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The Moderating Influence of Digitalization on Renewable Energy-Human Development Nexus in Developing Countries

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Abstract
Using data from 1997 to 2021, this study explores the moderating influence of digitalization on the impact of renewable energy on human development in 38 developing countries, using Cross-sectional Augmented Autoregressive Distributive Lag (CS-ARDL) estimators. The findings establish that the positive impact of renewable energy on human development is conditioned upon digitalization in developing countries. Also, the results of control variables reveal that financial development has a significant positive effect on human development. In contrast, lower environmental degradation, inflation, and control of corruption have negative and significant impact on human development. Therefore, the evidence obtained in this study confirmed the postulation in the literature that digitalization enhances the generation and distribution of renewable energy, which bolsters human development in developing countries. As a result, policymakers in developing nations should embrace digitalization as a policy tool to promote the generation and distribution of affordable renewable energy, as well as to smooth the transition to clean energy for greater human development.

Keywords
Renewable energy; Human development; Digitalization, Developing countries

INTRODUCTION

Human development is a fundamental indicator showing how citizens enjoy equal opportunities in education, healthcare service deliveries, decent living, employment opportunities, and gender. Sen (1989) considers human development as an enlargement of human choices and freedom to achieve higher functioning in life. The United Nations development Programme (UNDP) developed the Human Development Index (HDI) based on Sen's (1989) definition of human development, with three aspects of knowledge, health, and decent living. However, achieving higher human development is argued to be at the expense of a quality environment, hence bringing the issue of sustainable use of natural resources to cater to the growing human population and future generations. Even though the issues of climate change and global warming are receiving substantial attention, the extent of environmental degradation currently constitutes a significant threat to humanity and sustainable development (Khan et al., 2021). The insatiable quest to achieve higher economic growth and development necessitates higher energy consumption, which is responsible for CO_2 emissions contributing to ozone depletion (Amer, 2020).

Although the role of energy is critical in all sectors of the economy, the primary energy source globally is fossil fuels (non-renewable). According to the report by the International Energy Agency (IEA, 2022) more than 80% percent of the world's energy consumption came from non-renewable sources, with petroleum at 40%, coal energy at 35.8%, natural gas at 22.2%, hydropower 15.2%, and 9.3% from nuclear sources. Nevertheless, only 19% came from renewable energy sources. It is critical to note that the world's urban population is rapidly growing, which increases pressure on natural resources, energy use, and the ecosystem, consequently, a higher level of environmental degradation (Dabachi et al., 2020). However, the Paris Agreement (COP21) reached a global consensus that the world temperature should be kept below two degrees Celsius (20C) to reduce global warming and environmental degradation relative to the pre-industrial era. A considerable commitment to achieving this global target compelled the search for alternative sustainable energy sources to replace the traditional sources that significantly harm our planet Earth, jeopardizing attaining sustainable development goals (COP21, 2016).

Energy experts globally recommended that energy consumption from renewable energy sources might be essential in minimizing carbon emissions and maintaining environmental quality (Azam et al., 2023). Renewable energy comes from sources that cannot be depleted with time, such as water, wind, solar, biomass, and geothermal. These sources produce minimal greenhouse gas effects and provide efficient, low-cost, sustainable energy, hence inextricably linked with achieving sustainable development goals (Adekoya et al., 2021). However, the harmful effect of environmental degradation due to the rise of the global temperature degenerates the progress recorded in human development, especially in developing countries, where the effect is the most obvious. Thus, access to reliable, affordable, and clean energy is considered a fundamental factor that can guarantee quality living and sustainable human development (Gateway, 2023). Literature established a link between quality of life and environmental quality in the presence of digitalization (Elmassah & Hassanein, 2022; Shanty et al., 2018). Technological progress is regarded as the primary driver of a critical shift from fossil to non-fossil fuel energy to reduce the current phase of global warming and achieve sustainable development goals (Hussain et al., 2022).

Scholars argued that one of the critical strategies for limiting the average world temperature below the global target (1.5°C) is the use of renewable energy in the production of electricity, manufacturing, transportation, agriculture, and other services (Gateway, 2023; Hussain et al., 2022; Inglesi-Lotz & Dogan, 2018). Information and communication technology (ICT) is vital in enhancing the development of energy technologies capable of generating clean energy (Tariq & Xu, 2022). Thus, digitalization will augment a renewable energy revolution and propel energy transition to achieve sustainable development goals for better human development. Digitalization of the economy not only increases the GDP but also enhances the environmental quality that facilitates sustainable production of renewable energy that is considered to have minimal effect on the environment, thereby promoting quality of life (Chien et al., 2021; Kaewnern et al., 2023).

This study evaluates the moderating role of digitalization in the relationship between renewable energy and human development in developing countries. Most of the previous studies emphasized direct channels between renewable and well-being. However, exploring the indirect channel through the moderating role of digitalization will provide an important new insight into the renewable energy-human development nexus in developing countries. Even though theoretical literature confirmed the link between renewable energy consumption and environmental quality, the challenges of undertaking renewable energy projects are enormous and varied depending on the location. The universal challenges are the higher initial cost of installation and the space of land required, especially for the solar panels and wind turbines, which can be overcome when an economy is digitalized. Digitalization can provide efficient technology that can significantly reduce installation costs and minimize the space needed for the installation of solar panels and wind turbines. In addition, the digitalization of transmission and distribution of renewable energy can reduce energy consumption by determining where to deliver more power and at what time, thereby promoting a quality environment and overall well-being. As a result, our work makes an important contribution to the use of digitalization to mitigate the impact of renewable energy on human development. Another significant contribution comes from our use of the Cross-sectional Augmented Autoregressive Distributed Lag (CS-ARDL) technique, which accounts for cross-section dependence and endogeneity while providing efficient estimators (Chudik et al., 2016).

RELATED LITERATURE

Theoretical literature explains channels through which renewable energy consumption improves human development. The most notable channel is the assertion that increasing renewable energy consumption will reduce the consumption of fossil fuel, which will significantly reduce greenhouse gas emissions, global warming, and environmental degradations, consequently higher human development (Amer, 2020; Huskić & Šatrović, 2020; Kaewnern et al., 2023; Sasmaz et al., 2020). Another important channel is that renewable energy provides consistent and affordable energy to people, even in remote locations, which increases access to energy and promotes higher human development (Kumar & Rathore, 2023; Schislyaeva & Saychenko, 2022; Welsch & Biermann, 2017). However, Schislyaeva & Saychenko (2022) argued that the initial higher cost of renewable energy projects makes it difficult for low-income developing countries to undertake on a large scale, which exacerbates energy poverty and the usage of lower-cost fossil-fuel energy. Nonetheless, inexpensive energy sources, for instance, charcoal, firewood, etc., not only do more harm to the environment but also deteriorate the quality of life. Thus, affordable clean energy boosts economic activities, employment opportunities, and income and provides energy security, dramatically uplifting living standards.

Existing empirical literature connects the use of renewable sources of energy with rising human development (A. Azam et al., 2021; Banday & Kocoglu, 2022; Hashemizadeh et al., 2022; Huskić & Šatrović, 2020; Sasmaz et al., 2020; Tariq & Xu, 2022). Others established that renewable energy promotes a quality environment (Abid et al., 2020; Charfeddine & Kahia, 2019; Hao et al., 2021; Huang et al., 2023; Inglesi-Lotz & Dogan, 2018; Wolde-Rufael & Mulat-Weldemeskel, 2022) which has a positive effect on human development. Moreover, another set of evidence shows that renewable energy has a significant and positive impact on economic growth (Koçak & Şarkgüneşi, 2017; Ntanos et al., 2018; Rahman & Velayutham, 2020; Q. Wang et al., 2022). Similarly, Hussain et al., (2022) show that green technology promotes green GDP growth, which supports higher well-being. Kahia et al., (2017) reported that in countries that import oil, the relationship between renewable energy and economic development is bidirectional. Whereas Y. Wang, (2023) indicates that the digitalization of an economy has a significant positive effect on green total factor productivity in China.

Kumar & Rathore, (2023) maintained that the cost of energy has an influence on human development, with the effect being more pronounced for those ranked lower in the human development index. Li et al., (2023) analyses the determinants of China's switch from fossil fuels to renewable energy. They reported that information technology, financial development, and research and development significantly positively affect increasing renewable energy use in China. The study by Cheng et al., (2022) found that technological innovation efficiency promotes green energy development. Another finding shows a bidirectional causality exist in renewable energy and human development nexus in BRICS member countries (Wang et al., 2021). Furthermore, Amer, (2020) indicates that renewable energy significant impact on human development in middle-income economies but insignificant in higher-income countries. Non-renewable energy usage, on the other hand, is said to have a considerable detrimental impact on human growth (Abid et al., 2020; Adekoya et al., 2021; Matthew et al., 2018; Ouedraogo, 2013).

In contrast, a different empirical investigation conducted in Pakistan found no connection between the use of renewable energy and human development (Wang et al., 2018). Additionally, a neutral causation link between renewable energy and economic growth in emerging markets is revealed by Ozcan & Ozturk (2019). According to Akram et al. (2021), the GDP growth of the BRICS countries is negatively impacted by renewable energy. Zheng and Wang (2022) provide evidence that renewable energy has a notable short-term impact on human development, but a negligible long-term impact.

DATA AND METHODOLOGY

The study examines data from 38 developing countries from 1997 to 2021. These countries are chosen based on the availability of equal observations. Human development is the dependent variable in this study, and renewable energy and digitalization are the variables of interest. In order to achieve the study objectives, the Cross-sectional Augmented Autoregressive Distributed Lag (CS-ARDL) approach is used. For robustness, we also employ the Dynamic Common Correlated Effect (DCCE) and Augmented Mean Group (AMG) estimators.

Measurements of Variables

The variables are measured as follows:

Human Development

Human development is measured using the Human Development Index (HDI) and serves as a dependent variable in all the models estimated. The index is constructed with three crucial dimensions- knowledge, healthy life, and decent living. Despite the criticism of the HDI, it is still regarded as a better proxy than the previously used measures, such as GDP/GNP (Streeten, 1994). The HDI is constructed by the United Nations Development Program (UNDP) and released annually in the Human Development Reports.

Renewable Energy

The first variable of interest is renewable energy, which is expressed as a proportion of total energy consumption. Increasing the use of renewable energy benefits not just the environment but also the quality of life (Acheampong et al., 2019; Charfeddine & Kahia, 2019; Adekoya et al., 2021). Moreover, renewable energy provides an affordable energy source, especially solar energy, that can be generated for personal use by individuals, thereby promoting human well-being (Abid et al., 2020). This study argues that renewable energy promotes human development in developing countries when conditioned by digitalization.

Digitalization

Digitalization is the second variable of interest in this study. It is used to moderate the renewable energy-human development nexus in developing countries. Digitalization significantly propels the transition from fossil energy consumption to renewable energy consumption. It also increases efficiency in generating and lowers the cost of renewable energy (Zheng & Wang, 2022). Digitalization is used in this study to moderate the relationship between human progress and renewable energy. Thus, we use a digitalization index to proxy digitalization, constructed using Principal Component Analysis (PCA). The index uses three variables: internet subscription per 100 people, mobile phone subscribers per 100, and fixed broadband subscribers. The proxies of digitalization are from World Bank database (WDI, 2022).

Other Variables

The study uses four important determinants of human development as the control variables by following previous literature. Firstly, domestic credit to the private sector (%GDP) is used to proxy financial development. When the financial sector is developed, the amount of credit to the private sector increases, stimulating economic activities and creating jobs and income, hence, better human well-being in the long run (Kamalu & Ibrahim, 2023)(Ababio et al., 2020). Secondly, we use an institution proxy with a control of corruption index. Corruption harms human development by taking away resources from essential services, such as education, primary healthcare services, portable water, etc. This study argues that controlling corruption will increase the delivery of essential services, which promote human development (Kamalu & Wan Ibrahim, 2022)(Borja, 2020). Thirdly, the study uses environmental degradation measured with CO_2 per capita. Environmental degradation destroys ecosystems, biodiversity, and ecological footprint, directly harming human development (Dickerson et al., 2022) (Asongu & Odhiambo, 2019). The next variable is inflation, proxy by the consumer price index is also used as a control variable in this study. The general price level determines the level of well-being depending on a country's development level. All the control variables are sourced from the World Bank (WDI, 2022).

Methodology

This study's estimation approach is structured as follows. We estimate the correlation matrix and descriptive statistics in the first stage. In the second part of the study, homogeneity, cross-sectional dependency, unit root, and cointegration tests are performed. Lastly, the short-run and long-run coefficients are estimated using the Cross-Sectional Augmented Autoregressive Distributed Lag (CS-ARDL) estimator. For robustness, we further employ the DCCE and AMG estimators.

Homogeneity Test

One of the most important steps in panel data estimation is the testing of a slope coefficient. Hashem Pesaran & Yamagata (2008) proposes a slope homogeneity test that is valid even in an unbalanced panel. The test examines whether the distribution of a single categorical variable is the same across two or more cross-sections. Assuming a homogenous slope across individual units with a heterogenous slope may lead to misinterpretations of the slope coefficient, hence sporous regression. The following equation gives the LM

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2} \qquad (1)$$

From (1) $\hat{\rho}_{ij}^{2}$ is the pairwise correlation estimate of the residual. The null hypothesis for the LM test is set as no cross-section dependency in the series $(H_0: \beta_i = 0)$

***Cross-Sectional* Dependence Tests**

The cross-section dependence test is the second pre-estimation test that is conducted. The choice of following estimating techniques to be employed in this study will rely on whether cross-sectional dependency is present or not. Various exist with different approaches to detecting dependency. The notable among these tests include the Breusch & Pagan, (1980) LM test and the Pesaran, (2004) CD tests. The LM test performs better when T is greater than N, while the Pesaran CD test is appropriate, with T being sufficiently large and N going to infinity (Tugcu, 2018). The Pesaran CD test is given by the following.

$$Pesaran\ CD = \sqrt{\frac{2T}{N(N-1)}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right)} \qquad (2)$$

When the p-value is less than 0.05, the null hypothesis of no cross-section dependency is rejected.

Panel Unit Root Test

Another important diagnostic test is the stationarity test. There are two classes of panel unit root tests- the first-generation and second-generation panel unit root tests. The first-generation tests assume cross-sectional independence, such as Im et al., (2003), Levin et al., (2002), Maddala and Wu, (1999), and Hadri, (2000). In contrast, the second-generation tests account for cross-sectional dependence, which includes Pesaran, (2007), Moon and Perron, (2004), Bai and Ng, (2005), and Harris et al., (2009). With the exception of Hadri, (2000) and Harris et al. (2009), which specified a null of unit root, all tests established a null hypothesis (H0) that the series has a unit root. The type of test to be used will rely on the results of the cross-section dependency test.

Panel Cointegration Test

Testing cointegration is a significant diagnostic test to evaluate whether the variables have a long-run relationship. Panel cointegration test has achieved higher power and precision than the time series cointegration test because of the availability of various testing methods (Baltagi et al., 2007). There are three types of panel cointegration tests. Firstly, the residual-based tests are Kao, (1999) and Pedroni, (1999). Secondly, the Likelihood-based panel test such as Larsson et al., (2001) and(Groen & Kleibergen, 2003); Thirdly, the panel cointegration test based on error correction such as Westerlund, (2007). The choice of the cointegration test will be based on the outcomes of cross-sectional dependence tests.

Cross-Sectional Augmented Autoregressive Distributed Lag (CS-ARDL)

Evaluation of a long-run relationship between economic variables is critical in economics and is commonly connected with the steady-state solution of a structural macroeconomic model. Most long-run estimators ignore the importance of cross-sectional dependency; however (Chudik et al., 2016) provided a long-run estimator that blends the common correlated effects (CCE) and the ARDL-based Error Correction Modelling (ECM) technique to generate the CS-ARDL. The CS-ARDL estimator provides short- and long-run coefficients and accounts for cross-sectional dependency, heterogeneity, and endogeneity, thereby providing efficient estimators. We developed our models by following (Vo et al., 2022).

$$\Delta H_{it} = \delta_{1i} + \sum_{j=1}^{a} \delta_{2ij}\, \Delta H_{2it-j} + \sum_{j=0}^{a} \delta_{3ij}\, \Delta V_{3it-j} + \sum_{j=0}^{a} \delta_{4ij}\, \Delta \overline{W}_{4it-j} + \mu_{it} \qquad (1)$$

In equation (1), V is the vector of all the regressors, where V= ln (R, D, F, I, E, P, R*D). R stands for renewable energy, D is digitalization, F stands for financial development, I is institutions, E stands for environmental degradation, P represents inflation, and R*D is the interaction term between renewable energy and digitalization. Also, $\Delta\overline{W}$ is the average cross-section of the dependent $\overline{(\Delta H)}$ and all the regressors $\overline{(\Delta V)}$.

RESULTS AND DISCUSSIONS

The study presents descriptive statistics test results in Table 1. The results show that the average, maximum, minimum, and standard deviations are within the range showing no outliers. The results of the cross-sectional dependency tests in Table 2 reject the null of cross-sectional independence at 1% in all three types of tests run, with the exception of the control of corruption (CC) in Pesaran (2007) CD test. The results mean that all the variables have cross-sectional dependency. Based on the CD test results, the subsequent methods to use must account for cross-sectional dependency. The result also rejected the null hypothesis of homogeneity, which confirmed that all the variables have heterogeneous slope coefficients.

Moreover, Table 3 presents the panel unit root tests. The results reject the null hypothesis of a unit root in the CIPS and the CADF tests for all the variables at 1% except for inflation (IN). Therefore, all the variables have a unit root at a level but achieved stationarity at the first difference. In addition, the panel cointegration tests reject the null hypothesis of no cointegration in 8 of the 11 Pedroni (2010) test statistics. As a result, the findings revealed that the study variables are cointegrated and so have a long-run relationship.

Table 1 Descriptive statistics

Variable	OBS	Mean	Std. Dev.	Min	Max
Human development	927	-0.491	0.181	-0.989	-0.202
Renewable Energy	950	3.193	1.227	-2.813	4.546
Digitalization	909	0.279	0.388	-0.389	3.91
Financial development	950	3.776	0.685	1.747	5.356
Env. degradation	950	0.141	1.084	-2.589	2.134
Inflation	950	0.141	1.084	-2.589	2.134
Control of Corruption	949	7.296	4.905	-7.114	58.374
Interaction term	836	-0.445	0.562	-1.673	1.155

NB: ***, **&* means a 1%, 5% &10% level of significance. L means Logarithms

Table 2 Cross-sectional dependency tests

Variable	Pesaran CD test	Bias-correlated scaled LM test	Breusch-Pagan LM test
Human development	117.22***	365.59***	14441.4***
Renewable Energy	41.401***	149.32***	6331.7***
Digitalization	122.49***	384.34***	15143.9***
Financial development	68.989***	189.34***	7832.27***
Env. degradation	42.161***	171.15***	7150.37***
Inflation	39.916***	53.771***	2748.9***
Control of Corruption	1.1226	60.219***	2990.7***

Table 3 Panel Unit Root tests

Variables	CIPS Test		CADF Test	
	Level	1st Diff.	Level	1st Diff.
Human development (LH)	-1.455	-2.585***	-1.109	-2.901***
Renewable Energy (LR)	-2.003	-4.159***	-2.070	-2.890***
Digitalization (LD)	-2.193	-4.269***	-1.921	-2.243***
Financial development (LF)	-2.034	-4.228***	-1.962	-2.596***
Env. degradation (LE)	-2.058	-4.253***	2.007	-5.797***
Inflation (P)	-3.793***	-5.860***	-3.908***	-4.843***
Control of Corruption (C)	1.820	-3.538***	-1.988	-3.477***

Table 4 displays the results of the CS-ARDL models. For the baseline and interaction models, we computed both short- and long-term estimates. The findings show that the models are dynamically stable because the lag dependent variable [LH (-)] is positive and significant at 1%. Based on the baseline model results, the consumption of renewable energy has a positive and significant coefficient in the short-run (10%) and in the long-run (1%). Based on the interaction model's findings, renewable energy has a positive short-term coefficient that is not statistically significant, but a positive long-term coefficient that is at 10%. These results show that a 1% rise in the use of renewable energy boosts human development by 0.52% in the short-run period and in the long-run by 0.32%. Thus, our results are consistent with

Adekoya et al., (2021), Azam et al., (2023), Sasmaz et al., (2020), and Wang et al., (2021). According to Table 4's findings, digitalization (LD) has a negative and significant impact at 10% in the interaction model, while it is not significant at the baseline model in the near term. Also, in the baseline and interaction models, digitalization (LD) has a positive and significant coefficient at 5% in the long run. According to the findings, a 1% rise in digitalization increases human development by 0.002% to 0.052%, which is consistent with the work of Lazović et al., (2022; Zheng & Wang, (2022).

Table 4 shows that the interaction term (LR*LD) has a positive and negligible coefficient in the short run, but a positive and significant coefficient at 5% in the long run. The findings show that digitalization improves the long-term impact of renewable energy on human development. This finding is consistent with the result obtained by Zheng & Wang, (2022), and similar to the finding of Ma et al., (2022), which shows that research and development moderate the effect of digitalization (ΔLD) on carbon emission. The results of the control variables presented in Table 4 show that the short-run coefficients of financial development (ΔLD) are positive and significant at 5% in the baseline model while positive and insignificant in the interaction model. The long-run coefficients of financial development (LD) are positive and significant at 5% in the baseline model and at 10% in the interaction model, which reveals that a 1% rise in financial development will result in a 0.20% l increase in human development. The results are in line with the empirical findings of Datta & Singh, (2019; Kamalu & Ibrahim, (2023).

Table 4 shows the short-run coefficients of environmental degradation (LE), which are insignificant in the interaction model but significant at 5% in the baseline model. In the long-run, the environmental degradation (LE) coefficients are negative and significant ranging from 10% in the interaction model to 5% in the baseline model. Therefore, human development rises by 0.013% to 0.047% for every 1% decrease in environmental degradation. In Table 4, the coefficient of adjustment [ECT (-)] is also negative and significant at 1%, meaning any deviation from the long-run equilibrium will be corrected by 42.3% annually.

Furthermore, the short-run inflation (P) coefficients in Table 4 are negative and insignificant in the baseline model but significant in the interaction model. The inflation coefficients in the baseline and interaction models are negative and significant in the long run at 10%. According to these findings, a 1% decrease in inflation enhances human development by 0.013% to 0.025% in developing countries. In addition, the coefficients of control of corruption (C) are negative and significant at 5% in the baseline model but insignificant in the interaction model in the short run. The long-run coefficients in the baseline model are negative and significant at 5%, whereas they are negative and negligible in the interaction model. The evidence appears to show that a 1% increase in corruption control leads to a 0.007% to 0.266% decrease in human development over time.

Table 4 Results of the CS-ARDL estimator

DV: Human Development		
	Baseline Model	**Interaction Model**
Short Run Estimates		
Lagged DV [LH (-)]	0.577***	0.409***
Renewable Energy (ΔLR)	0.519*	0.686
Digitalization (ΔLD)	0.005	-0.003*
Financial development (ΔLF)	0.200**	0.163
Environmental degradation (ΔLE)	-0.003**	-1.096
Inflation (ΔP)	-0.002	-0.001*
Control of Corruption (ΔC)	-0.050**	-0.034
Interaction term (ΔLR*ΔLD)		0.250
ECT (-)	-0.423***	-0.591***
Long Run Estimates		
Renewable Energy (LR)	0.306***	0.449*
Digitalization (LD)	0.002**	0.523**
Financial development (LF)	0.160**	0.004*
Environmental degradation (LE)	-0.047**	-0.013*
Inflation (P)	-0.025*	-0.001*
Control of Corruption (C)	-0.266**	-0.007
Interaction term (LR*LD)		0.125**

The study employs the Dynamic Common Correlated Effect (DCCE) and Augmented Mean Group (AMG) estimators to supplement the CS-ARDL estimators. Table 5 shows that the lagged dependent variable [LH (-)] is positive and significant at 1%, indicating that the DCCE model is dynamic. Renewable energy (LR), digitalization (LD), and the interaction term (LR*LD) are all positively significant in the long run. Environmental degradation, on the other hand, is negative and significant at 1% in the long-run. Furthermore, the AMG results show that in the long run, renewable energy (LR) has a positive and significant coefficient of 1%, but inflation (P) has a negative and significant coefficient of 5%. These findings are similar to those in Table 4, where the CS-ARDL estimator is used. However, there are differences in the results for other control variables provided in Table 5, which reveal that the financial development is insignificant in the DCCE and AMG estimators. The interaction term (LR*LD) is insignificant in the AMG estimator, and the control of corruption (C) has positive and significant at 1% in the DCCE estimator.

Table 5 Results of the DCCE And AMG estimators

DV: Human development		
Variables	**DCCE**	**AMG**
Lagged DV [LH (-)]	0.432***	
Renewable Energy (LR)	0.202**	0.120***
Digitalization (LD)	0.240**	-0.127
Financial development (LF)	-0.009	0.011
Environmental degradation (LE)	-0.003***	0.040
Inflation (P)	0.024	-0.003**
Control of Corruption (C)	0.016***	-0.082
Interaction term (LR*LD)	0.053**	0.033
Constant	-0.082	2.526

Discussions

The main findings for the interaction term (LR*LD) show that digitalization boosts the positive impact of renewable energy on human development. These findings confirm the literature's argument that digital technology allows efficient generation and distribution of affordable renewable energy, reducing the use of non-renewable energy, carbon emissions, and degradation of the environment, consequently bolstering human progress. Therefore, digitalization is crucial in the development of renewable energy technology to speed up energy transition. It also lowers the cost of renewable energy generation and expands access to renewable energy, particularly in rural areas, promoting equitable growth and overall human development. Moreover, using machine learning and smart meters can significantly minimize the use of renewable energy, as it can determine the locations that need more energy, thereby reducing the intensity of energy consumption and increasing its availability. Therefore, the availability of clean and affordable energy may boost economic activities, provide job opportunities, facilitate the growth of small and medium enterprises, increase environmental quality, facilitate the delivery of healthcare services, and promote human capital development, which directly increases human development. Our findings show that the availability, accessibility, and use of renewable energy boost overall human development and help developing countries accomplish their sustainable development goals.

The baseline model's findings demonstrate that renewable energy and digitalization boost human development. thus, affordable renewable energy will provide not only efficient, and clean energy that have little harm to the environment, but also increase the quality of life in developing countries. Similarly, digitalization provides job opportunities, increases efficiency in the production process, facilitates business activities, and increases income and economic growth, hence, higher human development. Furthermore, the results imply that, as one of the control variables, financial development is a significant determinant of human development in developing countries. The developed financial sector promotes business activities, facilitates start-ups, finances new projects, promotes small and medium business, and increases financial deepening and intermediaries, directly promoting economic growth and human development. The negative relationship between environmental degradation and human development is means that lower carbon emissions decrease environmental degradation, which propel human development in developing countries. Furthermore, inflation has a detrimental impact on human development, hence, reducing inflation will help developing countries advance their human development. Because lower inflationary pressure increases purchasing power and stimulates effective demand, productivity, income, and higher living standards. However, the mixed coefficients of control of corruption show that, to some extent, lower/higher control of corruption may increase/decrease human development, depending on the situation.

CONCLUSION AND POLICY IMPLICATIONS

Conclusion

This study explores the moderating influence of digitalization on the renewable energy-human development nexus in 38 developing countries using full data from 1996 to 2020. We estimated our models using the CS-ARDL approach, with the DCCE and AMG estimators serving as robust. The findings of this study establish that digitalization in developing countries enhances the positive influence of renewable energy on human development. The study also provides strong evidence that renewable energy and digitalization promotes human development. These findings are robust when the DCCE and AMG estimators are used. Moreover, the results of control variables show that financial development promotes human development. Similarly, lower environmental degradation, inflation, and control of corruption promote human development in developing countries.

Policy Implications

The study's empirical evidence has profound implications for policymakers as well as stakeholders in emerging nations. The findings that digitalization enhances the positive effect of renewable energy on human development show the vital role that digitalization plays in generating and distributing renewable energy. Thus, policymakers should promote the digitalization crusade by installing information and communication technologies facilities to provide access to wireless broadband networks, increasing the number of internet subscriptions per 100 people, and ownership of personal computers. They should also increase the dissemination of technological education, such as basic ICT knowledge, programming skills, and artificial intelligence education, thereby promoting digitalization, which will significantly ignite renewable energy technology and higher human development.

In addition, policymakers in developing countries should strive to undertake large-scale renewable energy projects such as wind energy, solar power, bioenergy, and geothermal energy. That will supply clean energy and foster a switch from non-renewable to renewable energy. Moreover, policymakers should introduce incentives, for instance, subsidies/tax holidays, that will encourage firms' adaptation to clean technologies and facilitate smooth energy transition for better human development. Furthermore, policymakers ought to propose measures that would encourage the production of renewable energy on a personal basis. In addition, stakeholders concerned with sustainability should double their efforts in developing countries with energy poverty to generate energy from the abundant natural resources they have, like sunshine, wind, and bioresources, thereby improving their overall well-being and achieving sustainable development goals.

ETHICS DECLARATION

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