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The Role of Research and Development in Renewable Energy Consumption - Sustainable Human Development Nexus: Evidence from EAC Member Countries

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ABSTRACT

The pressing challenges of climate change and energy access in the East African Community (EAC) necessitate a strategic focus on research and development (R&D) to enhance renewable energy consumption and support sustainable human development. This study investigates the critical role of research and development (R&D) in promoting renewable energy consumption and its impact on sustainable human development within the East African Community (EAC). As global climate change intensifies, the transition from conventional energy sources to renewable alternatives is essential for fostering economic growth and improving human development indicators. Despite the recognized potential of renewable energy, EAC nations face challenges, including inadequate funding for R&D, limited technological capabilities, and ineffective policy frameworks. This paper analyzes the intricate relationship between R&D investments and renewable energy adoption, utilizing a comprehensive econometric approach with data spanning from 1996 to 2021. The study employs advanced econometric estimators, including Feasible Generalized Least Squares (FGLS) and Panel-Corrected Standard Errors (PCSE), alongside robustness tests such as Driscoll-Kraay standard errors and Fully Modified Ordinary Least Squares (FMOLS). The findings reveal that enhancing R&D is vital for overcoming barriers to renewable energy implementation, ultimately contributing to sustainable development goals. The study underscores the necessity for targeted policy interventions that leverage R&D to facilitate technological advancements, improve energy efficiency, and promote equitable access to renewable energy resources in the EAC region.

Keywords: Sustainable Human Development, Renewable Energy Consumption, Technological Progress, EAC Countries
JEL Classifications: O15, Q2, O3, O55

1. INTRODUCTION

The pressing need to tackle global climate change has resulted in a greater focus on the use of renewable energy sources as a viable and enduring solution. The Sustainable Development Goals (SDGs) set by the United Nations emphasize the urgency of taking immediate measures to address climate change and its consequences, with a specific focus on Goal 13. Renewable energy consumption is considered an essential aspect of sustainable human development, particularly in regions such as the East African Community (EAC), where energy access and environmental sustainability are closely tied to economic and social challenges (United Nations, 2020; Martínez and Ebenhack, 2008).

The shift from conventional energy sources such as biomass and fossil fuels to renewable options like solar, wind, and geothermal energy is essential for promoting economic progress and enhancing human development indicators in numerous developing nations, including those in the East African Community (EAC). Nevertheless, this shift is filled with difficulties, such as insufficient funding for research and development (R&D), restricted technological capacities, and ineffective policy structures. These constraints hinder the widespread use of renewable energy and worsen the already existing disparities in energy accessibility, thereby impeding advancements in human development (Wang et al., 2020; Tran et al., 2019).

The correlation between the utilization of renewable energy and the level of human development is intricate and diverse. Several studies indicate a clear link between energy consumption and positive changes in health, education, and income (Martínez and Ebenhack, 2008). However, other research emphasizes the negative environmental consequences that come with high energy consumption, especially in developed countries (Tran et al., 2019). In the East Africa Community (EAC) region, there is an unequal distribution of energy access. In this context, research and development (R&D) play a crucial role in making sure that renewable energy technologies are accessible and efficient in supporting sustainable development as has been highlighted by Alper and Oguz (2016) and Hickel (2020).

The slow rate of adoption of renewable energy in the EAC region raises important issues regarding the obstacles that are impeding this transformation, despite the acknowledged promise of renewable energy to drive human growth. An important problem is the inadequate allocation of funds towards research and development in order to create and implement technologies that are appropriate for the specific local circumstances. Although biomass remains a prevalent energy source in several EAC nations, its inefficient utilization persists as a significant factor in environmental degradation and negative health consequences (Wang et al., 2020; Dumor et al., 2022). Moreover, the implementation of more sophisticated renewable energy technologies, such as solar and wind power, is frequently impeded by exorbitant expenses and a scarcity of technical proficiency (Xu and Khan, 2023).

This study asserts that the allocation of resources towards research and development (R&D) is crucial in order to overcome the obstacles hindering the widespread acceptance of renewable energy in the East African Community (EAC) region. Furthermore, it emphasizes that such investment is necessary to ensure that these technologies effectively contribute to sustainable human development. Through the promotion of technological advancements and the enhancement of energy efficiency, research and development (R&D) can facilitate the shift of these nations towards renewable energy sources.

This transition not only improves their human development indicators but also reduces the negative environmental effects associated with conventional energy consumption (Nguyen et al., 2023; Imran et al., 2022). The data from other regions, such as the European Union (EU) and the BRICS countries (Brazil, Russia, India, China, and South Africa), highlights the significant role that research and development (R&D) has played in promoting the adoption of renewable energy. This emphasizes the potential advantages that the East African Community (EAC) may gain by investing in R&D for renewable energy (Alper and Oguz, 2016; Wang et al., 2020).

The relationship between the use of renewable energy and sustainable human development in the East African Community (EAC) has not been thoroughly studied, especially on the impact of research and development (R&D). This study aims to address this deficiency by investigating the impact of research and development (R&D) on the adoption of renewable energy technologies in the East African Community (EAC). Additionally, it aims to explore how these technologies might contribute to sustainable human development. The results of this study will offer significant knowledge for policymakers and stakeholders in the EAC area, enabling them to establish and execute plans that utilize research and development (R&D) to accomplish their sustainable development objectives (Shahbaz et al., 2022; Zeraibi et al., 2020).

Ultimately, the significance of research and development in aiding the shift towards renewable energy cannot be emphasized enough, as the member nations of the East African Community (EAC) work towards achieving their sustainable development goals. By tackling the technological and infrastructural obstacles that now impede the adoption of renewable energy, research and development (R&D) has the capacity to revolutionize the energy scenario in the East African Community (EAC), promoting both economic expansion and advancements in human development. The current article aims to thoroughly examine these dynamics, providing evidence-based suggestions for improving the contribution of research and development (R&D) to the sustainable development agenda of the region.

Figure 1 illustrates technological progress in East African countries from 1995 to 2020. Kenya shows the most significant growth, especially after 2010, indicating rapid advancements. Tanzania also exhibits notable increases, particularly from 2010 onward. Rwanda demonstrates consistent progress, while Uganda shows a gradual rise but remains lower than Kenya and Tanzania. In contrast, Burundi experiences minimal growth throughout the period, and the Democratic Republic of the Congo shows fluctuations, generally maintaining a lower level of technological progress. This highlights disparities in technological development, with Kenya leading and Burundi and the DRC lagging behind, suggesting areas for further investment and improvement.

Figure 1: Trend of EAC member nations' technological progress from 1996 to 2021

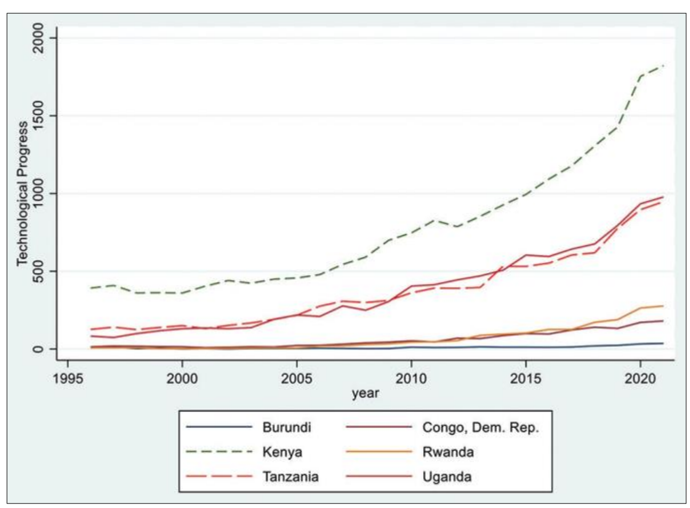


Figure 2 shows the Sustainable Human Development indices for East African countries from 1995 to 2020. Kenya exhibits the most significant growth, especially after 2010, indicating substantial improvements in health, education, and economic stability. Tanzania shows gradual progress, while Rwanda demonstrates notable increases, particularly post-2005. Uganda exhibits steady growth but at a slower pace. In contrast, Burundi shows minimal improvement, highlighting persistent challenges, and the Democratic Republic of the Congo remains relatively stagnant with slight fluctuations. This data reflects varying levels of sustainable human development, underscoring the need for targeted efforts in countries facing developmental challenges.

Figure 3 depicts trends in renewable energy consumption among East African countries from 1995 to 2020. Burundi shows stable but low levels of consumption, while Kenya initially peaks around 2005 before experiencing a decline. Tanzania exhibits a gradual decrease, reflecting shifts in energy sources. Rwanda maintains a relatively stable consumption level, whereas Uganda displays a steady decline, indicating a significant move away from renewable energy. The Democratic Republic of the Congo also shows a downward trend. Overall, the data highlights declines in renewable energy consumption across the region, suggesting a need for renewed focus on sustainable energy policies.

Figure 2: Trend of EAC member nations' sustainable human development from 1996 to 2021

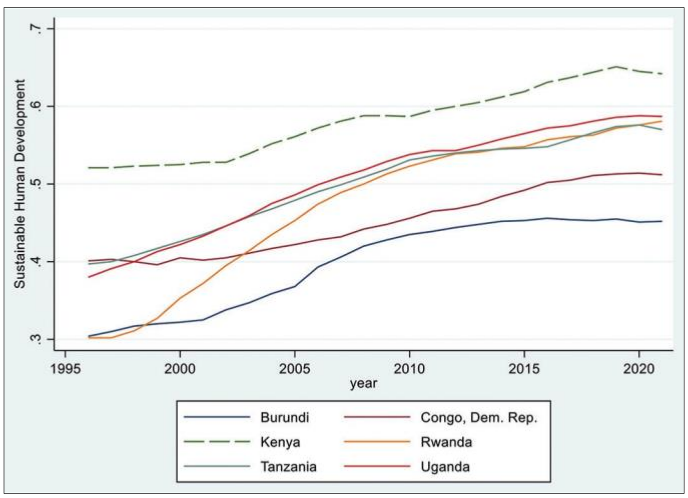
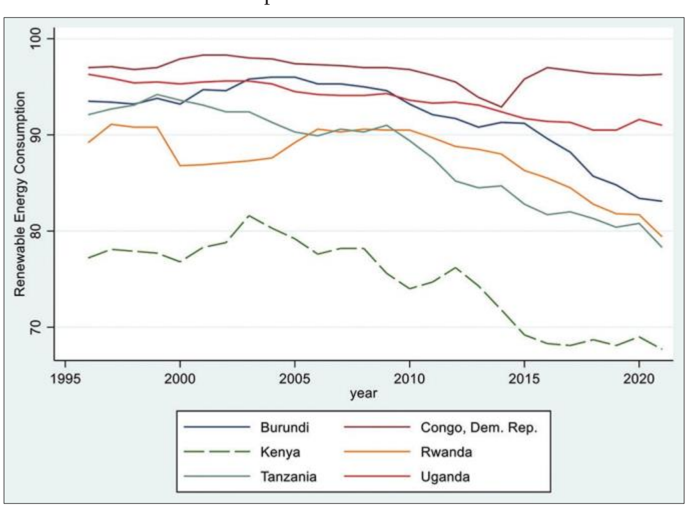


Figure 3: Trend of EAC member nations' renewable energy consumption from 1996 to 2021



2. LITERATURE REVIEW

2.1. Renewable Energy Consumption and Human Development

The United Nations Sustainable Development goal (SDG) 13 emphasizes the need to address the global challenge of climate change and its associated effects. One of the identified strategies to resolve climate change is the adoption of renewable sources of energy. There has been deliberate push towards renewable sources of energy especially in developing countries due to disproportionate adverse impact of climate change on their economies. Various studies have been published to discuss the connection between renewables sources of energy consumption and human development. The extant literature contends a direct correlation exists between renewable energy consumption and improvements in human development indicators such education, healthcare, foreign direct investment and infrastructure.

Energy consumption is an integral component in the development of any country. It is the engine that powers majority of the sectors including manufacturing and transport. Countries with high energy consumption levels are believed to rank highly in the human development index. According to Martínez and Ebenhack (2008) a strong correlation between index values and energy consumption is evident across most regions globally. Additionally, a notable secondary trend emerges from the data, highlighting major energy exporters such as OPEC countries and several former Soviet Union states. Preliminary analysis indicates that these two trends resemble saturation curves often seen in natural systems.

The primary trend can be broken down into three distinct regions: a sharp increase in human development relative to energy consumption for energy-poor countries, a moderate increase for nations in transition, and minimal growth in human development for energy-rich nations with high levels of modern energy consumption. These relationships suggest that even limited access to energy could significantly improve human development in the world's poorest regions. Martínez and Ebenhack (2008) most poor economies in the East African region heavily rely on biomass such wood fuel for energy sources despite having more efficient sources of energy such as coal that are not fully exploited by their government. Even though the study argues that transition to more efficient sources of energy spurs economic growth in these economies, it fails to provide specifics on these energy sources more specifically on renewable energy.

It is an irrefutable fact that high energy consuming countries especially developed economies such as China, European Union and North American are some of the largest polluters. This is largely attributed to the high levels of industrialization in these countries. However, boasts of a high development index. In contrast most countries in the developing economies have low energy consumption and low human development index. The pollution levels are significantly lower. Tran et al. (2019) argue of a tradeoff between the environment, energy consumption and human development index. Using system-generalized method of moment approach (SGMM) comparing energy consumption level, carbon emissions and human development index of various countries between 1990 and 2014. The findings suggest that increased human development correlates with lower carbon emissions globally and in developing countries. However, in developed nations, no significant link between carbon emissions and human development is observed. Additionally, no causal relationship is found between energy consumption and human development, either globally or within subpanels. Given the inclusion of a non-linear term for human development in environmental equations, the U-shape hypothesis is not supported by this study. Thus, despite some positive outcomes, the research indicates that environmental policies targeting carbon emissions and energy usage are unlikely to impact human development across different stages of economic growth. The results by Tran et al. (2019) dispute the hypothesis of being a direct correlation between renewable energy sources and human development. Adoption of renewable sources of energy is less likely to promote economic growth and sustainable development unless other underlying factors are addressed such as poor governance. This idea of using energy consumption as a measure of human development has been disputed by Hickel (2020) who argues, HDI only focuses on the income levels in a particular country without evaluating the ecological impact of the various economic activities. A strong correlation exists between income and ecological impact. High income countries contribute to the highest ecological breakdown. This suggests that a country with a high HDI is serious contributor to climate change which inadvertently negatively affective sustainable development. This also means that the source of energy irrespective of being renewable will not encourage sustainable development.

Despite the skepticism the relationship between renewable sources of energy and sustainable human development (Alper and Oguz, 2016) hypothesizes a strong correlation on the same issue. In their paper they explore the causal relationships among economic growth, renewable energy consumption, capital, and labor in new EU member countries from 1990 to 2009, using an asymmetric causality test and the autoregressive distributed lag (ARDL) approach. The empirical findings indicate that renewable energy consumption positively affects economic growth across all the countries studied. However, statistically significant impacts on economic growth were only found in Bulgaria, Estonia, Poland, and Slovenia. The results also support the neutrality hypothesis in Cyprus, Estonia, Hungary, Poland, and Slovenia, while the conservation hypothesis is evident in the Czech Republic. Additionally, a causal relationship from economic growth to renewable energy consumption is identified, with the growth hypothesis supported in Bulgaria, indicating causality from energy consumption to economic growth. This indicates that factors unique to every country are critical sustainable human development irrespective of energy consumption of levels.

Biomass as a renewable source of energy has gained prominence in literature. It is seen as a key factor in sustainable human and economic development due to limited environmental damage. Wang et al. (2020) explore the adoption of biomass in BRICS a key an element in their sustained economic success. Using multiple regression model the indicate that Human development is influenced by Biomass energy consumption in conjunction with other factors such trade openness, industrialization, foreign direction investment and economic growth. The study highlights the importance of renewable energy in sustainable human development but it also acknowledges the role of other integral elements whose absence portends negative HDI for a country. Rehman (2019) delves into the nexus between electric access, population growth and economic growth. He avers that electricity plays an indisputable role in the sustainable development of a country. Using Pakistan as a case study and applying the ARDL technique the results indicate that access to electricity and population growth in urban areas have a positive relationship with economic growth, whereas access to electricity and population growth in rural areas exhibit a negative relationship with economic growth.

This finding seems to suggest that energy consumption has mixed impact on a given population depending on subjective environment. Another key issue that has often stifled the development of many developing countries is public debt. These negative influences sustainable human development. Wang et al., (2021) argue adoption of renewable energy positively influences human development. However, when the mediating variable of public debt is introduced human development drops. This implies that even though renewable energy is critical for the improvement of key sectors in the economy such as education and healthcare, a country with crippling debt levels cannot experience human development growth. This has often resulted in developing countries applying for official development assistance (ODA) to cushion its citizens and stimulate economic growth. However, Ezako (2024) notes that ODA has negative impact in the economic development of many countries especially in the developing economies largely due corruption. Proper governance promotes positive economic growth regardless of whether a country transitions to renewable energy.

2.2. R&D, Renewable Energy Consumption, and Sustainable Human Development

Many policymakers prioritize energy efficiency as a key strategy for meeting various energy objectives, such as enhancing energy security and access, reducing air pollution and fuel poverty, boosting employment, and improving industrial competitiveness. Additionally, scenarios for reducing CO_2 emissions acknowledge the crucial role energy efficiency will play. Energy efficiency also has strong synergies with renewable energy, and together, they can achieve greater outcomes than they would independently. A key factor in achieving energy efficiency in the availability of the relevant technology. Billions of dollars have been invested in research and development of various technologies that are critical in promoting energy efficiency and minimizing carbon emissions. This is especially in storage, transmission and consumption. Lithium-ion batteries and solar panels have emerged as the most sustainable forms of energy in the modern era. Even though there has been massive uptake of this technologies in the developed economies, their adoption the developing countries is minimal. In East Africa countries usage is below 10%. Most people still rely on fossil fuel. According to Dumor et al. (2022)

universal access to renewable and modern energy technologies is essential in the improvement of the human development index of a country. Utilizing the dynamic autoregressive-distributed lag (DARDL) model with data from 1980 to 2020 for the East African Community (EAC), the research reveals that, in the long term, human development, electricity access, and trade are strongly correlated with increased carbon emissions, while fossil energy usage and economic growth have a negative relationship with emissions. In the short term, however, human development and fossil energy usage show a positive correlation with carbon emissions, while economic growth and foreign direct investment have a negative impact. The study highlights the importance of policy reforms that improve the political environment in East Africa to achieve realistic access to clean, modern electricity. In alignment with the EAC's environmental policy, the study advocates for initiatives that increase the availability of renewable energy and encourage investment in energy-efficient technologies.

A multiplicity of studies suggests that investment in research and development promotes renewable energy consumption which in terms leads to sustainable human development. According to Xu and Khan (2023) the simultaneous growth in research and development (R&D) drives economic growth, decreases CO2 emissions, and enhances the efficiency of clean energy production across various economic sectors. Additionally, the use of clean energy, along with oil, natural gas, and other forms of green energy, contributes to the reduction of carbon emissions. Nguyen et al., (2023) argues that renewable energy technology are instrumental in enhancing human development.

Their study investigates the impact of renewable energy on human development across 77 countries, including high- and middle-income nations, from 2000 to 2019. Using the panel-corrected standard error (PCSE) model to address heteroscedasticity, serial correlations, and cross-sectional dependencies (CD), the findings reveal a positive relationship between renewable energy adoption and human development in health, education, and income. This link holds across various renewable energy sources, such as hydropower, solar, and wind. However, when analyzing high- and middle-income nations separately, the results show differing effects. For instance, hydropower negatively affects income in high-income countries, while solar, wind, and hydro energy have negligible or less significant impacts in middle-income countries.

This study underscores the importance of renewable energy in advancing human development but highlights the need for tailored strategies based on income levels and specific energy sources. Even though the study discusses renewable energy it fails to identify the specific technologies and research and development efforts to achieve them. Imran et al. (2022) underscore the importance of R & D as key elements in creating renewable sources of energy that guarantee sustainable development. Using the Autoregressive Distributed Lag (ARDL) testing method, the study demonstrates that carbon emissions increase with the use of chemicals in production, the burning of fossil fuels, and economic expansion. Conversely, emissions decrease when nations invest in renewable energy technologies and effectively manage industrial waste. Granger causality estimations confirmed a feedback loop between industrial chemical usage and carbon emissions, while also showing a unidirectional causality from chemical use to demand for green energy and fossil fuel combustion. Furthermore, fossil fuel burning, and energy demand contribute directly to carbon emissions, and emissions are also generated from industrial waste handling.

Over the next few decades, chemical usage is expected to have the greatest influence on carbon emissions, followed by industrial waste, renewable energy supply, fossil fuel combustion, and renewable energy technologies. To achieve environmental sustainability through emissions reduction, the study proposes policies aimed at fostering a low-carbon economy, promoting renewable energy sources, and encouraging sustainable management practices.

It emphasizes the importance of investing in research and development (R&D) for clean energy and environmental sustainability to establish a long-term sustainable energy strategy that is environmentally friendly. The importance of R &D is farther elaborated by Shahbaz et al. (2022) who contend that R&D expenditures have a positive effect on clean energy consumption, while increased R&D leads to a reduction in both total energy consumption and the use of dirty energy sources. The study reveals that importance of R and D is guaranteeing energy efficiency is necessary for human development. A similar study by Zeraibi et al. (2020) confirmed that investment in technological innovation is a vital ingredient in fostering energy efficiency for the success for economic success. However, it fails to address the sectors of the economy that shall benefit from this innovation.

2.3. R&D and Technological Progress/Technological Innovation

The emergence of the fourth industrial revolution has seen unprecedent technological innovation in different sectors and the energy sector is not an exception. With the challenge of climate change efforts have been made towards promoting energy efficiency to reduce the impact of carbon emissions from fossil fuels. Khan et al., (2020) introduce the idea of eco-innovation in promotion renewable sources of energy. Using panel data from 1995 to 2017 for G-7 countries they discuss the heterogenous effect of eco-innovation on sustainable development of a country/The results indicate that eco-innovation fosters human development by focusing on alternative source of energy.

The renewable energy trends policy network presents key technological innovation and progress in renewable energy. The first is Biomass. Bioenergy, in both traditional and modern forms, is the largest contributor to the global renewable energy supply. In 2016, approximately 62.5 exajoules (EJ) of primary energy came from biomass, with supply growing at around 2.5% annually since 2010. Despite a 21% increase in global energy demand over the past decade, bioenergy's share of global primary energy consumption has remained steady at around 10.5% since 2005. Bioenergy's contribution to final energy demand for heating in buildings and industry significantly exceeds its use for electricity generation and transportation combined. Research and development has been key in converting biomass into liquid biofuel is which contributes to less carbon emissions compared to fossil fuels. Additionally the (*REN21*, 2017) acknowledges the importance of Research and Development in fostering the transition from wood fuel to Biofuels especially in developing economies in the East African region. The second is Geothermal power. Geothermal resources provide both electricity and thermal energy services, including heating and cooling.

In 2016, the estimated combined output from geothermal sources was 567 petajoules (PJ) or 157 terawatt-hours (TWh), with electricity and thermal energy contributing roughly equal shares. Some geothermal plants are designed to produce both electricity and thermal output for various heating applications. In 2016, approximately 0.4 gigawatts (GW) of new geothermal power capacity was added, increasing the global total to an estimated 13.5 GW. Indonesia and Turkey led the way in new installations, with Kenya, Mexico, Japan, and other countries also completing projects and developing future initiatives. Research and Development effort have seen new technologies emerge such as the enhanced (or engineered) geothermal systems which enable efficient exploitation of geothermal energy.

The third is hydropower. This is one of the most prevalent forms of renewable energy with adoption in East African countries. However, the lack of the necessary technology has limited the maximum exploitation of this form of energy and its transmission to the end user. Nuclear is another renewable sources energy that has been extensively cover by Baek (2016). He avers that advancements in nuclear technology has made it possible for countries to build nuclear reactors that generate energy that is sustainable. With the availability of raw materials in the East African region these economies can exploit nuclear energy to foster economic development.

3. METHODOLOGY

This study adopts a comprehensive econometric approach to assess the impact of technological progress and renewable energy consumption on sustainable human development within the East African Community (EAC). The methodology is structured into several detailed components, which aim to ensure rigorous analysis and reliable results.

3.1. Source of Data

Data for this study were gathered from various authoritative sources. The primary data set was derived from the World Bank, which provided essential macroeconomic indicators, including Gross Domestic Product (GDP), Gross Capital Formation (GCF), renewable energy consumption statistics, technological progress (TECH), and inflation rates. These indicators are crucial for understanding the economic landscape and the role of technology and energy in promoting sustainable development.

In addition to these macroeconomic indicators, the study utilized the Human Development Index (HDI) sourced from the United Nations Development Program (UNDP). This index offers valuable insights into the overall well-being and development status of countries within the EAC. Furthermore, the Sustainable Development Index (SDI), which serves as a proxy for sustainable human development, was obtained from Hickel (2020). This index provides a comprehensive perspective on the sustainability efforts and outcomes in the region.

The dataset covers the period from 1996 to 2021, which provides a robust temporal framework for analyzing trends and relationships among the selected variables. This extensive timeframe allows for the examination of long-term patterns and the identification of significant changes over the years.

Before proceeding with advanced econometric techniques, cross-sectional dependence tests were conducted to assess the interdependence among EAC countries. This preliminary analysis confirmed the presence of correlations and shared shocks among the countries, which is critical for ensuring that subsequent econometric models adequately account for these dynamics. Recognizing interdependencies between countries enhances the validity of the analysis and allows for a more accurate understanding of the relationships between technological progress, renewable energy consumption, and sustainable human development in the EAC context.

3.2. Theoretical Framework

Innovation that is designed to promote sustainability has become a critical focus area for empirical research (Schiederig et al., 2012). Technological innovation is considered an essential approach to providing sustainable products and services by contemporary researchers. Economic theory has long acknowledged the role of technological innovation as a catalyst for social and economic transformation. Against this backdrop, the theoretical framework for this study centers on the interplay between technological progress, renewable energy consumption, and sustainable human development within the East African Community (EAC). Grounded in innovation theory, it emphasizes R&D as a critical driver of technological advancement, fostering new renewable energy technologies essential for economic growth. Sustainable development theory underlines the importance of balancing economic, social, and environmental dimensions, aligning with the adoption of renewable energy to enhance human development indicators.

The framework further explores the nexus between energy consumption and human development, highlighting that increased access to renewable energy can improve health, education, and overall quality of life. Finally, the socioeconomic context of the EAC, marked by high poverty levels and reliance on traditional energy sources, shapes the dynamics of technological progress and renewable energy consumption, influencing energy policies and adoption rates. This comprehensive framework aims to elucidate the complex interactions among these elements, providing valuable insights for policymakers and stakeholders in the region.

3.3. Model Specification

The proposed model aims to analyze the relationship between technological progress, renewable energy consumption, and sustainable human development in the East African Community (EAC). This econometric model can be expressed as:

Main effect model:

$$InSDI_{it} = \beta_0 + \beta_1 \ln REC_{it} + \beta_2 \ln TECH_{it} + \beta_3 \ln GDP_{it} + \beta_4 \ln GCF_{it} + \beta_5 \ln INFL_{it} + \varepsilon_{it} \quad (1)$$

Interactive effect model:

$$InSDI_{it} = \phi_0 + \phi_1 \ln REC_{it} + \phi_2 \ln TECH_{it} + \phi_3 \ln GDP_{it} + \phi_4 \ln GCF_{it} + \phi_5 \ln INFL_{it} + \phi_6 \ln(TECH*REC)_{it} + \varepsilon_{it} \quad (2)$$

In this equation, SDI_{it} represents the Sustainable Human Development for country i at time \(t, while $TECH_{it}$, REC_{it}, GDP_{it}, and GCF_{it} denote the respective variables for technological progress, renewable energy consumption, gross domestic product, gross capital formation and inflation rate. The error term ε_{it} captures unobserved factors that may influence the dependent variable.

Sustainable Human Development (SDI) serves as the dependent variable, reflecting the overall sustainable development level of EAC countries. It encompasses economic, social, and environmental dimensions, providing a comprehensive measure of progress toward sustainability. The independent variable ($TECH_{it}$) assesses the level of technological advancements. Increased technological progress is hypothesized to enhance the development and adoption of renewable energy technologies, thereby positively influencing sustainable development.

Renewable energy consumption (REC) measures the amount of energy consumed from renewable sources. It is expected that higher REC will correlate with improved sustainable development outcomes through enhanced energy access and reduced environmental impacts. Moreover, gross domestic product (GDP) acts as an indicator of economic performance. Its inclusion is crucial as economic growth can provide the resources necessary for technological advancements and renewable energy investments, influencing sustainable development. Gross capital formation (GCF) reflects investments in physical assets, driving economic growth and technological advancements, which are posited to correlate with better sustainable development outcomes.

Given the nature of the data, which spans multiple countries and years, a panel data econometric model will be employed. This approach allows for controlling unobserved heterogeneity and capturing dynamics over time. Tests for cross-sectional dependence will be conducted to account for shared shocks and correlations among the countries. However, this model provides a structured approach to understanding the interplay between technological progress, renewable energy consumption, and sustainable human development in the EAC. By incorporating key economic indicators and utilizing advanced econometric techniques, the study aims to yield insights that can inform policy interventions to enhance sustainable development outcomes in the region.

3.4. Pre-estimation Approaches

Upon confirming cross-sectional dependence, this study employed second-generation econometric estimators to analyze the data effectively. To assess the stationarity of the time series data, the CIPS (Cross-sectionally Augmented Im-Pesaran-Shin) and CADF (Cross-sectionally Augmented Dickey-Fuller) tests were utilized, which are particularly suited for panel data exhibiting cross-sectional dependence. In examining long-run relationships among variables, the Kao, Pedroni, and Westerlund cointegration tests were applied, allowing the identification of stable long-term equilibria between research and development (R&D), renewable energy consumption, and sustainable human development metrics.

3.5. Main Estimation Methods

To address potential issues of heteroskedasticity and autocorrelation, contemporary econometric techniques were employed. The Feasible Generalized Least Squares (FGLS) method was used to provide efficient estimates by correcting both heteroskedasticity and autocorrelation in the residuals. Additionally, Panel-Corrected Standard Errors (PCSE) were applied to ensure robust standard errors that account for potential cross-sectional dependence across the countries in the dataset. To investigate directional relationships, the Dumitrescu-Hurlin causality test was performed, providing insights into whether changes in R&D and renewable energy consumption lead to subsequent variations in sustainable development indicators.

To validate the reliability of the findings, several robustness checks were conducted, including Driscoll-Kraay Standard Errors, which enable robust inference under conditions of cross-sectional dependence and autocorrelation. Furthermore, the Fully Modified Ordinary Least Squares (FMOLS) estimator was utilized to confirm the stability of the long-run relationships identified in the cointegration tests, effectively addressing potential endogeneity issues and reinforcing the study's conclusions.

The results from the econometric analyses were carefully interpreted to evaluate the relationships among R&D investment, renewable energy consumption, and sustainable human development. The rigorous framework employed in this study allowed for a nuanced understanding of these dynamics, thereby contributing valuable insights for policymakers and stakeholders in the EAC. This comprehensive methodology ensures a thorough examination of the interaction between technological progress, renewable energy, and sustainable development, addressing the specific challenges and opportunities present within the EAC context.

4. RESULTS AND DISCUSSION

Table 1 presents a detailed overview of the descriptive statistics for several key variables relevant to the analysis of the Sustainable Development Index (SDI) and its determinants among the six member countries of the East African Community (EAC). The average SDI value of 0.486 indicates moderate sustainable development, with a standard deviation of 0.083 suggesting low variability among countries. This clustering around the mean reflects some disparities in sustainable development levels, as shown by the range from 0.302 to 0.651. Renewable Energy Consumption (REC) averages 88.73, with a low standard deviation of 7.845, indicating relatively similar levels of renewable energy usage, while the range from 67.70 to 98.30 suggests a general

Table 1: Descriptive statistics

Variables	Obs	Mean	Standard deviation	Min	Max	Skew.	Kurt.
SDI	155	0.486	0.083	0.302	0.651	−0.228	2.348
REC	155	88.73	7.845	67.70	98.30	−1.012	3.151
GCF	155	19.711	8.027	2.100	39.726	0.277	3.119
TECH	155	279.036	353.283	0.930	1822.513	1.874	6.904
GDP	155	2.160e+10	2.300e+10	7.847e+08	1.097e+11	1.576	5.319
INFL	155	97.944	53.542	0.075	212.472	0.282	1.98

trend toward adopting renewable sources. Gross Capital Formation (GCF), with an average of 19.711 and a standard deviation of 8.027, highlights moderate variability in investment strategies, ranging from 2.100 to 39.726, thereby underscoring significant differences in economic priorities among the countries.

In addition, the average Technology (TECH) value of 279.036, coupled with a high standard deviation of 353.283, reveals substantial disparities in technological advancement, ranging from 0.930 to 1822.513. This variability can significantly impact economic growth and sustainable practices within the region. The average Gross Domestic Product (GDP) of approximately 2.160e+10 and a standard deviation of 2.300e+10 further emphasize the economic diversity, with values spanning from 7.847e+08 to 1.097e+11. Lastly, the inflation rate averages 97.944, with a standard deviation of 53.542, suggesting considerable variability that reflects economic instability in some countries, as indicated by the range from 0.075 to 212.472. Collectively, these findings underscore the need for tailored policy interventions that address the unique challenges and opportunities within the EAC, particularly in areas such as renewable energy adoption, capital investment, and technological advancement, all crucial for promoting sustainable development.

Table 2 presents the correlation coefficients among six key variables relevant to the analysis of the Sustainable Development Index (SDI) and its determinants. The strongest correlation is with Technology (TECH), showing a coefficient of 0.853, indicating that as technological advancement increases, sustainable development tends to improve significantly. Similarly, SDI is positively correlated with GDP in USD (GDP) at 0.808 and Gross Capital Formation (GCF) at 0.654, suggesting that higher GDP levels and increased capital investment are both associated with better sustainable development outcomes. Conversely, SDI has a notable negative correlation with Renewable Energy Consumption (REC) at −0.626. This unexpected result implies that higher renewable energy consumption may be linked to lower sustainable development outcomes, possibly reflecting inefficiencies or transitional challenges in implementing renewable energy strategies. Additionally, SDI shows a positive correlation with the Consumer Price Index (CPI) at 0.471, indicating that moderate inflation might be associated with improved sustainable development, highlighting complex economic dynamics.

Examining the relationships among the independent variables reveals further insights. REC is negatively correlated with both GCF (−0.267) and TECH (−0.569), suggesting that increased renewable energy consumption may relate to lower levels of capital formation and technological advancement. This could imply

Table 2: Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) LSDI	1.000					
(2) LREC	−0.626	1.000				
(3) LGCF	0.654	−0.267	1.000			
(4) LTECH	0.853	−0.569	0.659	1.000		
(5) LGDP	0.808	−0.443	0.619	0.883	1.000	
(6) LCPI	0.471	−0.296	0.55	0.345	0.318	1.000

LSDI: Log of Sustainable Development Index, LREC: Log of Renewable Energy Consumption, LTECH: Log of Technological Progress, LGDP: Log of Gross Domestic Product, LGCF: Log of Gross Capital Formation, LCPI: Log of Consumer Price Index, LREC_LTECH: Interaction term

Table 3: Cross-sectional dependence test results

Variable	CD-test	P-value
LSDI	18.91	0.000
LREC	13.82	0.000
LR&D	13.97	0.000
LGDP	17.84	0.000
LGCF	19.05	0.000
LINFL	18.05	0.000

that investments in renewable energy are not yet optimized for growth and innovation within the EAC context. In contrast, GCF demonstrates a strong positive correlation with TECH at 0.659, indicating that countries investing more in capital formation are also likely to have higher levels of technological advancement. Furthermore, GDP shows a strong positive relationship with TECH at 0.883, reinforcing the idea that economic growth and technological development are closely intertwined. Overall, these findings highlight the intricate relationships affecting sustainable development in the EAC, emphasizing the need for a holistic approach to policymaking that integrates economic growth, investment, and technological progress.

Table 3 presents the results of the cross-sectional dependence tests for key variables related to the Sustainable Development Index (SDI). Each variable exhibits significant cross-sectional dependence, with CD-test statistics ranging from 13.82 for Renewable Energy Consumption (REC) to 19.05 for Gross Capital Formation (GCF), all with P-values of 0.000. This indicates that changes in these indicators, including SDI, REC, R&D, GDP, and Inflation Rate (INFL), are correlated across the EAC countries. The low P-values suggest that the null hypothesis of no cross-sectional dependence can be rejected, emphasizing the need to account for this interdependence in econometric modeling. Thus, the study considers using econometric estimators that address the issue of cross-sectional dependence to ensure accurate estimates and inferences regarding sustainable development in the region.

Table 4: CIPS and CADF unit root test results

Variables	LSDI	LREC	LTECH	LGDP	LGCF	LINFL
Levels						
CIPS	−1.467	−1.608	−2.433**	−3.011***	−3.482***	−1.305
CADF	−2.385***	−2.260**	−1.567*	−2.709***	−4.775***	−1.331*
First difference						
CIPS	−2.636***	−3.404***	−5.914***	−4.714***	−5.547***	−3.362***
CADF	−1.978**	−4.040***	−5.897***	−4.671***	−7.541***	−3.329***

LSDI: Log of Sustainable Development Index, LREC: Log of Renewable Energy Consumption, LTECH: Log of Technological Progress, LGDP: Log of Gross Domestic Product, LGCF: Log of Gross Capital Formation, LCPI: Log of Consumer Price Index, LREC_LTECH: Interaction term

Table 4 presents the results of the cross-sectionally augmented Im-Pesaran-Shin (CIPS) and cross-sectionally-augmented Dickey Fuller (CADF) CADF unit root tests for key variables related to the Sustainable Development Index (LSDI) and its determinants. In the levels, LSDI, Renewable Energy Consumption (LREC), and Inflation Rate (LINFL) do not show stationarity, while Technology (LTECH), GDP (LGDP), and Gross Capital Formation (LGCF) indicate stronger evidence against the null hypothesis of a unit root. The CADF results also reveal mixed stationarity, with GDP and LGCF suggesting stationarity, while LSDI, LREC, and LINFL do not. However, when examining the first differences, all variables become stationary, with CIPS statistics confirming this trend across all variables. This indicates that differencing the data is necessary for proper econometric analysis, ensuring reliable results in the context of sustainable development in the EAC.

Table 5 presents the results of the Kao, Pedroni, and Westerlund cointegration tests applied to the variables related to the Sustainable Development Index (SDI) and its determinants, indicating strong evidence of a long-term equilibrium relationship among these non-stationary time series. The Kao test results demonstrate significant cointegration supports the rejection of the null hypothesis of no cointegration. In addition, the Pedroni test reveals significant evidence further reinforces the conclusion of cointegration. Complementing these findings, the Westerlund test indicates a stable long-term relationship among the variables provide significant evidence against the null hypothesis of no cointegration. Together, these results emphasize the importance of considering the long-term relationships among these variables in econometric modeling, which is crucial for understanding their influence on sustainable development outcomes within the region.

Table 6 presents the results from two econometric models applied to Sustainable Development Index (SDI) as the dependent variable. The models employed are the Feasible Generalized Least Squares (FGLS) and the Panel Corrected Standard Errors (PCSE) estimators. Each model is assessed under both direct and interactive specifications, elucidating the relationships among various independent variables and SDI.

The dependent variable, SDI, is analyzed alongside several independent variables, including Renewable Energy Consumption (REC), Technological progress variable (TECH), Gross Domestic Product (GDP), Gross Capital Formation (GCF), Inflation Rate (INFL), and an interaction term between Renewable Energy Consumption and technological prgress (LREC_LTECH).

Table 5: Kao, Pedroni and Westerlund cointegration tests

Cointegration approaches:	Statistic	P-value
Kao cointegration		
Modified Dickey–Fuller t	−4.821	0.000
Dickey–Fuller t	−4.547	0.000
Augmented Dickey–Fuller t	−3.539	0.000
Unadjusted modified Dickey–Fuller t	−3.077	0.001
Unadjusted Dickey–Fuller t	−4.338	0.000
Pedroni cointegration		
Modified Phillips–Perron t	3.0220	0.0013
Phillips–Perron t	1.2102	0.1131
Augmented Dickey–Fuller t	2.2685	0.012
Westerlund cointegration		
Variance ratio	2.7225	0.003

Table 6: FGLS and PCSE estimator results (direct and interactive model)

Variables	FGLS	FGLS	PCSE	PCSE
	LSDI	LSDI	LSDI	LSDI
LREC	−0.454***	−1.137***	−0.454***	−1.137***
	(0.0883)	(0.395)	(0.0507)	(0.357)
LTECH	0.0320***	−0.471*	0.0320***	−0.471*
	(0.00879)	(0.284)	(0.00704)	(0.245)
LGDP	0.0443***	0.0539***	0.0443***	0.0539***
	(0.0108)	(0.0120)	(0.0130)	(0.0121)
LGCF	0.0415**	0.0316	0.0415**	0.0316*
	(0.0190)	(0.0196)	(0.0174)	(0.0191)
LINFL	0.0214***	0.0198***	0.0214***	0.0198***
	(0.00721)	(0.00720)	(0.00500)	(0.00455)
LREC_LTECH	-	0.111*	-	0.111**
		(0.0624)		(0.0543)
Constant	4.521***	7.438***	4.521***	7.438***
	(0.431)	(1.699)	(0.375)	(1.645)
Observations	155	155	155	155
R-squared			0.810	0.814
Number of c_id	6	6	6	6

LSDI: Log of Sustainable Development Index, LREC: Log of Renewable Energy Consumption, LTECH: Log of Technological Progress, LGDP: Log of Gross Domestic Product, LGCF: Log of Gross Capital Formation, LCPI: Log of Consumer Price Index, LREC_LTECH: Interaction term.
Standard errors in parentheses; ***P<0.01, **P<0.05, *P<0.1

The results indicate that REC exhibits a significant negative relationship with SDI across both the FGLS and PCSE models. Specifically, a 1% increase in renewable energy consumption correlates with a decrease in SDI of 0.454% in the direct model and 1.137% in the interactive model. This suggests that while transitioning to renewable energy is essential, it may initially detract from sustainable development outcomes due to associated costs and inefficiencies. This finding resonates with Khan et al. (2020), who highlight the transitional challenges faced by developing regions, including the EAC, in adopting renewable energy sources.

In contrast to our findings, prior studies, such as those by Shahbaz et al. (2016), Aydin (2019), and Wang et al. (2020), established that the utilization of renewable energy not only has a positive impact on economic growth and environmental preservation, but also fosters advancements in human development.

Furthermore, GDP consistently demonstrates a positive effect on SDI, with coefficients of 0.0443 and 0.0539 in both models, indicating that higher GDP per capita in the U.S. contributes positively to SDI. This finding corroborates existing literature that posits a positive relationship between economic growth and development outcomes (Barro, 1991). It is crucial to contextualize these results within the EAC framework, where despite relatively high GDP growth rates, challenges such as income inequality and pervasive poverty continue to hinder sustainable development.

The results for GCF reflect a positive impact in the FGLS model (0.0415) but reveal a non-significant effect in the PCSE model (0.0316). This disparity suggests that while gross capital formation may positively influence SDI, its robustness is conditional on the modeling approach. This observation aligns with the broader investment literature, which underscores capital accumulation as vital for development, yet acknowledges the influence of contextual factors. In the EAC, enhancing investment in infrastructure and technology is essential for fostering economic growth and improving sustainable development outcomes.

The inflation rate (INFL) shows a positive and significant correlation with SDI in both models, indicating that moderate inflation may be associated with economic growth and improved sustainable development outcomes. This finding echoes the insights from Phillips curve literature, although in the EAC context, where inflation can be volatile, the relationship may reflect broader macroeconomic stability challenges.

In the interactive model, the coefficient for the interaction term LREC_LTECH is 0.111, suggesting that the synergy between renewable energy consumption and R&D investment positively influences LSDI, though it is significant only in the PCSE model. This finding underscores the importance of integrated approaches to energy and innovation, as supported by Fischer and Newell (2008), and highlights the necessity of fostering synergies in the EAC, where varying levels of technological advancement and resource availability present both challenges and opportunities. This finding is in line with Mengova and Green (2023).

The constant term is significant in both models, with values of 4.521 and 7.438, reflecting the baseline level of LSDI when all independent variables are held constant. Overall, the models are based on 155 observations and demonstrate substantial explanatory power, with R-squared values of 0.810 (FGLS) and 0.814 (PCSE), indicating that approximately 81% of the variation in LSDI is accounted for by the independent variables. This analysis incorporates six cross-sectional units, underscoring the balanced nature of the panel dataset.

In conclusion, the results from Table 6 illuminate the significant impact of renewable energy consumption on the Sustainable Development Index and reveal that its interaction with technological progress is critical for understanding this relationship. The findings further emphasize the roles of GDP, gross capital formation, and inflation in promoting sustainable development, suggesting that the interplay among these economic variables is essential for effective policymaking. This comprehensive understanding aligns with the broader literature on sustainable development, advocating for cohesive strategies that integrate economic growth, innovation, and environmental sustainability, particularly within the context of the East African Community, where collaborative efforts are imperative to address shared challenges and leverage regional opportunities.

Table 7 presents the results of a Pooled Ordinary Least Squares (OLS) regression analysis examining the impact of various independent variables on the Sustainable Development Index (SDI) across six East African countries: Burundi, Congo DR, Kenya, Rwanda, Tanzania, and Uganda. The analysis reveals that Renewable Energy Consumption (REC) has a mixed impact

Table 7: Pooled OLS results (Individual country analysis)

Variables	LSDI (Burundi)	LSDI (Congo DR)	LSDI (Kenya)	LSDI (Rwanda)	LSDI (Tanzania)	LSDI (Uganda)
LREC	0.0136	4.009*	1.975	−1.300	−2.677***	−15.27***
	(0.757)	(2.183)	(1.189)	(1.100)	(0.834)	(2.841)
LTECH	−0.445	4.282*	1.204	−2.596**	−2.205***	−10.96***
	(0.865)	(2.381)	(0.746)	(1.076)	(0.586)	(2.012)
LGDP	0.0878**	0.00649	0.0775***	−0.360**	−0.0635	−0.0333
	(0.0349)	(0.0210)	(0.0251)	(0.137)	(0.0488)	(0.0393)
LGCF	0.0591***	0.00889**	−0.0664**	−0.129	0.0550**	0.0516
	(0.0183)	(0.00411)	(0.0256)	(0.167)	(0.0236)	(0.0805)
LCPI	0.156***	0.00346	0.0824***	1.289***	0.179***	0.0639
	(0.0186)	(0.00243)	(0.0283)	(0.234)	(0.0569)	(0.0757)
LREC_LTECH	0.0939	−0.916*	−0.294	0.564**	0.514***	2.442***
	(0.190)	(0.519)	(0.176)	(0.243)	(0.134)	(0.441)
Constant	0.968	−15.06	−6.088	12.58**	15.89***	72.89***
	(3.888)	(9.878)	(5.370)	(4.711)	(3.996)	(12.88)
Observations	25	26	26	26	26	26
R-squared	0.988	0.983	0.989	0.967	0.990	0.980

LSDI: Log of Sustainable Development Index, LREC: Log of Renewable Energy Consumption, LTECH: Log of Technological Progress, LGDP: Log of Gross Domestic Product, LGCF: Log of Gross Capital Formation, LCPI: Log of Consumer Price Index, LREC_LTECH: Interaction term.
Robust standard errors in parentheses; ***P<0.01, **P<0.05, *P<0.1

on SDI. In Congo DR, REC shows a significant positive effect with a coefficient of 4.009, indicating that increased renewable energy consumption is strongly associated with improvements in sustainable development. Kenya also demonstrates a positive coefficient of 1.975, although it is not statistically significant. In contrast, Rwanda, Tanzania, and Uganda exhibit negative coefficients, particularly Uganda's highly significant value of −15.27. This suggests that in these countries, higher renewable energy consumption may be linked to lower sustainable development outcomes, highlighting potential inefficiencies in the implementation of renewable energy initiatives.

Technological progress (TECH) further complicates the picture of sustainable development across these countries. In Congo DR, TECH has a significant positive coefficient of 4.282, reinforcing the idea that technological advancements can enhance sustainable development. However, Burundi shows a negative coefficient of −0.445, while Rwanda, Tanzania, and Uganda report highly significant negative effects, indicating that technological factors may not contribute positively in those contexts. The results of GDP reveals that it positively affects SDI in Burundi and Kenya, with significant coefficients suggesting that economic growth supports sustainable development. However, Rwanda's negative coefficient of −0.360 raises concerns about the relationship between GDP growth and sustainable development, suggesting that growth does not always translate into positive outcomes in this context.

Additionally, Gross Capital Formation (GCF) and the Consumer Price Index (CPI) demonstrate varying influences on SDI. GCF generally shows a positive impact in Burundi and Uganda, suggesting that increased capital investment supports sustainable development. In contrast, Kenya reports a negative coefficient, indicating inefficiencies in capital formation. CPI appears to have a significant positive effect across most countries, particularly in Burundi, Rwanda, and Tanzania, suggesting that moderate inflation may correlate with better sustainable development outcomes. The interaction term between renewable energy consumption and technology (REC_TECH) reveals further complexities, with Congo DR showing a negative and significant coefficient, while Rwanda, Tanzania, and Uganda exhibit positive and significant interactions. Overall, these findings emphasize the need for tailored policies that consider each country's unique economic and technological landscape to effectively foster sustainable development.

Table 8 presents the results of the Dumitrescu-Hurlin panel causality test, designed to assess the direction and strength of causal relationships among the Sustainable Development Index (SDI) and its determinants: Renewable Energy Consumption (REC), Technology (TECH), GDP, Gross Capital Formation (GCF), and Inflation (CPI). The values in the table represent the test statistics. The results reveal that SDI has a significant causal influence on all other variables, suggesting that improvements in SDI are associated with positive changes across the examined determinants.

Specifically, the test results indicate that SDI promotes increased REC. Similarly, there is a strong causal relationship between SDI and TECH. The relationship between SDI and GDP is also significant, indicating that higher SDI contributes to economic growth. Additionally, enhanced SDI appears to drive greater GCF and influences inflation rates. Collectively, these results suggest that improvements in the Sustainable Development Index are likely to foster positive changes across all determinants.

On the other hand, the results show varying levels of influence from the other variables back to SDI. REC has a significant impact on SDI, indicating that increased renewable energy consumption contributes to sustainable development. Similarly, TECH demonstrates a strong causal link to SDI, while GDP shows a substantial positive impact. GCF also supports improvements in SDI. Inflation appears to influence sustainable development outcomes as well. However, some relationships do not demonstrate significant causality. For instance, TECH does not significantly influence REC, and GCF shows a negative statistic, indicating no meaningful impact on renewable energy consumption. These findings underscore the nuanced interplay of factors involved in sustainable development, highlighting the importance of a holistic approach to understanding these relationships.

4.1. Robustness Test

Table 9 presents the results of a robustness test using the Driscoll-Kraay estimator to assess the impact of various independent variables on the Sustainable Development Index (SDI) and the Human Development Index (HDI) across six groups. The analysis incorporates both direct and interaction models, allowing for a comprehensive examination of how these variables influence the indices both independently and in conjunction with one another. In the direct models, Renewable Energy Consumption (REC) demonstrates a significant negative relationship, with coefficients around −0.540, indicating that higher renewable energy consumption is associated with lower values of both indices. This suggests potential inefficiencies or challenges in the implementation of renewable energy initiatives, raising concerns about their effectiveness in promoting sustainable development.

Table 8: Dumitrescu-Hurlin panel causality test

Variables	LSDI	LREC	LTECH	LGDP	LGCF	LINFL
LSDI	------	4.782***	10.564***	7.246***	8.053***	6.079***
LREC	4.634***	------	4.436***	7.678***	3.065***	7.671***
LTECH	11.528***	1.585	------	5.915***	1.009	9.349***
LGDP	17.164***	0.981	4.121***	------	2.975***	2.137**
LGCF	7.224***	−0.904	4.104***	5.778***	------	
LINFL	6.298***	−0.496	1.819*	4.866***	−0.079	------

LSDI: Log of Sustainable Development Index, LREC: Log of Renewable Energy Consumption, LTECH: Log of Technological Progress, LGDP: Log of Gross Domestic Product, LGCF: Log of Gross Capital Formation, LCPI: Log of Consumer Price Index, LREC_LTECH: Interaction term.
Robust standard errors in parentheses; ***P<0.01, **P<0.05, *P<0.1

Table 9: Driscol-Kraay estimator results (direct and interactive model)

Variables	LSDI (Direct model)	LSDI (Interaction model)	LHDI (Direct model)	LHDI (Interaction model)
LREC	−0.540***	−1.038**	−0.541***	−1.043**
	(0.112)	(0.409)	(0.112)	(0.406)
LTECH	0.0265**	−0.340	0.0264**	−0.343
	(0.0119)	(0.279)	(0.0118)	(0.277)
LGDP	0.0268	0.0345**	0.0268	0.0345**
	(0.0163)	(0.0162)	(0.0163)	(0.0162)
LGCF	0.0774***	0.0693***	0.0780***	0.0698***
	(0.0215)	(0.0237)	(0.0214)	(0.0236)
LCPI	0.0299***	0.0278***	0.0298***	0.0277***
	(0.00922)	(0.00904)	(0.00914)	(0.00895)
LREC_LTECH	-	0.0806	-	0.0812
		(0.0611)		(0.0607)
Constant	0.598*	2.717	0.526	2.662
	(0.344)	(1.762)	(0.342)	(1.751)
Observations	148	148	148	148
R-squared	0.852	0.855	0.852	0.855
Number of groups	6	6	6	6

LTECH: Log of Technological Progress, LGDP: Log of Gross Domestic Product, LGCF: Log of Gross Capital Formation, LCPI: Log of Consumer Price Index, LREC_LTECH: Interaction term.
Robust standard errors in parentheses; ***P<0.01, **P<0.05, *P<0.1

Technology (TECH) presents a contrasting picture, with a positive coefficient of approximately 0.0265 for both SDI and HDI, indicating that advancements in technology contribute positively to sustainable development outcomes. However, in the interaction model, the effect of technology becomes negative and statistically insignificant, suggesting that when considered alongside other factors, technology does not significantly enhance the indices. Gross Capital Formation (GCF) consistently shows a significant positive impact in both direct models, with coefficients around 0.0774 for SDI and 0.0780 for HDI, highlighting the importance of capital investment for improving sustainable development. Additionally, the Consumer Price Index (CPI) shows a positive relationship, indicating that moderate inflation may correlate with better outcomes in both indices.

In the interaction model, the interaction term between REC and TECH is positive but not statistically significant, implying that their combined effect does not yield meaningful improvements in the indices. The constant term remains positive in this model, indicating a baseline level of the indices when all independent variables are zero. With consistent observations across all models and R-squared values ranging from approximately 0.852 to 0.855, the results suggest a strong fit, reinforcing the robustness of the findings. Overall, Table 9 highlights the complexities of the relationships among these variables, particularly the varying impacts of technology when analyzed in isolation versus in conjunction with other factors. The robustness test strengthens the validity of these findings, emphasizing the critical role of capital formation and the nuanced effects of renewable energy consumption on sustainable development outcomes.

Table 10 presents the results of a Fully Modified Ordinary Least Squares (FMOLS) estimation, focusing on the Human Development Index (HDI) as the dependent variable. This analysis examines the relationships between several independent variables,

Table 10: FMOLS estimator results (dependent variable: human development index – HDI)

Variable	Coefficient	Standard error	P
LREC	−1.941328	0.648201	0.0032
LTECH	−0.877893	0.466405	0.0618
LGCF	0.005879	0.032021	0.8546
LGDP	0.063037	0.019851	0.0018
LCPI	0.021250	0.011762	0.0728
LREC_LTECH	0.197204	0.102491	0.0563
C	6.301535	2.784964	0.0251
R-squared		0.784487	
Adjusted R-squared		0.775750	

LTECH: Log of Technological Progress, LGDP: Log of Gross Domestic Product, LGCF: Log of Gross Capital Formation, LCPI: Log of Consumer Price Index, LREC_LTECH: Interaction term.
Robust standard errors in parentheses; ***P<0.01, **P<0.05, *P<0.1

including Renewable Energy Consumption (REC), Technology (TECH), Gross Capital Formation (GCF), Gross Domestic Product (GDP), and the Consumer Price Index (CPI). Notably, the model includes an interaction term between REC and TECH, allowing for an exploration of their combined effects on HDI, which is crucial for understanding the multifaceted nature of human development.

The findings reveal that REC has a significant negative coefficient of −1.941, with a P-value of 0.0032, suggesting that higher levels of renewable energy consumption are associated with lower HDI values. This finding is in line with Hickel (2020) who critiqued the Human Development Index (HDI) for focusing primarily on income without considering ecological impacts, arguing that high-income countries negatively contribute to ecological breakdown despite having high HDI. The result of this study raises concerns about the effectiveness of renewable energy initiatives in enhancing human development, potentially indicating inefficiencies in how these projects are implemented. In contrast, while Technology (TECH) shows a marginally significant negative coefficient of −0.8779, with a P-value of 0.0618, it implies that technological progress might not be translating into improved human development outcomes. Conversely, Gross Domestic Product (GDP) demonstrates a positive relationship with HDI, having a significant coefficient of 0.0630 and a P-value of 0.0018, reinforcing the notion that economic growth is beneficial for human development.

Additionally, Gross Capital Formation (GCF) does not significantly impact HDI, with a coefficient of 0.0059 and a high P-value of 0.8546, indicating that increases in capital investment alone may not lead to improvements in human development. The Consumer Price Index (CPI) shows a marginally positive relationship with HDI, with a coefficient of 0.0213 and a P-value of 0.0728, suggesting that moderate inflation could have some beneficial effects, though not strongly conclusive. The interaction term LREC_LTECH has a positive coefficient of 0.1972, with a P-value of 0.0563, indicating a potentially positive but not definitively significant combined impact on HDI. Overall, the model has an R-squared value of approximately 0.7845, reflecting a strong fit. These results underscore the complexity of the relationships among the examined variables and highlight the necessity for careful policy design to effectively promote human development.

5. CONCLUSION

This study has thoroughly examined the critical relationship between research and development (R&D), renewable energy consumption, and sustainable human development within the East African Community (EAC). The findings highlight the pivotal role of R&D investments in facilitating the transition to renewable energy sources, which is essential for addressing the region's pressing energy and environmental challenges. Enhanced R&D not only promotes technological advancements but also significantly contributes to improving human development indicators, thereby fostering economic growth and social progress.

To effectively capitalize on these findings, several recommendations emerge. First and foremost, EAC member states should prioritize funding for R&D in renewable energy technologies. This can be achieved through public-private partnerships and international collaborations that pool resources and expertise. Additionally, implementing targeted policy frameworks that encourage innovation, and the development of renewable energy technologies is crucial. Governments must create supportive regulatory environments that facilitate investments in R&D, ensuring that new technologies can be effectively developed and deployed.

Furthermore, capacity building is essential. Investing in training and education programs will enhance local expertise in renewable energy technologies, empowering communities to engage effectively with these advancements. This local knowledge is vital for the successful implementation and maintenance of renewable energy projects. Moreover, fostering regional cooperation among EAC member states can lead to the sharing of knowledge and best practices in renewable energy R&D. A collaborative approach can help address common challenges while leveraging collective resources for greater impact.

The implications of this study are significant for policymakers and stakeholders in the EAC. By recognizing the importance of R&D in promoting renewable energy, decision-makers can better align their strategies with sustainable development goals. The insights gained from this research can guide the formulation of effective policies that not only enhance energy access but also contribute to economic growth and environmental sustainability.

However, this study is not without limitations. The reliance on secondary data may introduce biases, as the accuracy of the conclusions drawn depends on the reliability of the sources used. Additionally, the focus on EAC member states may limit the generalizability of the findings to other regions with different socio-economic contexts, necessitating caution in extrapolating results.

Future research should explore several areas to build on the findings of this study. Longitudinal studies could assess the long-term impacts of R&D investments on renewable energy adoption and human development in the EAC, providing a more comprehensive view of these dynamics over time. Additionally, technology-specific analyses would be beneficial in investigating the effectiveness of renewable energy technologies and their respective contributions to sustainable development outcomes.

Examining the influence of governance structures and policy frameworks on the effectiveness of R&D investments in renewable energy is another promising avenue for future inquiry. Lastly, exploring the role of socio-economic factors, such as public debt and governance quality, in shaping the relationship between R&D, renewable energy consumption, and human development would provide deeper insights into the complexities of this nexus. By addressing these areas, future research can contribute to a more nuanced understanding of the intricate dynamics surrounding renewable energy and sustainable development in the EAC and beyond.

REFERENCES

Alper, A., Oguz, O. (2016), The role of renewable energy consumption in economic growth: Evidence from asymmetric causality. Renewable and Sustainable Energy Reviews, 60, 953-959.

Baek, J. (2016), Do nuclear and renewable energy improve the environment? Empirical evidence from the United States. Ecological Indicators, 66, 352-356.

Dumor, K., Li, Y., Amouzou, E.K., Ampaw, E.M., Kursah, M.B., Akakpo, K. (2022), Modeling the dynamic nexus among CO_2 emissions, fossil energy usage, and human development in East Africa: New insight from the novel DARDL simulation embeddedness. Environmental Science and Pollution Research, 29(37), 56265-56280.

Ezako, J.T. (2024), The nexus between human development, official development assistance, carbon emissions, and governance in developing countries for the realization of sustainable development goals. Cogent Economics and Finance, 12(1), 2330452.

Hickel, J. (2020), The sustainable development index: Measuring the ecological efficiency of human development in the anthropocene. Ecological Economics, 167, 106331.

Imran, K., Jian, Z., Nadeem, M., Ahmad, M. (2022), The role of renewable energy and technological innovation in carbon emissions reduction:

Evidence from selected countries. Environmental Science and Pollution Research, 29, 12345-12356.

Imran, M., Khan, S., Zaman, K., Khan, H.R., Rashid, A. (2022), Assessing green solutions for indoor and outdoor environmental quality: Sustainable development needs renewable energy technology. Atmosphere, 13(11), 1904.

Khan, M.T.I., Yaseen, M.R., Ali, Q. (2020), Nexus between financial development, energy consumption, and carbon emissions in the context of the fourth industrial revolution: Evidence from G-7 countries. Environmental Science and Pollution Research, 27, 17473-17484.

Khan, Z., Malik, M.Y., Latif, K., Jiao, Z. (2020), Heterogeneous effect of eco-innovation and human capital on renewable & non-renewable energy consumption: Disaggregate analysis for G-7 countries. Energy, 209, 118405.

Martínez, D.M., Ebenhack, B.W. (2008), Understanding the role of energy consumption in human development through the use of saturation phenomena. Energy Policy, 36(4), 1430-1435.

Nguyen, C.P., Le, Q.T., Hoang, P.T. (2023), The impact of renewable energy on human development: Evidence from panel corrected standard error (PCSE) estimation across 77 countries. Journal of Cleaner Production, 355, 131713.

Nguyen, T.T.H., Phan, G.Q., Tran, T.K., Bui, H.M. (2023), The role of renewable energy technologies in enhancing human development: Empirical evidence from selected countries. Case Studies in Chemical and Environmental Engineering, 8, 100496.

Rehman, A. (2019), The nexus of electricity access, population growth, economic growth in Pakistan and projection through 2040: An ARDL to co-integration approach. International Journal of Energy Sector Management, 13(3), 747-763.

REN21. (2017), Renewables 2017 Global Status Report. Renewable Energy Policy Network for the 21st Century (REN21). France: REN21.

Shahbaz, M., Balsalobre-Lorente, D., Sinha, A. (2022), Role of research and development in clean energy and environmental sustainability: Can innovation foster human development? Journal of Cleaner Production, 345, 131076.

Shahbaz, M., Song, M., Ahmad, S., Vo, X.V. (2022), Does economic growth stimulate energy consumption? The role of human capital and R&D expenditures in China. Energy Economics, 105, 105662.

Tran, N.V., Tran, Q. Van, Do, L.T.T., Dinh, L.H., Do, H.T.T. (2019), Tradeoff between environment, energy consumption and human development: Do levels of economic development matter? Energy, 173, 483-493.

Tran, T.P., Tuan, V.A., Nguyen, T.P. (2019), Energy consumption, carbon emissions, and human development index in emerging markets: New evidence using a system-GMM approach. Journal of Environmental Management, 245, 110-122.

Wang, Z., Bui, Q., Zhang, B. (2020), The relationship between biomass energy consumption and human development: Empirical evidence from BRICS countries. Energy, 194, 116906.

Wang, Z., Bui, Q., Zhang, B., Nawarathna, C.L.K., Mombeuil, C. (2021), The nexus between renewable energy consumption and human development in BRICS countries: The moderating role of public debt. Renewable Energy, 165, 381-390.

Wang, Z., Jiang, T., Wu, Y. (2020), Biomass energy consumption, human development, and economic growth in BRICS: Evidence from panel data analysis. Renewable Energy, 155, 351-360.

Xu, Q., Khan, S. (2023), How Do R&D and renewable energy consumption lead to carbon neutrality? Evidence from G-7 economies. International Journal of Environmental Research and Public Health, 20(5), 4604.

Xu, Z., Khan, M. (2023), The role of research and development (R&D) in renewable energy adoption and its impact on carbon emissions: Evidence from panel data analysis. Energy Economics, 118, 106404.

Zeraibi, A., Balsalobre-Lorente, D., Shehzad, K. (2020), Examining the asymmetric nexus between energy consumption, technological innovation, and economic growth; does energy consumption and technology boost economic development? Sustainability (Switzerland), 12(21), 1-17.

Zeraibi, A., Zerga, A., Bouras, B. (2020), Technological innovation and energy efficiency: Evidence from North Africa. Journal of Innovation and Knowledge, 5(4), 271-279.