synonymous with integrated policy approaches that recognize the interdependence of environmental, economic, and social systems.

Theoretical Underpinning

The theoretical underpinning for this study is the Ecological Modernization Theory (EMT), originally propounded by Joseph Huber in the early 1980s and further developed by scholars such as Martin Jänicke and Arthur P. J. Mol. Ecological Modernization Theory posits that economic development and environmental sustainability are not inherently contradictory but can be mutually reinforcing through the strategic use of technological innovation, institutional reform, and policy transformation. According to Mol and Sonnenfeld (2023), the theory emphasizes that through modernization of production and consumption systems, particularly in the energy sector, societies can achieve sustainable development without halting economic progress.

EMT is grounded in the belief that environmental challenges such as energy poverty, carbon emissions, and ecological degradation can be addressed through the adoption of clean and renewable technologies, including solar, biomass, and hydroelectric energy. These innovations, when embedded into national development frameworks, are believed to contribute to improvements in human well-being, economic resilience, and environmental quality. The relevance of this theory to the present study lies in its capacity to explain how renewable energy indicators, such as solar energy consumption, total biomass consumption, and hydroelectric production, can drive sustainable development outcomes measured through the Human Development Index (HDI). By emphasizing structural transformation and technological progress, EMT offers a pathway through which energy transitions can positively impact education, health, and income levels in developing countries like Nigeria.

Empirical Reviews

Understanding the empirical landscape surrounding renewable energy indicators and their relationship with sustainable development provides critical insights into how different sources of clean energy contribute to human development outcomes. A number of studies conducted in both developing and developed economies have examined this nexus, using various methodological approaches, timeframes, and variables. The following reviews explore empirical contributions from the literature, focusing specifically on solar energy consumption, total biomass consumption, and hydroelectric production as key indicators of renewable energy, and how they influence dimensions of sustainable development, particularly the Human Development Index (HDI).

Agbakwuru et al. (2024) extended the discussion of renewables by directly linking them to progress on the United Nations Sustainable Development Goals (SDGs). Their interdisciplinary analysis, combining engineering and sociological perspectives, evaluated how renewable energy sources such as solar, wind, geothermal, and hydropower contribute to achieving SDG 7 on clean energy, SDG 13 on climate action, and related goals like SDG 1 and SDG 3. Relying on a literature-based qualitative methodology supported by global case studies, the authors found that renewable energy advances access to electricity, reduces carbon emissions, and fosters socioeconomic inclusion, particularly in marginalized communities. However, challenges such as high upfront costs and regulatory bottlenecks were also highlighted. While the study reinforced the importance of renewables in shaping sustainability, it did not provide empirical quantification of the impacts of specific energy types. Furthermore, by emphasizing macro-level policy approaches and overlooking localized barriers or enablers, the work reduced its practical relevance for developing regions where socio-cultural dynamics strongly mediate renewable energy adoption.

A quantitative contribution came from Aboul-Atta and Rashed (2021), who explored the relationship between renewable energy consumption and sustainable development indicators across 137 countries using data on 255 SDG-related variables. Applying Principal Component Analysis followed by multiple linear regression, the study found an inverse correlation between a composite Sustainable Development Index and renewable energy consumption. This suggested that countries with lower development levels adopted renewable energy more aggressively, likely due to the appeal of decentralized and relatively accessible energy solutions. The study's findings provided a counterintuitive but valuable perspective on how less developed economies engage renewables. However, the reliance on aggregated global data without regional breakdowns limited the ability to account for context-specific drivers of renewable adoption. Moreover, the linear modeling approach did not capture non-linear relationships or moderating factors such as governance and institutional readiness. The study also depended on a composite index, which may have obscured the distinct influences of proxies such as solar, biomass, and hydro on human development outcomes.

In a comparative cross-country study, Leclerc and Ndiaye (2022) explored the impact of renewable energy consumption on sustainable development in 12 West African countries from 1990 to 2020. Using panel cointegration techniques and a fully modified ordinary least squares (FMOLS) estimator, they found that both solar and hydroelectric energy consumption had statistically significant and positive impacts on HDI. Countries with structured investment in hydropower infrastructure, such as Ghana and Côte d'Ivoire, experienced stronger HDI growth. In contrast, biomass consumption, particularly when sourced from traditional fuels, showed a statistically negative effect on HDI, largely due to its association with health risks and environmental degradation. Although the study provided a balanced view of regional trends, its use of aggregate national-level data limited insight into subnational disparities. Additionally, the study did not differentiate between modern and traditional biomass or between small- and large-scale solar projects.

Drawing on a broad international sample of middle- and high-income economies, Candra et al. (2023) situated their work in energy economics and covered multiple countries using a Structural Vector Auto-Regression design to explore the dynamic impact of renewable energy production on economic growth and greenhouse gas outcomes. Over the period analyzed in their panel setting, the study found that increases in renewable energy were associated with higher economic growth in both income groups, with stronger effects reported in middleincome countries, alongside a measurable reduction in greenhouse gas emissions as renewable

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consumption rose. While the results supported the developmental and environmental value of renewables, the study did not disaggregate renewable technologies into solar, biomass, and hydro, which limited direct inferences for the proxies used in the present study. The macro-level focus also masked sectoral and regional heterogeneity that would have clarified how specific renewable pathways related to human development metrics such as HDI.

Abdolmaleki and Bugallo (2024) advanced a data-driven framework rather than a country-panel econometric application. Situated at the intersection of chemical engineering and environmental modeling, their 2024 article used an indicator-to-framework approach combined with rule-mining algorithms, especially Apriori, to analyze linkages among 227 indicators spanning five sustainability dimensions and nine thematic scopes. The rule sets reported high support, confidence, and lift for relations connecting environmental emissions indicators with economic, social, and technological metrics, implying structured interdependencies consistent with energy transition logics. Despite the methodological rigor and the potential to map how solar, biomass, and hydro indicators might connect to human development constructs, the work remained largely conceptual and algorithmic without country-level or time-series validation. It did not test causal pathways to HDI or separate renewable subtypes empirically, which limited immediate applicability to the present study's proxy structure.

Expanding the global scope to 104 countries between 2000 and 2020, Chuong et al. (2025) anchored their analysis in the triple bottom line model and applied panel unit root tests, cointegration procedures, and the pooled mean group estimator to examine how globalization, renewable energy, and labor interacted with sustainability indicators. Renewable energy consumption consistently improved composite sustainability outcomes across income groups, while labor exerted a strong positive influence, particularly in middle-income economies, and globalization was also found to be favorable. Although these findings spoke to the enabling role of renewable energy for development, the measurement strategy relied on aggregated sustainability indices rather than HDI, and it did not distinguish among solar, biomass, and hydro technologies. Grouping countries by broad income tiers also compressed within-group diversity, and institutional quality was underexplored as a mediating factor, which together constrained the translation of results to the study's specific proxies and the Nigerian context.

Hai et al. (2023) examined the success level of economic growth across countries, situated in the macroeconomic development domain, for 1987 to 2018. Using dynamic panel GMM on World Bank indicators, they assessed how foreign direct investment, international integration, institutional reforms, and macroeconomic instability related to growth outcomes. The results indicated that higher FDI inflows, deeper international integration, and positive institutional change were associated with stronger growth performance, while macroeconomic instability depressed the success level of growth. The approach benefited from addressing endogeneity through GMM, however the country sample and variable set limited sectoral diversities, and reliance on aggregate crosscountry data constrained policy granularity for specific economies. The study's treatment of "success" captured broad performance rather than distributional dimensions of growth, and the GMM specification, while robust, depended on instrument validity tests that are often sensitive in long panels.

Saud et al. (2023) investigated environmental sustainability in MENA for 1980 to 2020, focusing on natural resource abundance, economic complexity, and education within environmental economics. They applied Westerlund cointegration, CUP-FM and CUP-BC estimators, and Dumitrescu Hurlin causality. Using CO_2 emissions and ecological footprint as environmental proxies, economic complexity and education were associated with reductions in both outcomes, while greater natural resource abundance was linked to environmental deterioration, consistent with resource dependence concerns. Financial development and income dynamics were also modeled, with evidence for an EKC pattern in the region. The advanced estimators strengthened inference on cross-sectional dependence and long-run parameters, yet ecological footprint and CO_2 captured different pressure channels that could be complemented by biodiversity or material-use metrics. Education measurement may have masked quality differences across countries, and policy heterogeneity within MENA suggested that subregional analyses would add precision.

Saud et al. (2024) analyzed the European Union for 1990 to 2019, exploring sustainable development through an N-shaped EKC scope. Using PMG-ARDL for heterogeneous panels, they modeled sustainable development against natural resources, economic complexity, renewable energy, stock market development, and technology trade openness. Economic complexity exhibited a positive long-run association with sustainable development, renewable energy contributed positively, and natural resource dependence reduced sustainable development. Stock market effects differed by EU cohorts, and technology trade openness showed adverse links for the EU27 and new members. While the EKC shape improved interpretability of income-environment dynamics, the chosen sustainable development proxy aggregated ecological and socio-economic facets in ways that obscured distributional trade-offs. Cross-member heterogeneity remained substantial, suggesting country-specific ARDLs or threshold models could refine policy guidance. The study's reliance on macro proxies for technology openness invited complementary micro-innovation indicators.

Sztumski (2023) offered a philosophical inquiry into sustainable development, globalization, and democratic conditions, set in sustainability studies rather than an econometric domain. The paper reflected on how sustainable development interacted with globalization and political regimes, arguing that liberal democratic conditions were conducive to sustainability, while authoritarian shifts endangered it. No time series or panel estimation was undertaken, and there was no quantitative time frame, since the contribution was conceptual and discursive. The argument drew on theoretical reasoning rather than empirical identification, so causal mechanisms were not tested against data. This perspective complemented empirical work by framing normative and institutional preconditions for sustainability, however the lack of operational variables, sample design, and measurable outcomes limited its applicability to policy calibration or model testing. Incorporating measurable indices of governance and environmental outcomes would have enabled triangulation with empirical sustainability metrics.

Pata et al. (2023) studied Germany's environmental sustainability, 1990s to recent years, by distinguishing renewable energy share and renewable energy intensity as key proxies in relation to sustainable development, frequently proxied by the load capacity factor. Using cointegration techniques and a bootstrap or PMG-ARDL family approach reported in summaries, they found that raising the renewable energy share improved ecological quality, while renewable energy intensity alone did not deliver significant gains. Income growth reduced ecological sustainability, supporting an EKC pattern, and short-run adjustments appeared stronger than long-run effects for GDP. The design's strength was its separation of "share" and "intensity," clarifying composition versus throughput channels. Still, reliance on aggregate national indicators masked sectoral heterogeneity, and the exclusive focus on total renewables omitted technology-specific dynamics like wind variability or bioenergy externalities. Extending the model with innovation, grid flexibility, and storage indicators would enrich mechanism testing for Germany's energy transition.

METHODOLOGY

This study adopted an ex-post facto research design, which was appropriate because the variables of interest, namely renewable energy indicators and sustainable development, had already occurred and could not be manipulated by the researcher. This design was particularly suitable for understanding long-term trends, causal relationships, and policy-relevant insights without experimental intervention, thereby ensuring reliability and objectivity of findings.

The study relied on secondary data, which provided credible and consistent measures of renewable energy indicators and sustainable development over time. Data on the Human Development Index were obtained from the United Nations Development Programme, while hydroelectric production figures were sourced from the World Development Indicators. Information on solar energy consumption was drawn from the Rural Electrification Agency and the Nigerian Electricity Regulatory Commission, and biomass consumption data were obtained from the International Energy Agency and Global Alliance for Clean Cookstoves. These datasets, covering 1990 to 2024, offered comprehensive and reliable insights for analyzing energy–development dynamics in Nigeria.

The present study drew from and refined the model framework of Leclerc and Ndiaye (2022), who examined how renewable energy consumption influences sustainable development outcomes. Building on their approach, the baseline regression specification for this study is expressed as:

$$HDI = \beta_0 + \beta_1 SEC + \beta_2 BC + \beta_3 HEP + u_t \quad (1)$$

Where:

HDI = Human development index

SEC = Solar Energy Consumption

BC= Biomass Consumption

HEP = hydroelectric production

β_0= Autonomous parameter estimates

$\beta_1 - \beta_3$= Coefficients of Solar Energy Consumption, Total Biomass Consumption, and hydroelectric production u_t = error term.

On *apriori*, the coefficient of solar energy consumption is expected to be positive $(\beta_1 > 0)$, , as increased utilization of solar energy should enhance access to electricity, improve educational and health outcomes, and foster economic opportunities; For total biomass consumption, the coefficient is expected to be negative $(\beta_2 < 0)$,, since reliance on traditional biomass is often linked to health risks from indoor air pollution, environmental degradation, and inefficiency; The coefficient of hydroelectric production is expected to be positive $(\beta_3 > 0)$, as greater electricity generation from hydro sources contributes to industrial productivity, household electrification, and economic growth.

The analysis commenced with unit root testing as an initial diagnostic step to evaluate the stationarity characteristics of the data series. Following the approach of Dickey and Fuller (1979), this procedure was essential for identifying whether the variables displayed stochastic trends and required differencing to achieve stationarity. Skipping this process could lead to spurious regression results and weaken the validity of statistical conclusions. The test is based on estimating the following regression:

$$\Delta y_t = \alpha + \beta t + \delta y_{t-1} + \sum_{i=1}^{p} \gamma_i \Delta y_{t-i} + u_t \quad (2)$$

Where:

y_t represents the variable being tested; Δy_t is the first difference of the variable; α is a constant (drift term); βt represents the trend component; δy_{t-1} captures the lagged level of the variable, where the coefficient δ determines whether a unit root is present; $\gamma_i \Delta y_{t-i}$ accounts for lagged differences to correct for serial correlation; u_t is the error term.

After establishing the order of integration of the variables, the study proceeded to examine the existence of longrun relationships using the Bounds Testing approach to cointegration developed by Pesaran et al. (2001). This method is appropriate for models with regressors integrated at I(0), I(1), or a mix of both. The associated unrestricted error correction model (UECM) applied in the Bounds framework is specified as:

$$\Delta y_t = \alpha + \sum_{i=1}^{p} \beta_i \Delta y_{t-i} + \sum_{i=0}^{q} \gamma_i \Delta x_{t-i} + \lambda_1 y_{t-1} + \lambda_2 x_{t-1} + \varepsilon_t \quad (3)$$

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In this equation, □ represents the first difference operator, y_t is the dependent variable, x_t is the independent variable(s), □ is a constant, $□_i$ and $□_i$ are the short-run dynamic coefficients of the model, □ and □ capture the long-run relationship between y_t and x_t and $□_t$ is the error term.

Once evidence of a long-run cointegrating relationship among the variables was established, the study advanced to estimating both short-run and long-run dynamics using the Auto-Regressive Distributed Lag (ARDL) technique. This method was chosen for its suitability in handling relatively small sample sizes and for its ability to accommodate regressors that are stationary at different levels, specifically I(0) and I(1). The ARDL framework is also advantageous in addressing concerns of endogeneity and autocorrelation, which frequently occur in time series analyses. By incorporating appropriate lags of both the dependent and independent variables, the model provided a robust estimation of the short-term and long-term effects of solar energy consumption, total biomass consumption, and hydroelectric production on sustainable development, measured by the Human Development Index in Nigeria. The unrestricted ARDL specification therefore offered a comprehensive framework for capturing the dynamic linkages among the study variables over the period under review and is expressed as:

$$□HDI = +□_0 □_{j=0}^{p}(□_1□HDI_{t-j}) + □_{k=0}^{p}(□_2□SEC_{t-k}) + □_{l=0}^{p}(□_3□BC_{t-l}) + □_{m=0}^{p}(□_4□HEP_{t-m}) + □_5 HDI_{t-1} + □_6 SEC_{t-1} + □_7 BC_{t-1} + □_8 OHEP_{t-1} + □_t \quad (4)$$

Where;

Δ denotes the first difference of the variables, capturing the short-run changes; □ $□_1 - {}_4$ are the short-run coefficients for the lagged differences of Human development index, Solar Energy Consumption, Total Biomass Consumption, and hydroelectric production, respectively; while □ $□_5 - {}_8$ are the long-run coefficients. As soon linear combination was established among the variables, the paper proceeded to examine the long-run effect and the short-run dynamics using restricted error correction model modified as follows:

$$□HDI = +□_0 □_{j=0}^{p}(□_1□HDI_{t-j}) + □_{k=0}^{p}(□_2□SEC_{t-k}) + □_{l=0}^{p}(□_3□BC_{t-l}) + □_{m=0}^{p}(□_4□HEP_{t-m}) + □ect_{t-1} + v_t \quad (5)$$

RESULTS AND DISCUSSIONS

Descriptive Statistics Results

Descriptive statistics provide a preliminary understanding of the data by summarizing the central tendency, dispersion, and distributional characteristics of each variable under study. They are particularly useful for identifying the nature of the data before applying advanced econometric techniques. In this study, the descriptive statistics cover the Human Development Index (HDI), Total Biomass Consumption (BC), Solar Energy Consumption (SEC), and Hydroelectric Production (HEP), offering insights into their behavior over the 1990– 2024 period.

Table 1: Summary statistics

	HDI	BC	SEC	HEP
Mean	0.486857	5127.226	55.89657	28.14876
Maximum	0.540000	10598.70	319.2300	41.86490
Minimum	0.410000	2135.200	0.250000	13.01205
Std. Dev.	0.040567	2496.549	83.03970	8.517616

Skewness	-0.36667	0.663404	1.775067	-0.07824
Kurtosis	1.870436	2.276804	5.250080	1.709638
Jarque-Bera	2.645001	3.330004	25.76338	2.463880
Probability	0.266468	0.189190	0.000003	0.291726
Observations	35	35	35	35

Source: Researcher's Computation Using EViews-12 (2025)

The Human Development Index showed a mean value of 0.487, with a maximum of 0.540 and a minimum of 0.410. This indicated a gradual but modest improvement in human development outcomes in Nigeria over the years, with relatively low variability as reflected in a standard deviation of 0.041. The negative skewness (0.367) suggested that HDI values were slightly concentrated at the higher end, while the kurtosis value (1.870) being below the normal benchmark of 3 implied a flatter distribution. The Jarque-Bera test produced a probability of 0.266, indicating that HDI data were approximately normally distributed, which supports the reliability of the variable for regression analysis.

Total Biomass Consumption recorded a mean of 5127.226 PJ, with the highest value at 10,598.7 PJ and the lowest at 2135.2 PJ. The standard deviation of 2496.55 reflected significant variation over time, highlighting the increasing reliance on biomass in Nigeria. The positive skewness (0.663) indicated a concentration of data points at the lower consumption end, while the kurtosis value (2.277) suggested a relatively normal distribution but slightly flatter tails. The Jarque-Bera statistic yielded a probability of 0.189, showing no strong evidence against normality. However, the high dispersion emphasized the uneven trends in biomass reliance, which may have implications for health and environmental sustainability.

Solar Energy Consumption exhibited a mean of 55.90 GWh, with a sharp contrast between the maximum of 319.23 GWh and a minimum of only 0.25 GWh. The standard deviation of 83.04 demonstrated considerable variability, reflecting Nigeria's late but rapid adoption of solar technologies. The skewness value of 1.775 revealed strong rightward skewness, meaning most observations were concentrated at the lower levels of consumption, with only recent years showing substantial growth. The kurtosis of 5.250 was above 3, indicating a leptokurtic distribution with extreme peaks. The Jarque-Bera probability of 0.000003 confirmed nonnormality, which is expected given the exponential rise of solar energy use in recent decades.

Hydroelectric Production had a mean share of 28.15 percent of total electricity, ranging from a maximum of 41.86 percent to a minimum of 13.01 percent. The standard deviation of 8.52 showed moderate variability in hydro's contribution over the period, with fluctuations driven by water availability and infrastructural challenges. The skewness of -0.078 suggested near symmetry, while the kurtosis of 1.710 indicated a flatter distribution compared to normal expectations. The Jarque-Bera probability of 0.292 implied that hydroelectric production data were normally distributed. This stability suggested that while hydro has fluctuated, its role remained consistently significant within Nigeria's energy mix.

Unit Root Test

Unit root testing is an essential preliminary step in time series analysis, as it helps determine whether variables are stationary or require differencing to achieve stationarity. Stationarity ensures that the statistical properties of the data, such as mean and variance, remain constant over time, thereby preventing spurious regression results. In this study, the Augmented Dickey-Fuller (ADF) test was employed to assess the integration order of the variables.

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Table 2: Summary of Unit Root Test Results

Variable	Levels: ADF Test Statistics (Critical Values)	1st Difference: ADF Test Statistics (Critical Values)	Order of Integration
HDI	-2.505614 (-3.548490)	-6.473624 (-4.262735)*	I(1)
BC	-3.245880 (-3.23805)***	-	I(0)
SEC	-1.489267 (-3.65844)	-3.583839 (-3.268973)***	I(1)
HEP	-1.572125 (-3.548490)	-6.490985 (-4.262735)*	I(1)

Note: The tests include intercept with trend; * & *** significant at 1 and 10 percent.

Source: Researcher's Computation Using EViews-12 (2025)

The Human Development Index (HDI) was found to be non-stationary at levels, with a test statistic of -2.505614 against a critical value of -3.548490. However, after first differencing, it became stationary with a value of 6.473624, significant at the 1 percent level. This confirmed that HDI was integrated of order one, I(1), making it suitable for cointegration analysis within the ARDL framework.

Total Biomass Consumption (BC) showed evidence of stationarity at level, with an ADF statistic of -3.245880, which exceeded the 10 percent critical value of -3.23805. This indicated that biomass data were integrated of order zero, I(0). The implication is that biomass consumption has a relatively stable trend over the study period, unlike other renewable energy indicators that required differencing.

Solar Energy Consumption (SEC) did not attain stationarity at levels, as its test statistic of -1.489267 was above the 5 percent critical value of -3.65844. However, after first differencing, it became stationary with a test statistic of -3.583839, significant at the 10 percent level. This confirmed that solar energy was integrated of order one, I(1), which reflects the exponential growth pattern of solar adoption in Nigeria in recent years.

Hydroelectric Production (HEP) also displayed non-stationarity at levels, with a test statistic of -1.572125 against a critical value of -3.548490. At first difference, however, it achieved stationarity with a test statistic of 6.490985, significant at the 1 percent level, confirming its integration order of one, I(1). This outcome highlighted the fluctuations in hydroelectric production that became more stable only after accounting for changes in differences over time.

Cointegration Test

Cointegration analysis is a vital step in time series modeling as it helps to determine whether a long-run equilibrium relationship exists among variables that may individually be non-stationary. By establishing cointegration, one can confirm that the variables move together over time despite short-term fluctuations. In this study, the Bounds Test approach to cointegration was employed due to the mixture of I(0) and I(1) variables, making it suitable within the ARDL framework.

Table 3: Bound Test-Co-integration Results

F-Bounds Test		Null Hypothesis: No levels relationship		
Test Statistic	Value	Signif.	I(0)	I(1)
F-statistic	4.283872	10%	2.37	3.20

k	3	5%	2.79	3.67
		1%	3.65	4.66

Source: Researcher's Computation Using EViews-12 (2025)

The results from the Bounds Test reported an F-statistic value of 4.283872. When compared to the critical values at the 5 percent level of significance, the F-statistic was greater than the upper bound I(1) value of 3.67. This outcome indicated a rejection of the null hypothesis of no levels relationship, confirming that a long-run cointegrating relationship existed among the variables.

ARDL-ECM and Long Run Results

The study confirmed the existence of a cointegrating relationship between renewable energy indicators and sustainable development in Nigeria. Consequently, it advanced to the estimation of both the error correction model and the long-run dynamics. The ARDL-ECM framework was employed to demonstrate how the system adjusts toward long-run equilibrium following short-term fluctuations.

Table 4: ARDL-ECM and Long Run Estimates

Dependent Variable: D(RGDP)

Short-run Estimates				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(HDI(-1))	1.0318	0.2679	3.8511	0.0018
D(HDI(-2))	0.6666	0.2168	3.0745	0.0082
D(HDI(-3))	0.6717	0.2022	3.3216	0.0050
D(BC)	0.0991	0.0362	2.7357	0.0161
D(BC(-1))	-0.2968	0.0721	-4.1188	0.0010
D(BC(-2))	0.0936	0.0584	1.6010	0.1317
D(BC(-3))	0.0973	0.0461	2.1087	0.0535
D(SEC)	0.5927	0.1288	4.6018	0.0004
D(SEC(-1))	-0.7850	0.1948	-4.0301	0.0012
D(SEC(-2))	1.0750	0.2191	4.9061	0.0002
D(HEP)	-0.0008	0.0012	-0.7068	0.4913
D(HEP(-1))	-0.0018	0.0011	-1.6256	0.1263
CointEq(-1)*	-0.6126	0.1167	-5.2478	0.0001
Long-Run Estimates				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
BC	0.0144	0.0147	0.9831	0.3423
SEC	0.0812	0.0341	2.3787	0.0322

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HEP	0.0284	0.0087	3.2784	0.0055
C	-0.0450	0.4226	-0.1066	0.9166
Goodness of Fit				
R-squared	0.6724			
Adjusted R-squared	0.4540			
Durbin-Watson stat	1.7636			

Source: Researcher's Computation Using EViews-12 (2025)

The error correction term [CointEq(-1)] from the ARDL short-run dynamics provided valuable insight into the speed of adjustment toward long-run equilibrium when deviations occur. The coefficient was negative and statistically significant at the 1 percent level, with a value of -0.6126 and a probability of 0.0001. This confirmed the presence of a stable long-run relationship among the variables, consistent with the earlier cointegration results. The magnitude of the coefficient suggested that approximately 61 percent of the disequilibrium in the Human Development Index from the previous period was corrected in the current period. This implied a relatively fast speed of adjustment back to equilibrium whenever shocks or short-term fluctuations disturbed the system

The long-run estimates from the ARDL model provided insights into the sustained effects of renewable energy indicators on sustainable development. Total Biomass Consumption (BC) recorded a positive coefficient of 0.0144, suggesting that an increase in biomass use was associated with improvements in HDI. However, the relationship was not statistically significant at the 5 percent level, with a probability value of 0.3423. This outcome implied that biomass, despite being widely consumed in Nigeria, did not exert a meaningful long-term influence on human development. The lack of significance could be attributed to the dominance of traditional biomass use, such as firewood and charcoal, which poses health and environmental risks and limits its developmental benefits when compared to modern bioenergy technologies.

Solar Energy Consumption (SEC) yielded a negative and statistically significant coefficient of -0.0812, with a probability value of 0.0322. This indicated that in the long run, higher levels of solar energy consumption were associated with reductions in HDI. This result appeared counterintuitive, given the potential of solar power to enhance access to electricity and development outcomes. One possible explanation is that Nigeria's solar deployment, although growing rapidly, has faced challenges of high costs, inconsistent policy support, and limited grid integration, which may have hindered its broader developmental impact. Thus, while solar energy adoption has expanded, its long-term contribution to human development remained constrained by structural and institutional bottlenecks.

Hydroelectric Production (HEP) showed a positive and statistically significant coefficient of 0.0284, with a probability value of 0.0055, making it the most robust determinant of HDI among the renewable energy indicators. This result suggested that increases in hydroelectric generation contributed significantly to long-run improvements in human development outcomes. As a relatively mature and large-scale energy source in Nigeria, hydroelectricity has supported electrification, industrial activity, and household energy access, thereby reinforcing its positive role in human development. However, the reliance on hydro is still subject to vulnerabilities such as climate variability and infrastructural limitations, which can affect its stability over time.

The R-squared value of 0.6724 indicated that about 67 percent of the variation in the Human Development Index was explained by the independent variables, solar energy consumption, total biomass consumption, and hydroelectric production, alongside other model dynamics. This suggested that renewable energy indicators accounted for a substantial proportion of the variations in sustainable development in Nigeria over the study period.

The adjusted R-squared, which adjusts for the number of predictors, was lower at 0.4540. This implied that while the model retained a fair level of explanatory strength, some of the variation in HDI was influenced by other factors not captured in the model, such as governance, education policy, or healthcare infrastructure. Nevertheless, the value remained acceptable for time series analysis where multiple external influences often affect development outcomes.

The Durbin-Watson statistic of 1.7636 was close to the benchmark value of 2, suggesting that the model did not suffer from serious autocorrelation problems. This enhanced the reliability of the regression results and indicated that the residuals were relatively independent over time.

DISCUSSION OF FINDINGS

Findings from the study showed that total biomass consumption had a positive but insignificant impact on sustainable development in Nigeria. The implication of this result is that although biomass remains the most widely consumed renewable energy source in Nigeria, its traditional form of use, through firewood, charcoal, and inefficient stoves, has not translated into tangible improvements in the Human Development Index. The continued reliance on biomass has been associated with negative health outcomes, environmental degradation, and low productivity, thereby limiting its developmental potential. This outcome aligns with the findings of Sztumski (2023), who argued that biomass energy has not achieved its potential due to unsustainable practices and lack of investment in clean cooking technologies. Similarly, Pata et al. (2023) in their German study reported that traditional biomass consumption often constrained human development, especially in rural areas where poverty and limited access to modern energy services are prevalent. However, the result contradicts the findings of Saud et al. (2024), who found a positive and significant relationship between bioenergy and human development in ECOWAS countries, emphasizing that with proper modernization, biomass could play a crucial developmental role.

The study also revealed that solar energy consumption had a negative and significant impact on sustainable development. This finding implied that although solar power has expanded considerably in recent years, structural, institutional, and financial barriers have limited its ability to enhance HDI outcomes in Nigeria. Challenges such as high installation costs, unreliable maintenance frameworks, and weak policy support have hindered solar's developmental effectiveness. This result agrees with the argument of Saud et al. (2023), who noted that despite the rapid solar expansion in the United Arab Emirates, inadequate integration and poor financing structures reduced its broader development impact. In the Nigerian context, Agbakwuru et al. (2024) similarly found that while solar projects improved energy access, their overall contribution to human development remained weak due to governance and regulatory inefficiencies. Nonetheless, this result stands in contrast with the study of Zhang and Li (2024) in China, which reported that solar energy significantly improved human development, particularly in provinces where government subsidies and technological investments were strong, underscoring the importance of institutional capacity in shaping outcomes.

Furthermore, the findings indicated that hydroelectric production had a positive and significant impact on sustainable development. This suggested that hydropower remains the most reliable renewable energy source in Nigeria, with substantial contributions to electrification, industrial output, and improvements in education and health through enhanced energy access. The result corroborates the findings of Candra et al. (2023), who found that hydroelectric power played the most significant role in improving human development outcomes in Brazil due to its large-scale capacity and infrastructure. Likewise, Leclerc and Ndiaye (2022) in their study on West Africa reported that countries with stable hydro infrastructure recorded stronger improvements in HDI compared to those relying on other renewable sources. However, the finding differs from Aboul-Atta and Rashed (2021), who argued that hydropower in Sub-Saharan Africa faces significant vulnerabilities from climate change and seasonal water variability, which undermine its long-term developmental contribution.

CONCLUSION AND RECOMMENDATIONS

This study set out to examine the impact of renewable energy indicators, solar energy consumption, total biomass consumption, and hydroelectric production, on sustainable development in Nigeria, measured by the

Human Development Index. The findings established that the long-run effects of these indicators varied significantly, highlighting their distinct developmental roles. First, biomass consumption, though positive, was insignificant, implying that its current reliance in traditional forms has limited developmental value. This underscored the persistent challenge of health risks and inefficiencies associated with unsustainable bioenergy practices. Second, solar energy consumption exerted a negative but significant influence, suggesting that despite its potential, structural bottlenecks such as high costs, weak policy support, and inadequate integration have hindered its contribution to human development. Third, hydroelectric production showed a positive and significant impact, reinforcing its role as the most dependable renewable source in driving long-term improvements in education, health, and income outcomes. Collectively, these results confirmed that renewable energy is crucial, but its developmental benefits are uneven across sources.

Based on the findings, a key recommendation are as follows:

For biomass consumption is the urgent modernization of the sector to transition from traditional to clean bioenergy solutions. The Federal Ministry of Environment, in collaboration with the Global Alliance for Clean Cookstoves and the Energy Commission of Nigeria, should intensify efforts to promote clean cooking technologies, subsidize efficient stoves, and invest in sustainable forestry programs. Such measures would reduce the health and environmental burdens associated with biomass while enhancing its developmental contribution. ii. For solar energy, the negative but significant impact calls for policy and institutional strengthening to unlock its potential. The Rural Electrification Agency (REA) and the Nigerian Electricity Regulatory Commission (NERC) should prioritize transparent financing frameworks, expand publicprivate partnerships, and ensure better integration of solar into the national grid. Additionally, the Central Bank of Nigeria (CBN) can provide low-interest credit facilities for small-scale solar projects to improve accessibility and affordability. iii. In terms of hydroelectric production, the positive and significant result indicates that consolidating and safeguarding this energy source is vital. The Federal Ministry of Power, in partnership with the Transmission Company of Nigeria (TCN) and the Nigerian Hydrological Services Agency, should prioritize maintenance of existing dams, expand hydropower capacity, and strengthen climate resilience measures to safeguard water resources. These institutions should also work with state governments to ensure that infrastructural and ecological challenges are addressed to preserve hydroelectricity’s long-term developmental benefits.

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