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Digital economy, financial development and energy transition in Africa: Exploring for synergies and nonlinearities

Sylvester Senyo Horvey [a,*], Jones Odei-Mensah [a], Tankiso Moloi [b], Godfred A. Bokpin [c]

[a] Wits Business School, Faculty of Commerce, Law and Management, University of the Witwatersrand, Johannesburg, South Africa
[b] Johannesburg Business School, University of Johannesburg, Johannesburg, South Africa
[c] Department of Finance, University of Ghana Business School, University of Ghana, Accra, Ghana

HIGHLIGHTS

- This study explores the synergies and nonlinear impacts of the digital economy and financial development on renewable energy.
- The digital economy exhibits a significant positive impact on renewable energy.
- The impact of the digital economy on renewable energy is moderated by financial development.
- The digital economy and financial development present a nonlinear U-shaped relationship with renewable energy.

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ABSTRACT

The transition to sustainable energy for all is a crucial aspect of the sustainable development goals, particularly Goal 7, which underscores the need for clean and affordable energy. This requires the development of digital infrastructure and a strong financial system. As a result, this study contributes to knowledge by exploring the synergies and nonlinear effects of the digital economy and financial development on renewable energy, which remains underexplored. To this effect, this study recruits the dynamic panel threshold and the generalised method of moments estimations to evaluate the linear, synergies and nonlinearities among these factors using a panel of forty-seven African countries. The key empirical results are stated as follows: (1) renewable energy is positively impacted by the digital economy; (2) the impact of the digital economy on renewable energy is moderated by financial development. This suggests that to ensure the propelling effect of the digital economy on renewable energy, there is a need for a stable and robust financial system; and (3) the study further found nonlinear effects of the digital economy and financial development on renewable energy, which takes a U-shaped relationship, implying that low level of digitalisation and financial development may hinder the transition to renewable energy, while high levels of these factors are essential to expedite the transition to a more sustainable energy system. Hence, African countries must embrace digitalisation and commit significant financial resources to developing their digital infrastructure to facilitate the achievement of the net zero agenda.

1. Introduction

Environmental sustainability has emerged as one of the most pressing economic challenges in recent years. This is due to the release of greenhouse gas emissions into the atmosphere, which has increased the earth's temperature by 1.4 degrees Fahrenheit since 1880 [1]. This leads to extreme weather events, including heat waves, floods, droughts, heavy rains, and severe global climate change, which pose severe threats to life on earth [2]. Hence, governments and scholars have given the issue of environmental degradation a lot of attention. During the 26th United Nations Climate Change Conference (COP26) in Glasgow in November 2021, a consensus was achieved to guarantee the 2050 net zero agenda globally. In this regard, accelerating the energy transition to renewable energy sources and encouraging sustainable environmental practices have become imperative [3]. The urgency of transitioning to sustainable energy is further accentuated by the Sustainable

* Corresponding author at: Wits Business School, Faculty of Commerce, Law and Management, University of the Witwatersrand, 2 St Davids Pl &, St Andrew Rd, Parktown, Johannesburg 2193, South Africa.
E-mail addresses: sylvester.horvey@wits.ac.za, sylvester.horvey@gmail.com (S.S. Horvey).

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Development Goal (SDG) 7, which underscores the need to ensure clean and affordable energy for all. Energy transition refers to the shift from a strong reliance on carbon-intensive energy fuel and biomass energy to the use of renewable sources of energy [4]. This includes using geothermal, hydroelectric, solar, wind, and bioenergy to lessen the dangers of fossil fuels and climate change. One key benefit is that renewable energy sources emit very little to no greenhouse gases and other pollutants, which greatly reduces their total environmental impact [5]. Furthermore, the inherent safety of renewable energy sources eliminates the possibility of accidents like fires or explosions that are frequently connected to fossil fuels [6].

The smooth transition to sustainable renewable energy sources requires developing the digital infrastructure, technologies, and social dimensions - collectively called the "digital economy" - and financial investment [4]. Digital advancement has significantly changed several domains, transforming how industries operate, engage customers, and drive economies [7]. The amalgamation of digital technologies, including artificial intelligence, the Internet of Things, and big data analytics, has enabled improved productivity, connectedness, and creativity in several sectors, including the energy sector. Thus, digitalisation presents hitherto unseen possibilities for optimising energy generation, distribution, and consumption in the context of renewable energy [8]. Digitalisation promotes utilising natural resources by increasing productive capacity in the extractive industries. It can cause significant changes in the energy industry, particularly by promoting the expansion of renewable energy [9]. This is because the low fossil fuel use, low marginal cost, minimal pollution, and low emissions associated with green growth are characteristics of the digital economy that alter economic production methods and energy structures. This implies that renewable energy sources are significantly impacted by the digital economy. Hence, assessing this relationship is essential.

Information gleaned from the empirical literature suggests that few scholars have explored the role of technological innovation and environmental innovation by way of simple proxies such as total patents on renewable energy [10–13]. Others have explored the impact of information and communications technology (ICT) on renewable energy [14–16], revealing inconclusive results. For instance, Chavan and Chavan [17] indicate a strong positive relationship between ICT and renewable energy sources. They argue that ICT-based facilities enhance the monitoring of plant conditions, flaws, anomalies, end uses, etc. Scholars reveal that developments in the Internet of Things offer a low-cost, direct, and user-friendly way to remotely monitor power facilities. On the other hand, Bano et al. [18] predict a significant negative relationship between ICT and renewable energy, arguing that most countries' ICT sector consumes high amounts of fuels harmful to the environment. Further, there has been growing interest in how the digital economy affects various factors such as total factor productivity [19], technological innovations [20], CO2 emissions [21] and energy consumption [4,6]. Despite these efforts, there does not seem to be much empirical research on the connection between the use of renewable energy and the digital economy, particularly in Africa, which is highly affected by global warming. Africa has several natural resources supporting renewable energy consumption; however, the progress towards sustainable energy consumption has been slow [22]. Another limitation of previous studies is using simple indices as proxies in their technology assessment. This limits our understanding of how the digital landscape of an economy triggers the transition to renewable energy sources. Thus, the digital economy is considered in this study, which includes several components categorised into infrastructure, social effect, digital trade and social support [4].

More so, scholars have provided an impression of the impact of financial development [23] and the digital economy [4,9] on the consumption of renewable energy. However, very little attention has been given to this issue, especially in Africa. Additionally, these studies offer some understanding of the direct impacts of these factors without considering their combined effect. Hence, there remains a notable gap in the possible interaction of these factors on renewable energy. This limitation is both a missed opportunity and an epistemological setback to our knowledge of the interactive nature of the two - digital economy and financial development. Scholars assert that the impact of the digital economy on energy transition will be less achievable without a robust financial system [23]. This is because the digital infrastructure for renewable energy requires significant financial investment; therefore, it is critical to have access to a range of reliable financial tools, including venture capital, green bonds, and innovative financing options. Also, following the fourth industrial revolution, robust financial systems are necessary for economies to function; hence, there remains no better time to explore the joint effect of energy transition and financial development on renewable energy. Even though the literature provides some knowledge on the impact of the digital economy on energy transition, it is still yet to be known whether financial developments influence this relationship. More so, some studies demonstrate that the digital economy and financial development are likely to propel renewable energy consumption [11,20,24]; it is still unclear what thresholds these factors might exert on energy transition. To ensure that the digital economy and financial development support the energy transition process, conducting further analysis in this area is prudent. In light of this, the novelty of this study lies in answering the following questions: (1) What impact does the digital economy have on renewable energy in Africa? (2) What is the moderating influence of financial development on the relationship between the digital economy and renewable energy in Africa? (3) Does Africa's renewable energy, financial development and digital economy have a nonlinear relationship?

The chosen context is motivated by several factors. Renewable energy has grown in popularity in Africa to reduce climate change consequences, promote sustainable development, and ease electricity access problems. Also, Africa has a wealth of renewable energy resources, such as wind, hydroelectricity, solar power, geothermal, and biomass, driving up interest in technology [2]. Despite socioeconomic challenges, Africa has seen a significant increase in technological innovation and digitalisation. Often dubbed the "next frontier" for innovation and technology, the continent is undergoing a digital revolution driven by rising internet usage, mobile connectivity, and a growing youth population ready to adopt digital solutions [25]. The proliferation of cost-effective smartphones and high-speed internet infrastructure - including 3G, 4G, and now 5G networks in certain urban areas - has accelerated this process. This has led to an increasing demand for sustainable energy practices. Africans are thus becoming more involved in digital transformation, which is raising the need for creative digital solutions, including sustainable energy practices. Is it against this backdrop that this study explores the synergy and threshold effects of financial development and the digital economy on Africa's energy transition?

This research contributes to knowledge in several ways. First, as far as we know, this is the first study examining the combined effects of financial development and the digital economy on Africa's renewable energy consumption. This offers governments a valuable resource for developing energy-related policy from a new digital economy standpoint. This is relevant to Africa's ongoing digital transformation agenda, which seeks to prioritise digital technologies that promote environmental sustainability (Union, [26]). It also aligns with SDG 7, which targets access to affordable and clean energy through innovative means. Hence, this study provides an excellent framework to empirically investigate this relationship by shedding light on how increased digital transformation can boost renewable energy. Also, assessing the contingent role of financial development on the digital economy-renewable energy nexus is very critical to Africa's economy. It offers practical implications for governments to expand their financial channel to ensure the development of the digital economy in order to accelerate the energy transition process. This enhances our understanding of the critical role of financial development in promoting digitalisation and environmental sustainability. Again, by exploring the nonlinearities in the relationship, the study provides insight into the level of digitalisation and financial development required to optimise the production and consumption of renewable energy. This can help policymakers create interventions and set focused targets to improve the digital economy and financial sector. This, in turn, enables the development of more focused policies, adjustments to the energy structures, promotion of digital transformation, and acceleration of renewable energy sources. Also, focusing on Africa provides an intriguing context, given that the continent is the most vulnerable to the effects of climate change, with temperatures exceeding 1.5 degrees Celsius. Hence, the findings will inform tailored policies that take into consideration the specific challenges and opportunities on the continent.

The remainder of this study is presented as follows: The theoretical and empirical literature relating to the subject matter are discussed in the second section. The third section presents information on the data and empirical approaches for analysis. The results and discussion are presented in the fourth section, and the summary, conclusion and recommendations are presented in the final section.

2. Literature review

2.1. Graphical insights

This study tests the preliminary relationship between the digital economy, financial development and renewable energy through scatter plots. The results in Fig. 1 present the relationship between the consumption of renewable energy and digital energy. The figure reveals an uphill pattern moving from left to right, indicating a positive correlation between Africa's digital economy and renewable energy. This is plausible given that the digital economy depends heavily on ICT and other digital infrastructure, which have become increasingly energy-efficient over time. Thanks to advancements in hardware design, software optimisation, and data centre management techniques, digital services now use less energy. Renewable energy sources like solar and wind power may be distributed and used more effectively thanks to the digitalisation of energy infrastructure, which includes smart grids and energy management systems. These technologies improve the integration of intermittent renewable energy into the grid while preserving dependability by enabling real-time monitoring, demand response, and energy storage.

According to the graph in Fig. 2, we also find a direct positive association between financial development and renewable energy consumption. Generally speaking, financial development entails the growth and sophistication of financial markets, which improve renewable energy projects' access to funding. Infrastructure for renewable energy, including wind and solar farms, frequently needs a significant upfront of funds. To finance these initiatives, developed financial markets provide a range of financing choices such as bonds, loans, and equity investments. In other words, financial development facilitates project funding, fosters innovation, manages risks, makes money more accessible, encourages sustainable investment, and supports favourable regulatory environments - all of which help to increase the consumption of renewable energy.

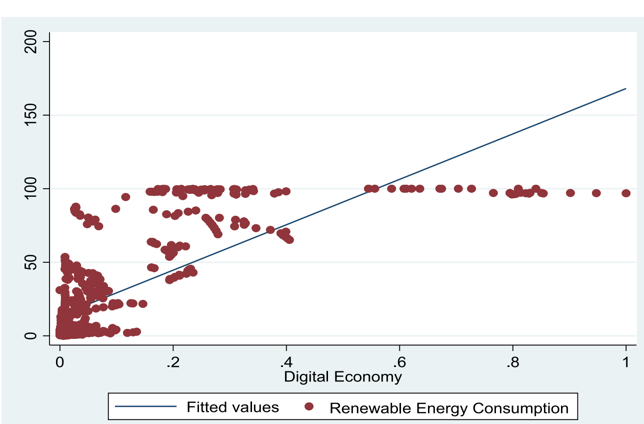

Fig. 1. Scatter plot of the consumption of renewable energy and digital economy.

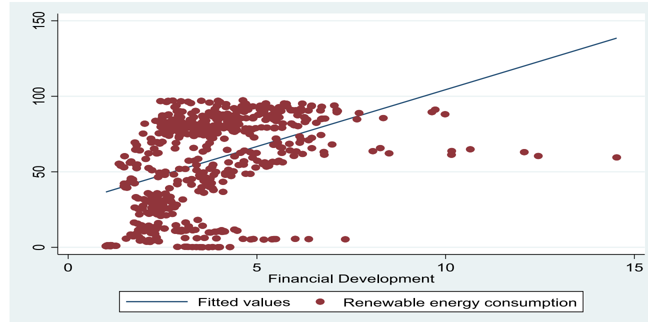

Fig. 2. Scatter plot of the consumption of renewable energy and financial development.

Another interesting finding in Fig. 3 suggests a strong positive correlation between digital economy and financial development, implying that digital economy and financial development are mutually reinforcing. Financial development provides an avenue to sponsor several digital infrastructure initiatives, including data centres, broadband networks, and telecommunications infrastructure. Investments in digital infrastructure are necessary to expand internet connectivity, improve internet access, and support the development of digital services and applications. Financial development receives funding for infrastructure projects that sustain the resilience and growth of the digital economy.

Generally, the observation from the scatter plots offers some interesting revelations, implying a positive association between renewable energy, digital economy and financial development. Even though these bivariate results provide preliminary evidence on the link among the main variables of interest, we cannot categorically depend on these bivariate results to draw a reliable conclusion. The bivariate relationship omits additional factors that influence renewable energy. Hence, these bivariate results exhibit omitted variable bias, which needs attention. This issue is addressed in the subsequent section, where further empirical tests are provided to offer a more robust result.

2.2. Theoretical underpinnings

The relationship between digital economy, financial development and energy transition can be explained by the ecological modernisation theory, which suggests that environmental issues can addressed economically, politically and technologically [27,28]. Thus, this theory contends that digital technology can help address environmental problems, which provides a theoretical framework for examining the role of the digital economy in energy transition [29]. Energy transition refers to

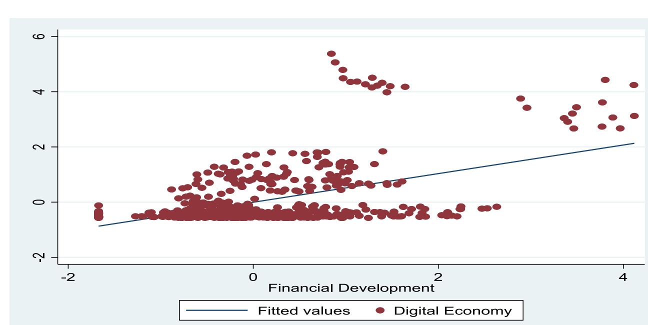

Fig. 3. Scatter plot of digital economy and financial development.

the process of moving away from fossil fuels and towards renewable energy sources, including hydropower, wind, and solar power. This transition is influenced by the digital economy in several ways. For instance, digital technologies like smart grids make energy systems reliable and efficient. It ensures the appropriate use of renewable energy sources, reduces energy waste, and improves demand-response management [30]. The digital economy helps disperse the distributed energy resources, such as solar panels and household batteries. This reduces dependency on centralised fossil-fuel-based power facilities and enables localized energy generation.

This aligns with the diffusion of innovation theory, as explained by [31]. They posit that the growth and use of technologies like big data, cloud computing, artificial intelligence and mobile internet are the cornerstones of the digital economy. Hence, the growth of the digital economy may give rise to a more extensive channel for information exchange and a more significant impact on the diffusion of knowledge. For instance, digital technologies like artificial intelligence and machine learning aid in the prediction of demand and supply of energy, optimisation of renewable energy sources, and energy storage systems. The digital economy helps disperse distributed energy resources (DERs), such as rooftop solar panels and household batteries. This reduces dependency on centralised fossil fuel-based power facilities and enables localized energy generation. As a result, the relevance of information technology's involvement in environmental governance has grown in light of the energy and environmental crises [32].

Further, the ecological modernisation theory expounds that interventions from countries and the involvement of institutions are vital to achieving the desired environmental outcomes [22,33]. This suggests that digital infrastructure with interactive factors such as financial development will ensure environmental sustainability [34]. Financial development provides the resources required for research and development in digital and renewable energy technologies. Hence, a strong financial system makes it easier for startups and established companies to obtain capital and implement innovative strategies to increase energy efficiency and transition [2,35]. As a result, green technology-focused firms can invest in digital technologies that facilitate energy transitions. It is against this backdrop that this study elucidates the intervening role of financial development on the digital economy-energy transition nexus.

2.3. Review of renewable energy consumption and digital economy

Digital technologies are essential parts of the modern infrastructure in the present globalisation, with wide-ranging applications in the many sectors of modern society [36]. It offers a new standard for the systemisation of knowledge derived from physical phenomena because of enhanced sensors, artificial intelligence algorithms, cloud computing, remote control, and other factors. In terms of the ecological transition, the adoption and usage of digital technologies expand the information available, which is crucial for individuals and organisations to make more sustainable decisions and for businesses to manage their operations more sustainably [37]. This is especially true for energy systems, which involve a range of energy conversion, transmission, and consumption processes [38]. Therefore, to facilitate the transition to renewable energy consumption, the integration of a digital economy is essential. This is not without empirical support.

Researchers contend that there is a positive association between the use of renewable energy and the digital economy. For instance, research by Sun et al. [20] shows that the shift to renewable energy consumption is significantly influenced by the digital economy. They explain that there is a rise in the transition to renewable energy for every growth in the digital economy. This is consistent with Shahbaz et al. [4], who show that growth in the digital economy will increase renewable energy consumption and generation. This indicates that a strong digital environment is crucial to ensuring sustainable energy consumption. Kahia et al. [39] add that environmental innovation through the use of modern technologies enhances the environment. Thus, the improvement in environmental quality can be attributed to the use of renewable energy sources and technological developments, which aligns with the above findings. In addition to reducing pollution and energy consumption, technological developments can also enable the production of environmentally friendly products like electric vehicles and green buildings, contributing to a sustainable environment.

This is essential given that a low-carbon economy is one of the primary strategies for addressing global warming, and technological innovation in the energy sector is seen as a crucial component of that approach. Using the autoregressive distributed lag technique, Kahia et al. [11] present that green energy use and environmental innovations have a long-term effect on CO2 emissions. That is, the use of technology connected to environmental patents does not result in environmental degradation. Similarly, Tzeremes et al. [40] explored this relationship among BRICS nations between 2000 and 2017 and found that ICT drives the development of energy transitions, whereas CO2 emissions encourage the use of renewable energy sources. This is affirmed by Lin and Huang [41], who revealed that digitalisation promotes the integration of renewable energy. This shows that a strong digital environment is crucial to ensuring sustainable energy consumption. Zeng et al. [42] provide more evidence by narrating that the digital economy might enhance a country's energy consumption structure, which would help the country's energy transformation. Wang et al. [43] also found a long-run relationship between renewable energy consumption and digitalisation. More so, Talan et al. [44] found a bidirectional causal relationship between digitalisation and renewable energy, and they suggested that to hasten the G7 nations' energy transition, governments should provide incentives for renewable energy products.

Lee et al. [45] explored this relationship using ICT as a proxy and found a significant positive relationship, concluding that the digital economy will improve clean energy production. This is confirmed by Ishida [46], who estimates that a decrease in fossil fuel consumption can be achieved by progressively making investments in the ICT sector. Khan et al. [47] affirm this argument, stating that ICT and governance are essential factors in reducing carbon dioxide emissions. Kouton [48] states that ICT growth has a significant and favourable influence on energy consumption in the African countries under study. Both internet usage and energy demand have unidirectional causal ties, as does the relationship between energy demand and mobile cellular subscriptions. Atsu et al. [49] indicate that a 1 % increase in ICT activities will result in a long-term rise in CO2 emissions of 0.565 %, with any transient shock to this connection being reversed by 93.20 %. Additionally, there is no proof that ICT has a threshold effect on carbon emissions.

Contrarily, Schulte et al. [50] found an inverse relationship between ICT and energy production. The negative relationship is possible when there is energy inefficiency in ICT goods and services [51]. This suggests an intentional effort to finance digital energy resources. These arguments align with the findings of Li et al. [52], who observed that one of the significant indicators of the transition to low-carbon energy is digital finance. Similarly, Li et al. [52] found a significant positive relationship between financing and renewable energy using bootstrapped ARDL results for quarterly data between 2000 and 2020. Also, Wang et al. [43] examine the BRICS data asymmetrically and discover that positive shocks to ICT and finance lead to high consumption of renewable energy while negative shocks lead to a decreased use of renewable energy consumption. This is supported by Yu et al. [23], who assert that financing increases investment in renewable energy and further indicates a threshold relationship between these factors.

2.4. Review of renewable energy consumption and financial development

The financial sector plays a key role in monitoring energy emissions by encouraging digitalisation and technological innovation in the energy supply industry to reduce emissions. This indicates how financial development, which demonstrates the actual availability of funds, contributes to the fight against environmental degradation, particularly through the reduction of CO_2 emissions [53]. This argument is supported by Charfeddine and Kahia [54], who posit that financial development reduces environmental degradation. This is because financial development often initiates research and development, attracts foreign direct investment and progressively accelerates economic operations to impact environmental quality through funding environmentally related initiatives. This is consistent with Tamazian and Rao's [55] argument that financial development is essential to addressing environmental issues and promoting environmental performance. Hence, weak financial development may be detrimental to environmental quality.

Sun et al. [20] narrate that financial development is one of the most significant subjects in technology innovation. Regarding renewable energy, there is a substantial imbalance in the resources available to promote technical innovation and research and development to locate innovative resources for services related to renewable energy. Their results support Mukhtarov et al.'s [56] finding, which shows that financial development has a statistically significant influence on the utilisation of renewable energy. According to these scholars, there is a rise in the usage of renewable energy for every improvement in financial development; thence, there is a need to boost investments in renewable energy sources while promoting sustainable social and economic growth. Further, financial development enhances the demand for renewable energy projects by expanding the available financing channels. It also reduces the financial barriers faced by environmentally conscious businesses and increases the affordability and accessibility of financing [57]. These contribute to the gradual reduction of carbon emissions and the improvement of carbon reduction performance. Li et al. [52] affirm this argument and reveal that financial development ensures the creation of funding channels supporting technological development and the shift to a low-carbon economy. This implies that a strong financial system promotes the efficiency of the energy industry and encourages investment in sustainable energy production [58]. Using a Vector Error Correction Model (VECM), Islam et al. [59] illustrated the positive impacts of Malaysian financial growth on energy consumption and the reverse causality that exists between the two. Ozturk and Acaravci [60] discovered that financial development has a significant positive impact on energy consumption. This is because digital finance employs modern information technology to increase the efficiency with which funds are provided and required in the environmental sector, thereby reducing the financial barriers that arise during an economy's transition to a low-carbon economy [52]. These assertions show that by making investments in renewable energy, countries may be able to shield themselves from the effects of climate change and keep their energy infrastructure free of carbon-intensive development patterns.

Further, Çoban and Topcu [61] discovered that financial development significantly increases energy consumption among older European Union members using a sample of 27 European Union nations. The impact on the new member states, however, depends on the financial development proxy that is employed. An inverted U-shaped pattern may be seen in the system-generalised Method of Moments (GMM) model findings when bank-related variables are used as a proxy for financial development. Anton and Nucu [62] further highlight that each of the three financial development dimensions - the capital market, bond market, and banking sector - has a favourable influence on the share of renewable energy use. However, no significant association was discovered when stock index variables were used to quantify financial progress [62]. Also, Lahiani et al. [63] argue that the use of renewable energy is considerably impacted in the short term only by unfavourable changes in overall and stock-based financial development metrics. At the one-legged period, the latter influence is concurrently beneficial and negative. Consumption of renewable energy is not affected in the short term by changes in bank-based financial development.

2.5. Novelty and gaps in the literature

Although a large body of scholars have considered various aspects of climate change, very few scholars have begun to investigate the potential impact of the digital economy on energy transition. More so, the direction of this relationship is far from being established, which is further compounded by the inconclusive results. Furthermore, no attention has been paid to the intervening role of financial development in the nexus between the digital economy and renewable energy consumption. As the literature reveals, progressive investment in a digital economy will facilitate the transition from carbon emissions and fossil fuel to sustainable energy consumption [46,47]. This is supported by Li et al. [52], who contend that one of the key factors propelling the low-carbon energy transition is digital finance. This allows for investment in digitalisation and promoting renewable energy technologies such as wind and solar power, which reduces a country's dependency on fossil fuels for energy production [39]. This perspective holds that sufficient funding is required for the transition from fossil fuel-based to renewable energy. However, empirical investigation to validate this assertion remains incipient, which is a gap considered in this study. Given this, this study's novelty lies in examining the contingent role of financial development on the relationship between the digital economy and the consumption of renewable energy.

In a similar vein, previous studies mostly demonstrated the direct, bidirectional, long run and short run effects of financial development and digital economy on renewable energy; however, there are still gaps in the existing literature on the nonlinearities and threshold effects these factors might exert, which is another novel issue addressed in this study. As Yu et al. [23] and Feng et al. [9] present, an improved financial system and digital economy are essential for an enhanced investment in renewable energy, implying some threshold levels in the relationships. However, despite the scholarly efforts, there has not been much discussion about the presence of non-linearities and thresholds in the relationships, particularly in Africa, which is highly impacted by global warming. Africa is endowed with several natural resources that support renewable energy consumption; however, progress towards sustainable energy consumption has been slow [22]. This requires several resources, including digitalisation and financial development. As a result, this study offers a fresh perspective on the literature by exploring the synergistic, nonlinearities, and threshold levels at which renewable energy consumption in Africa is impacted by financial development and the digital economy, which is an essential contribution to knowledge.

3. Methods

3.1. Data and variables

This paper examined a sample of 47 countries in Africa between 2006 and 2019. These include Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Dem. Rep., Congo Rep., Cote d'Ivoire, Egypt, Equatorial Guinea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Seychelles, Sierra Leone, South Africa, Sudan, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe. The motivation for the chosen sample is based on the constraints in the availability of data at the time of the study. The World Development Indicators (WDI) database was used to obtain information for the variables employed for analysis.

3.1.1. Dependent variable

The dependent variable in this study is energy transition, which is represented by renewable energy consumption. This represents the share of renewable energy in the total final energy consumption. The use of renewable energy is understood to be the optimal approach to energy transition [2]. This is because renewable energy sources such as solar, wind, and hydropower, among others, produce electricity without emitting greenhouse gas and carbon dioxide. It is believed that the transition to renewable energy is a useful strategy for limiting world average temperature increases to 1.5 °C [4].

3.1.2. Independent variable

There is a lack of a common standard for evaluating the digital economy and a dearth of all-inclusive metrics for tracking its overall growth. Information was published by the International Telecommunication Union (ITU), and the Information and Communication Technology (ICT) sector's degree of development was measured by the Communication Technology Development Index (IDI); however, it was discontinued in 2018 [9]. To measure the independent variable, the study follows [4,9,20,24] to construct a comprehensive index for the digital economy. As a result, this study thoroughly evaluates the digital index, considering digital trade (exports and imports of ICT goods). Exports and imports of ICT goods and services allow countries to access advanced technology and skills that may not be available, particularly in developing countries. This makes it possible to capitalise on their digital expertise and makes it easy for cutting-edge technology to be implemented, leading to a strong digital economy [24]. Given this, Shahbaz et al. [4] posit that the consumption of ICT equipment implies a developing digital economy. Another sub-indicator is social effect (medium and high-tech manufacturing value-added and internet use by individuals, compulsory education). Value-added medium and high-tech manufacturing stimulates innovation and the creation of advanced technology necessary for the growth of the digital infrastructure in an economy. Internet usage for personal use and compulsory education contribute to the digital transformation of society by increasing digital literacy, providing access to online resources, and developing a tech-savvy workforce that is essential for successfully utilising digital technology [20].

The other indicators for the digital economy include the development of ICT infrastructure (fixed telephone, mobile subscriptions, fixed broadband, secure internet services) and social support (service industry per capita added). The expansion of these infrastructures ensures high-speed internet connectivity and access, improved communication and data transfer [40]. This connectivity supports numerous digital services and societal transformations in the digital age. It also fosters innovation and technological development, contributing to renewable energy sources [45]. The results in Fig. 4 provide further insights into the trend analysis of the digital economy variables. As can be seen, variables such as fixed broadband, mobile cellular, internet use, compulsory education and service industry display an upward trend. This demonstrates the progress of digital transformation over the period under consideration. The increase in these factors is helpful in ensuring that the digital transformation agenda is realised in Africa (Union, 2020). Also, it can be seen that fixed telephone subscriptions peaked in 2009 and have since experienced a decline. The decline can be attributed to the ongoing transition from traditional telephony products to mobile phones; hence, it is unsurprising that mobile cellular subscription reveals an upward trend contrary to the trend for fixed telephones. More so, the study finds that factors such as ICT goods imports and exports have been volatile over the period. This can be explained by the fluctuations in the economic cycles in Africa, which influence the demand and supply of ICT goods. To promote a digital economy, strategies must be implemented that support investment in digital infrastructure. The description of the variables are listed in Table C1.

3.1.3. Moderating variable

The study aligns with Hassan et al. [64] and Pradhan et al. [24] to create an index for financial development. Our proxy indicators for financial development incorporate information from banks, other financial intermediaries, and lending markets. The first indicators include domestic credit from the private sector and domestic credit from banks. A higher domestic credit to the banking sector signifies a greater reliance on the banking industry for funding. Thus, banks are more likely to supply financial services, as expressed by [65]. The domestic credit sector overcome any limitations from the banking sector because they are not obliged to provide loans to priority sectors. According to Hassan et al. [64], a high domestic credit-to-GDP ratio denotes a higher

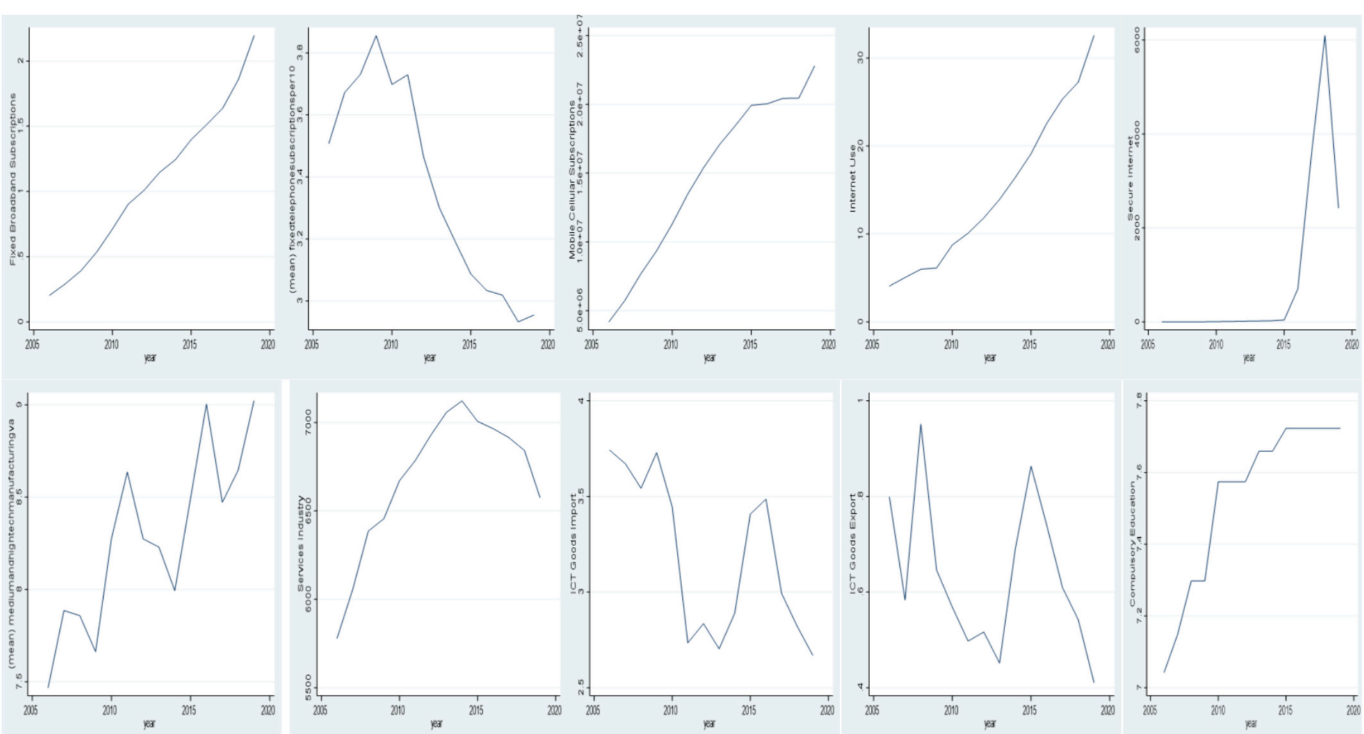

Fig. 4. Data visualisation of digital economy variables. Source: Author's computation.

Table A1
Principal component analysis and eigenvalues of digital economy.

Components	Eigenvalues	Difference	Proportion	Cum. Proportion	KMO Stat.
Comp 1	3.16018	1.39129	0.4160	0.4160	0.6304
Comp 2	1.76889	0.632305	0.2069	0.6229	0.653
Comp 3	1.13658	0.12054	0.1137	0.7366	0.4948
Comp 4	1.01604	0.100143	0.0816	0.8182	0.7343
Comp 5	0.915898	0.263817	0.0624	0.8806	0.5681
Comp 6	0.652081	0.140267	0.0420	0.9226	0.7694
Comp 7	0.511814	0.093466	0.0312	0.9538	0.623
Comp 8	0.418347	0.128362	0.0210	0.9748	0.7532
Comp 9	0.289986	0.1598	0.0122	0.9870	0.5229
Comp 10	0.130186	–	0.0130	1.0000	0.634
Overall					0.6469

domestic investment and degree of financial system development. Higher levels of financial development are necessary for financial systems that provide more credit to the private sector because they are more likely to mobilise savings, conduct borrower research, provide risk management control, facilitate transactions and exercise corporate control [66].

In addition, we include liquid liabilities of the banking system in the economy and utilise the broadest definition of money (M3) as a percentage of GPD as a measure of financial depth (Khan & Snehadji, [67]). Another indicator is the ratio of gross domestic savings to GDP. It is anticipated that increased gross domestic savings will be beneficial to financial development and increased investment. Furthermore, financial repression and credit regulations result in negative real interest rates in most developing countries, which lessens the incentives to save. This perspective holds that increased gross domestic savings encourage investment and growth [24]. The other indicators include the ratio of trade to GDP and the ratio of general government final consumption expenditure to GDP. These metrics evaluate the importance of fiscal policy and the size of the real sector. In order to achieve growth and development, most developing countries frequently rely significantly on international trade, even as financial liberalisation continues to advance. Additionally, countries modify government expenditure through expansionary or contractionary fiscal policies to achieve growth and development [24]. An index for financial development was constructed using the principal component analysis. The descriptions of the variables are presented in Table C2.

The results in Fig. 5 illustrate the growth in financial development in African countries. For instance, variables such as domestic credit by banks and the private sector, broad money and government final consumption have been increasing over the period under review. This suggests a more robust and developing financial system where resources are easily accessible to the public and private sectors. However, there were fluctuations in domestic savings and trade. Maintaining a stable financial system is essential to ensure enough cash stream for investment, which requires stability and growth in these factors. Therefore, it is important to implement comprehensive policies to stabilise savings rates and ensure a growing trade pattern in Africa.

3.1.4. Control variables

For the control variables, the following variables were selected as informed by the literature as key drivers of renewable energy consumption. These include economic growth, which is measured by GDP per capita. GDP per capita is a useful metric for evaluating shifts in local production of goods and services while considering the costs related to manufacturing and consumption that affect the environment and society (Sarkodie et al., [68]). This is believed to impact climate change as it could imply access to technological transfer towards cleaner energy and a sustainable environment. Another control variable is foreign direct investment (FDI). FDI encourages industrial growth, which is counterproductive to the shift towards renewable energy [2]. As a result, foreign direct investment (FDI) has a significant influence on renewable energy; however, the specific direction of this influence remains unclear. Labour force and inflation, which are measured using the consumer price index, were also included as proxies for macroeconomic in/stability.

3.2. Principal component analysis

Considering the multiple factors in measuring digital economy and financial development, the study creates an index for these variables using the Principal Component Analysis (PCA). This is a strong dimensional reduction method which aids in maintaining the multidimensionality of a collection of variables by reducing the number of indices down to a small set referred to as the principal component (Greenacre et al., [69]). The results of the PCA and eigenvalues for digital economy and financial development are reported in Tables A1 and B1, respectively, while the corresponding eigenvectors are reported in Tables A2 and B2. Also, the Kaiser-Meyer-Olkin (KMO) statistics, which display the total and partial intercorrelations between the indicators, are displayed in Tables A1 and B1 for both variables. If the KMO statistics are more than 0.5, it implies that the sample size used to calculate the digital economy and financial development index is adequate. Given the overall KMO statistics of 0.6469 and 0.5539 for digital economy and financial development, the study concludes that the variables, or the sample, are large enough and adequate for empirical research. The scree plot shows the total number of Kaiser thresholds of 1 for choosing components to create the digital economy and financial development, which is reported in Figs. 6 and 7. Four factors were extracted for the digital economy because their eigenvalues were closer to or beyond 1. For the digital

Table B1
Principal component analysis and eigenvalues of financial development.

Components	Eigenvalues	Difference	Proportion	Cum. Proportion	KMO Stat.
Comp 1	2.61652	1.1061	0.4361	0.4361	0.547
Comp 2	1.51042	0.564197	0.2517	0.6878	0.5481
Comp 3	0.946222	0.422573	0.1577	0.8455	0.643
Comp 4	0.523649	0.255779	0.0873	0.9328	0.3403
Comp 5	0.26787	0.132546	0.0446	0.9774	0.5246
Comp 6	0.135324	.	0.0226	1	0.5737
Overall					0.5539

Table A2
Eigenvectors of digital economy index.

Variable	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6	Comp7	Comp8	Comp9	Comp10
Fixed Broadband	0.4651	−0.3033	0.0373	0.0969	0.025	0.0046	−0.2956	0.246	0.1302	−0.718
Fixed Telephone	0.4661	−0.2183	−0.1575	−0.0575	−0.1224	−0.2584	−0.254	0.1363	0.4258	0.6007
Mobile Subscriptions	0.0444	0.533	0.4741	0.0697	0.0598	0.3975	−0.1567	0.4632	0.2658	0.1137
Internet use	0.4544	−0.0053	0.2416	−0.1797	0.1869	0.1671	−0.2733	−0.1707	−0.6985	0.2199
Medium/High-tech manufacturing	0.243	0.5046	0.0605	0.0352	0.3566	−0.3403	−0.0534	−0.571	0.2906	−0.1586
ICT goods export	0.2844	0.1703	−0.4349	0.1942	−0.3705	0.6364	0.0632	−0.3302	0.0873	−0.0163
ICT goods import	0.2561	0.3838	−0.25	0.4497	−0.1539	−0.3942	0.2573	0.3775	−0.3668	0.0005
Services value added	0.2997	0.0844	−0.1687	−0.6521	0.2006	0.0886	0.5838	0.2206	0.0703	−0.0827
Internet Servers	0.1637	−0.365	0.2152	0.5301	0.4638	0.1923	0.4685	−0.0606	0.1009	0.165
Compulsory education	0.1893	−0.0703	0.6005	−0.0528	−0.6343	−0.162	0.3399	−0.2175	0.0396	−0.054

Table B2
Eigenvectors of financial development index.

Variable	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6
Domestic credit by financial inst.	0.4333	−0.4198	0.194	0.5663	−0.1088	0.5157
Domestic credit to private	0.5198	−0.3734	0.0416	−0.0111	−0.0857	−0.7623
Broad money	0.5017	−0.0946	−0.0594	−0.7578	0.124	0.3823
GDP	0.1433	0.3753	0.8667	−0.0087	0.287	−0.0709
Trade/GDP	0.346	0.5992	−0.0777	0.0522	−0.7156	0.0179
Gen. Gov final Cons	0.3874	0.419	−0.4471	0.3194	0.6091	−0.0385

Table C1
Definition of digital economy variables.

Variable	Definition	Source
Fixed telephone	Fixed telephone subscriptions (per 100 people)	WDI
Fixed broadband	Fixed broadband subscriptions (per 100 people)	WDI
Mobile subscriptions	Mobile cellular subscriptions (per 100 people)	WDI
Secure internet services	Secure Internet servers (per 1 million people)	WDI
Internet use by individuals	Individuals using the Internet (% of population)	WDI
Medium and high-tech manufacturing value-added	Medium and high-tech manufacturing value added (% manufacturing value added)	WDI
Compulsory education	Compulsory education, duration (years)	WDI
ICT imports	ICT goods imports (% total goods imports)	WDI
ICT exports	ICT goods exports (% of total goods exports)	WDI
Service industry	Service industry per capita added US$	WDI

Table C2
Definition of financial development variables.

Variable	Definition	Source
Domestic credit_Private	Domestic credit to private sector (% of GDP)	WDI
Domestic credit_Banks	Domestic credit provided by financial sector (% of GDP)	WDI
Broad Money	Broad money (M3) (% of GDP)	WDI
Domestic Savings	Gross domestic savings (% of GDP)	WDI
Trade	Trade (% of GDP)	WDI
Government consumption	General government final consumption expenditure (% of GDP)	WDI

economy index, factor 1 had an eigenvalue of 3.160 and explained 41 % of the overall variance, while factor 2 had an eigenvalue of 1.768, accounting for 20 %, factor 3 also had an eigenvalue of 1.136, recording a variance of 11 % while factor 4 had an eigenvalue of 1.016, accounting for 8 %. Generally, these factors explain 82 % of the overall variance. Also, for the financial development index, factor 1 had an eigenvalue of 2.616 and explained 43 % of the overall variance, while factor 2 had an eigenvalue of 1.510, accounting for 25 %. Generally, these factors explain 69 % of the overall variance. Individual factors with high loading factors were minimised using the orthogonal varimax rotation (kaiser off) to determine the contribution of each factor. We then find the total of each underlying variable's contribution to all retained factors to derive the structural transformation index.

3.3. Empirical strategies

The estimation techniques are twofold. First, the generalised method of moments (GMM) was employed to examine the direct and interaction effects of the digital economy and financial development on energy transition. Following this, the dynamic panel threshold estimation was used to determine the presence of nonlinearities among the threshold.

3.3.1. Linear and interaction analysis

The study employs Arellano and Bond's [70] GMM estimator to evaluate the association between financial development, digital economy and renewable energy. The choice of the estimation technique is motivated by several factors. First, the primary condition for the application of the GMM technique is based on the assumption that the number of cross-sections must be greater than the time-periods, which is the situation in the data structure of this study, where the countries (i.e., $N = 47$) is greater than the time-period (i.e., $T = 14$). Second, the literature claims that because the GMM technique can account for measurement errors and missing data, it performs better than the static model as it considers unobserved country-specific effects and employs time series changes in the data [71]. Third, it addresses endogeneity issues in the model [72]. The first endogeneity issue is the incorporation of the lagged dependent variable. Using this technique, the study built a model in which a vector of observations for the independent variable and its lag determine the dependent variable. The significant positive result of the lagged dependent variable indicates the persistence of energy transition, thereby affirming the dynamic nature of the model. It is also essential to highlight that the addition of the lagged dependent variable creates endogeneity issues which is associated with the error term [2]. Another endogeneity issue is the possible bi-causal relationship among the variables of interest, as the literature reveals. For instance, some scholars argue that the digital economy influences energy transition and vice versa [45,73,74]. One of the major drawbacks of the GMM technique is its inability to handle long panels, where $T > N$. However, the study overcomes this drawback as it examines cases where $N > T$. Hence, the dynamic GMM estimation technique is used. Additionally, the study adopts the two-step system GMM over the one-step system GMM because the two-step GMM can more effectively handle overfitting and possible instrument proliferation. Its asymptotically consistent and dependable results make it more effective as well [72]. Consequently, the following is how the model is expressed.

$$RENW_{it} = \beta_1 RENW_{it-1} + \beta_2 DE_{it} + \beta_3 GDP_{it} + \beta_4 FDI_{it} + \beta_5 LABOUR_{it} + \beta_6 INFL_{it} + \mu_i + \partial_t + \varepsilon_{it} \quad (1)$$

$$RENW_{it} = \beta_1 RENW_{it-1} + \beta_2 FD_{it} + \beta_3 GDP_{it} + \beta_4 FDI_{it} + \beta_5 LABOUR_{it} + \beta_6 INFL_{it} + \mu_i + \partial_t + \varepsilon_{it} \quad (2)$$

$$RENW_{it} = \beta_1 RENW_{it-1} + \beta_2 DE_{it} + \beta_3 FD_{it} + \beta_4 (DE^*FD)_{it} + \beta_5 GDP_{it} + \beta_6 FDI_{it} + \beta_7 LABOUR_{it} + \beta_8 INFL_{it} + \mu_i + \partial_t + \varepsilon_{it} \quad (3)$$

where RENW represents renewable energy, which is the dependent variable, $RENW_{it-1}$ is the lag of the dependent variable, DE stands for digital economy, FD for financial development, GDP is gross domestic product per capita, FDI for foreign direct investments, LABOUR for labour force, and INFL for inflation, (DE*FD) represents the interaction term. The parameters to be estimated are denoted by β, the temporal fixed effect is represented by ∂_t, the unobserved country-specific fixed effects are represented by μ_i and the idiosyncratic error component is denoted by ε_{it}.

To capture the net effects, the study applies the principles given by (Brambor et al., [75]). This involves determining the combined effect of the interaction and constitutive terms. This is done by taking the first

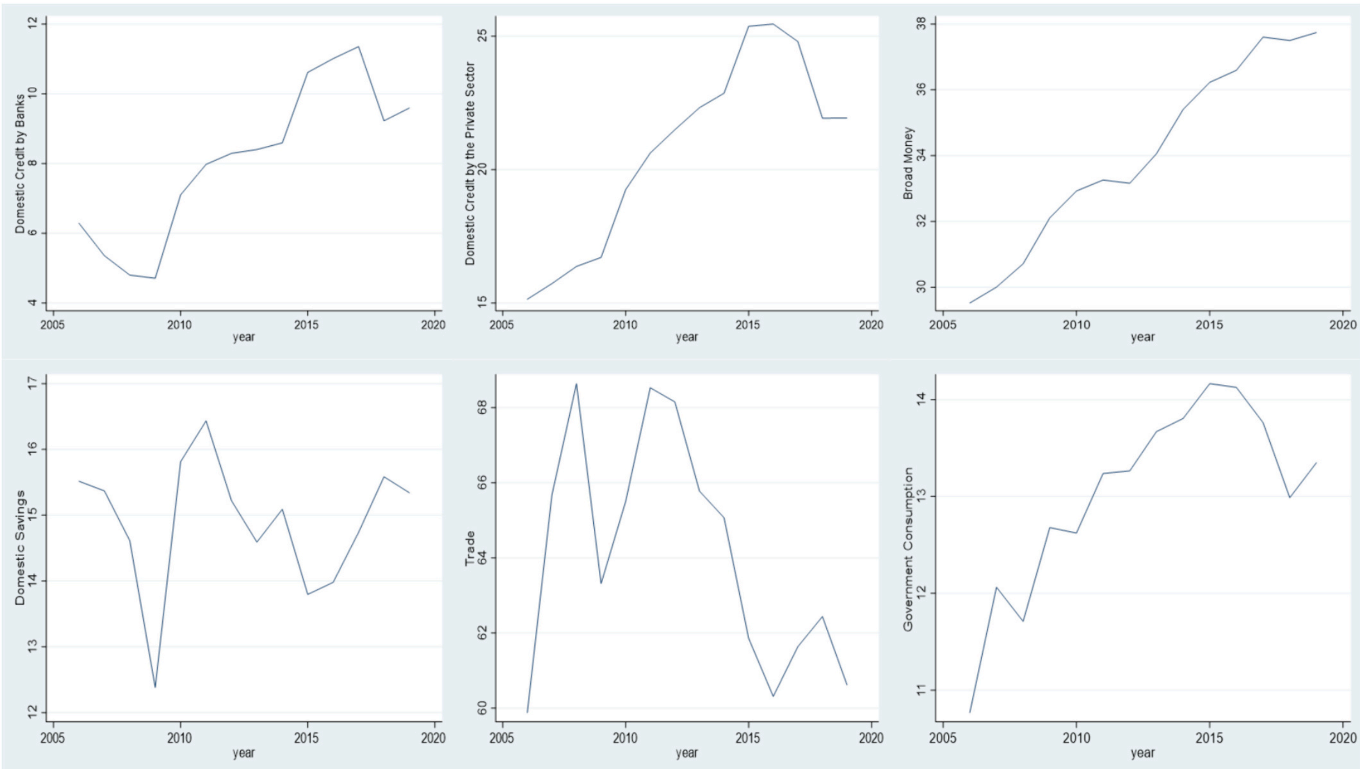

Fig. 5. Data visualisation of financial development variables. Source: Author's computation.

derivative of Eq. (3) with regard to the digital economy. Consequently, the model is specified as:

$$\frac{\partial RENW}{\partial DE} = \beta_2 + \beta_4 FD_{it} = 0 \tag{4}$$

Given this, the level of digital economy interacted by financial development is determined by summing the coefficients of ($\beta_2 + \beta_4$) and the significant test of their combined effects.

It is crucial to highlight that the GMM technique's post-estimation testing, which is taken into consideration, determines the accuracy and reliability of the results. Hansen's test for over-identifying conditions helps to assess the validity of the instruments [2]. The Hansen test is based on the null hypothesis, stating that the residuals and specified instruments have no correlation. Consequently, the precision of our computations and the suitability of the instruments are determined by not rejecting the null hypothesis. The instruments are not resilient when the null hypothesis is rejected since the restrictions resulting from depending on the instruments are valid. Again, other post-estimation tests are employed to further evaluate the validity of the estimates. To assess this, there must be no second-order serial correlation in the residuals. Also, the number of instruments must not be greater than the number of groups, and the model must be jointly significant.

3.3.2. Nonlinear analysis

Further, the study analyses the nonlinear relationship using the dynamic panel threshold model proposed by Seo and Shin [76] and Seo et al. [77] to better inform decision-makers about the threshold required and adequate for financial development and the digital economy to improve the consumption of renewable energy. Additionally, the method is used since it is based on the GMM principles and addresses problems with simultaneity and endogeneity that arise in the relationships which cannot be avoided. This technique offers more advantages than the threshold techniques provided by [78], Caner and Hansen [79], and González et al. [80], which are only useful for static models and do not consider endogeneity issues. The dynamic threshold model addresses this issue and treats the threshold variable and regressors as endogenous, aligning with the principles of dynamic models [76]. More so, the above static threshold models, including the Kremer et al. [81] threshold model, treat the regressors and transition variables as exogenous [76]. More so, they report the threshold level and estimates of the variables only at one level, without revealing their true coefficient estimates at lower and upper levels. The dynamic panel threshold estimation overcomes the shortcomings of these models by providing comprehensive information on the direction of the coefficient estimates of the variables at different regimes. It does this by indicating the effect of the coefficient estimates at different levels [77]. Thus, the dynamic threshold model helps by splitting the sample into two groups: the lower regime and the upper regime. This helps the sample for the study to be divided into two using this technique, which provides the threshold level at which the digital economy and financial development impact energy transition. In addition, it offers the threshold value's confidence interval and shows the effects of the threshold variables, regardless of whether it falls beyond or below the threshold, which is ignored by other threshold models [82]. Like the GMM technique, a major limitation of this dynamic panel threshold model is that it is mostly suitable for situations where the number of cross-sections is greater than the time, which is the situation for this study [76]. Another major limitation of the dynamic panel threshold estimation is its inability to estimate multiple thresholds [76]. Notwithstanding, this technique is designed to address a single threshold level, which aligns with the study's purpose. Hence, the chosen technique is appropriate and expressed as:

$$y_{it} = x'_{it}\beta + (1, x'_{it})\delta 1\{q_{it} > \gamma\} + \mu_i + \varepsilon_{it} \text{ where that } i = 1, \dots, n \text{ and } t = 1, \dots, T \tag{5}$$

Such that y_{it} represents renewable energy, which is the dependent variable, q_{it} represents digital economy and financial development, which are the threshold variables, and x_{it} includes the dependent variables' lag, n is supposed to expand indefinitely, T is considered to be fixed, and γ is the model's threshold parameter, which divides the

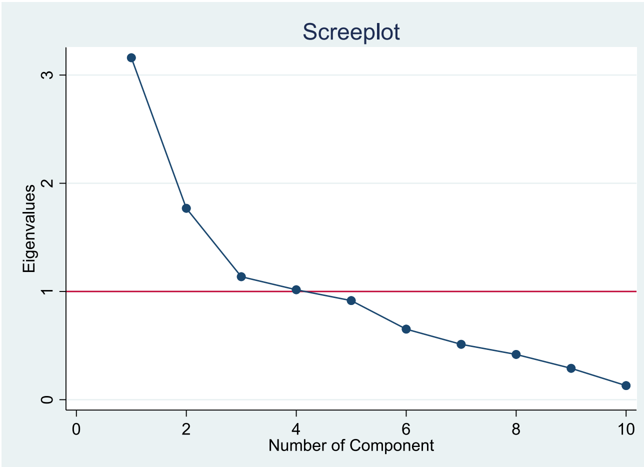

Fig. 6. Scree plot of principal components of digital economy index.

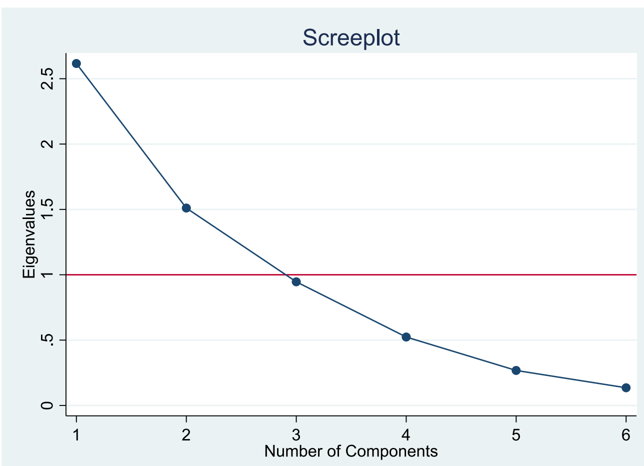

Fig. 7. Scree plot of principal components of financial development index.

coefficients into two regimes. The first difference procedure is used to eliminate the fixed effect $\boldsymbol{\mu}_i$, and GMM is then used to estimate the unknown parameters. Hence, $\theta = (\beta^{'}, \delta^{'}, \gamma)^{'}$.

4. Interpretation and discussion of the results

4.1. Descriptive results

An overview of the variables is provided before delving into the empirical investigation, as depicted in Table 1. Africa's average renewable energy consumption is 60.184, suggesting that the continent is still transitioning towards renewable energy sources. Also, the digital economy and financial development recorded average values of 0.356 and 0.417, with variations of 1.123 and 1.432, respectively. The average value for economic growth is 7.237, while foreign direct investment is 4.666. Inflation averages 6.927 over the sample period, while the labour force presents an average score of 61.955. The correlation matrix is further reported in Table 2. The results show no high correlation among the independent variables, which is further validated by the variance inflation factor (VIF) in Table 1; hence, multicollinearity is not an issue in the model. The study further indicates that the digital economy has a strong positive correlation with the dependent variables, implying that higher digital transformation leads to the adoption of renewable energy sources.

4.2. The direct and interaction effect of the digital economy and financial development on renewable energy consumption

The primary objective of this section is to examine the impact of the digital economy and financial development on renewable energy sources and the contingent role of financial development on the digital economy-renewable energy nexus. These results are estimated using the two-step system GMM estimation technique. All the assumptions regarding the use of the GMM technique are met. For instance, there is no second-order serial correlation AR(2), and the number of instruments is less than the number of groups. More so, the statistically insignificant values of the Hansen test imply instrument validity. The lagged dependent variable is significantly positive, suggesting the persistence of renewable energy consumption. Thus, previous years' consumption is more likely to enhance its consumption in the current year.

The digital economy index is a composite measure that takes into account several dimensions of digital infrastructure and usage. Hence, the analysis begins by first exploring the impact of these individual factors on renewable energy consumption, as presented in Table 3 (Models 1–10). This enhances our understanding of how these factors contribute to the development of renewable energy sources. The study reveals that fixed broadband and telephone significantly and positively influence renewable energy consumption. Similarly, internet use presents a significant positive relationship. This is not surprising, considering that the use of fixed broadband and telephone subscriptions is increasing in Africa, which is projected to be the fastest-growing fixed broadband market. This development allows for the implementation of Internet of Things devices and smart grid technologies that monitor and control renewable energy installations. These systems can improve the dependability and efficiency of renewable energy sources by optimising energy production, storage, and consumption. More so, the digitalisation of economies through telephone and internet technologies increases the effectiveness and integration of essential components required for the production of renewable energy [20]. This supports Atsu et al. [49], who found a positive relationship between ICT infrastructure, such as fixed broadband, telephone and renewable energy consumption. This is because high-speed broadband and internet use simplify complicated data analytics and sustainable energy system monitoring. Real-time data from wind turbines, solar panels, and smart grids may be examined to optimise energy production, reduce waste, and enhance efficiency and performance. Kouton [48] supports this argument by narrating that internet use favours renewable energy consumption. Further, the positive result for secure internet servers could be explained by the fact that secure internet servers guard against cyberattacks on sensitive energy data. This comprises details on the generation, distribution, and utilisation of renewable energy to maintain energy systems' reliability and integrity. Additionally, the findings illustrate that medium and high manufacturing sectors record a positive relationship. Extensive research and development (R&D) and innovation are frequently conducted in the medium- and high-tech manufacturing sectors, which results in the development of cutting-edge renewable energy technology.

Table 1
Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max	VIF
Renewable Energy	658	60.184	30.207	0.061	97.33	–
Digital Economy	658	0.356	1.123	−0.570	5.375	1.81
Financial Development	658	0.417	1.342	−1.671	4.118	1.71
Economic Growth	658	7.237	1.035	5.114	9.896	2.09
Foreign Direct Investment	658	4.666	8.516	−11.197	103.337	1.01
Inflation	658	6.927	12.043	−16.860	255.305	1.02
Labor Force	658	61.955	14.714	0.001	88.350	1.74

Table 2
Matrix of correlations.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) Renewable Energy	1.000						
(2) Digital Economy	0.691	1.000					
(3) Financial Development	0.032	0.022	1.000				
(4) Economic Growth	−0.775	0.617	0.036	1.000			
(5) Foreign Direct Investment	0.028	0.048	0.021	−0.018	1.000		
(6) Inflation	0.087	−0.059	0.047	−0.077	−0.000	1.000	
(7) Labor Force	0.614	−0.537	−0.044	−0.589	−0.025	0.058	1.000

Further, according to the empirical results, ICT imports present a significant positive impact. In Africa, a significant portion of ICT materials consumed originates from external sources, which facilitate the growth of the digital sector within African economies (Union, 2020). These ICT imports provide Africa access to cutting-edge technology necessary for updating its energy infrastructure. These innovations, which improve the dependability and efficiency of renewable energy sources, include smart grids, sophisticated data management systems, and sophisticated metering infrastructure in Africa. This is consistent with Shahbaz et al. [4], who state that ICT has the potential to increase adaptability to centralised energy systems, change technical operations, and facilitate the development of distributed energy and renewable energy sources. Hence, by importing ICT, African countries may gain access to the latest global technical innovations and expertise. This might speed up the adoption of renewable energy technology [9]. Despite the importance of ICT, the study failed to reveal any significant relationship between ICT exports and renewable energy. This is because poor infrastructure is a problem in many African nations; this includes unstable electrical supplies, limited internet access, and poor transportation networks. These restrictions impede the growth and expansion of the ICT sectors. In addition, the continent lacks the capacity and insufficient expertise to develop and commercialise ICT solutions. More so, the focus is mostly based on ICT services and not advanced technologies that could significantly impact the growth of renewable energy systems. Even though the African continent benefits greatly from ICT imports, there is a need to build a strong ICT infrastructure which encourages technological developments within the continent.

For compulsory education and mobile use, the study found a negative relationship. The negative result could be attributed to the fact that only 43 % of the African population has subscribed to mobile services. This indicates a significant gap on the continent, which has implications for renewable energy use on this continent. For instance, mobile technology supports access to information, monitoring and management and facilitation of data on energy use [4]. Hence, without the widespread mobile connection, these technologies cannot be fully utilised, which might lead to less sustainable energy use and a potential rise in reliance on non-renewable resources. More so, there is a high illiteracy rate in Africa, with more than 50 % of the global illiteracy rate living in this continent. In addition, there is a problem of job mismatch between the skills acquired in school and those required for renewable energy jobs in Africa, which could impede the adoption of renewable technology. Given this, African countries need to ensure significant investment in mobile technologies and align the educational curriculum with the growing demands of the labour market, particularly technological skills. These measures will contribute greatly to the digital transformation agenda (Union, 2020), which presents significant potential for producing and using renewable energy. More so, African countries must adopt integrated development strategies that combine investments in renewable energy with the growth of mobile networks [20]. By focusing on e-waste management, promoting the use of renewable energy to power mobile infrastructure, and encouraging prudent energy usage, the advantages of mobile connectivity may be matched with the need for sustainable energy solutions.

The findings in Table 3 further show the result for the overall digital economy index. The findings reveal that the digital economy positively influences renewable energy, which was statistically significant at 10 %. The positive result affirms the argument that the digital economy facilitates improvement in a country's renewable energy sources. This aligns with previous findings [4,11,41], which suggest that the digital economy drives innovation and development in renewable energy technologies. According to the African Union report, digital transformation drives creative, inclusive and sustainable growth. The growth in the digital transformation system ensures the adoption of advanced technology, which is essential to the transition to renewable energy sources in Africa. In light of global warming, which greatly affects Africa, it is essential for African countries to facilitate their digital transformation system and ensure the transfer of such technologies in the production of sustainable energy sources. Countries can facilitate the design and development of renewable energy systems using digital modelling and simulations. Also, collaboration and information sharing can be facilitated on digital platforms, leading to advancements in renewable energy generation, storage, and grid integration [20]. Renewable energy sources can be integrated into smart grids thanks to digital technology. Smart grids distribute energy more effectively by utilising communication networks, sensors, and meters. This integration makes integrating renewable energy sources into the current energy infrastructure easier, improves grid stability, and lowers energy losses during transmission. As a result, the widespread use of renewable energy technologies as they become more accessible and inexpensive would enable cleaner air, less climate change consequences, and enhanced energy security on the continent.

Again, the empirical evidence reveals that financial development has a positive and statistically significant effect on renewable energy consumption. The significant positive result is supported by previous findings [56], which establish that financial development has a statistically significant and positive effect on the use of renewable energy. This suggests that financial development is essential in accelerating the transition to renewable energy consumption because it promotes investment, reduces financing costs and expands financing possibilities [22]. Financial development enhances the demand for and expansion of financing channels available for renewable energy projects. It also reduces the financial barriers faced by environmentally conscious businesses and increases the affordability and accessibility of financing [57]. Also, improved financial markets attract foreign investors and facilitate financing large-scale renewable energy projects, such as hydropower plants, solar energy and wind farms. These supports have greatly benefited nations like Morocco and South Africa, leading to notable growth in their capacity for renewable energy. These again contribute to the gradual reduction of carbon emissions and the improvement of carbon reduction performance. Further, Anton and Nucu [62] argue that improved banking and capital markets are two examples of financial infrastructure that can reduce the cost of financing for renewable energy projects. Lower financing costs make renewable energy projects more attractive to developers and investors, which leads to the deployment of additional renewable energy capacity. Therefore, financial development expands the range of finance options available to renewable energy projects.

While the above findings acknowledge that the consumption of renewable energy is improved by the digital economy, how this pathway can be realised needs to be explored. Given this, the study examines the

Table 3
System GMM results for digital economy, financial development and renewable energy.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
VARIABLES	RENW	RENW	RENW	RENW	RENW	RENW	RENW	RENW	RENW	RENW	RENW	RENW	RENW	RENW
Renw Energy (−1)	1.042***	1.022***	1.021***	1.026***	0.028***	1.036***	1.034***	1.032***	1.023***	1.028***	1.027***	1.026***	1.036***	1.037***
	(0.054)	(0.041)	(0.048)	(0.039)	(0.048)	(0.054)	(0.052)	(0.051)	(0.046)	(0.050)	(0.051)	(0.049)	(0.052)	(0.052)
Fixed Broadband	0.094***													
	(0.012)													
Telephone		0.043*												
		(0.028)												
Mobile			−0.032											
			(0.103)											
Internet Use				0.025*										
				(0.016)										
Medium/high-tech					0.017*									
					(0.011)									
ICT export						0.094								
						(0.176)								
ICT import							0.072**							
							(0.039)							
Services value added								0.012						
								(0.007)						
Secure internet									0.013					
									(0.010)					
Compulsory education										−0.026				
										(0.024)				
Digital Economy											0.020*		0.383*	0.378*
											(0.012)		(0.257)	(0.226)
Financial Development												0.013***	0.009**	0.016***
												(0.001)	(0.004)	(0.005)
Dig. Eco.*Fin. Dev.														0.127***
														(0.009)
Net Effects														0.431***
Economic Growth	0.759	0.367	0.478	0.372	0.546	0.715	0.680	0.361	0.521	0.602	0.558	0.566	0.587	0.596
	(0.912)	(0.573)	(0.858)	(0.542)	(0.815)	(0.920)	(0.900)	(0.677)	(0.837)	(0.907)	(0.916)	(0.890)	(0.765)	(0.770)
FDI	−0.011*	−0.009	−0.009**	−0.007	−0.006	−0.007	−0.004	−0.004	−0.008	−0.008	−0.008	−0.008	−0.012	−0.012
	(0.006)	(0.006)	(0.004)	(0.004)	(0.004)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.008)	(0.008)
Labour Force	−0.021	−0.011	−0.013	−0.012	−0.021	−0.025	−0.025	−0.028	−0.016	−0.019	−0.018	−0.017	−0.015	−0.015
	(0.026)	(0.018)	(0.031)	(0.017)	(0.031)	(0.033)	(0.033)	(0.036)	(0.028)	(0.029)	(0.029)	(0.028)	(0.019)	(0.019)
Inflation	0.011*	0.011**	0.010**	0.011**	0.011**	0.011**	0.010**	0.010**	0.010**	0.010**	0.010**	0.010*	0.009*	0.009*
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.004)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Observations	607	607	604	607	607	607	607	607	607	607	607	607	607	607
Time/Country Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of ID/instrument	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/11	47/11
AR(1)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AR(2)	0.085	0.079	0.081	0.076	0.079	0.079	0.081	0.082	0.081	0.083	0.075	0.089	0.188	0.185
Hansen	0.957	0.863	0.903	0.952	0.881	0.906	0.913	0.910	0.856	0.871	0.714	0.708	0.611	0.704

Note: The values in parentheses are the standard errors; the significant values are represented as 1 %(***), 5 %(**) and 10 % (*); renewable energy is represented as RENW energy, while foreign direct investment is represented as FDI; Dig. Eco represents the digital economy, and Fin. Dev. represents financial development.

interactive effects of the estimates and indicates that the impact of the digital economy on the use of renewable energy sources is contingent on financial development. The finding is affirmed by computed net effect, following Brambor et al.'s [75] procedure. The net effect results suggest that the combined impact of the digital economy and financial development on renewable energy consumption is significantly positive. This indicates that financial development significantly moderates the digital economy's role in using renewable energy. This evidence supports the ecological modernisation theory, which suggests the need to consider state interventions such as financial development to achieve the desired environmental outcomes [22,33]. Therefore, to promote renewable energy consumption, there must be a significant investment in digitalisation and technology, which provides the basis for renewable energy production [2] because building and enhancing digital infrastructure may require greater investment [9]. The results align with Africa's 2030 digital transformation agenda, which suggests the need for a harmonised environment which encourages investment and financial development. This will help bridge the digital infrastructure gap and provide technologies that are affordable, secure, and accessible, thereby promoting sustainable energy use (Union, 2020). Also, financial development fosters innovation, facilitating the switch to a more technologically enabled energy and sustainable future. It ensures the creation of funding channels supporting technological development and the shift to a low-carbon economy [52]. Hence, enough funding is needed to support projects that advance digitalisation in renewable energy. Research initiatives aimed at lowering costs, improving effectiveness, and boosting the reliability of renewable energy systems can get funding from venture capitalists, financial institutions, and governmental agencies. This innovation cycle leads to the development of advanced renewable energy solutions and speeds up the adoption of renewable energy across many sectors.

For the control variables, the findings present a positive relationship between economic growth and renewable energy. This can be explained by the fact that growth in economies frequently results in higher disposable incomes and more purchasing power for both consumers and companies [4]. Investments in renewable energy, like wind turbines, solar, and energy-efficient appliances, are, therefore, more affordable. Because they are now more affordable, people are using more renewable energy sources, which increases demand for them. On the other hand, foreign direct investment and labour force present an inverse relationship. As explained by Horvey and Odei-Mensah [2], it is possible that environmental sustainability in Africa will not be able to be promoted by FDI. This happens when FDI is directed towards using non-renewable energy sources, which aligns with Dube and Horvey's [22] argument that the low percentage of renewable energy consumption in the energy mix is due to the inadequate investment in renewable energy in Africa.

For the labour force, the study argues that the renewable energy sector requires specialised skills and training for installing solar panels, servicing wind turbines, and integrating renewable energy systems into the grid. Where there is a shortage of skilled labour or insufficient training programs, the development and execution of renewable energy projects may be hindered. This might lead to project execution delays and a reduction in the overall quantity of renewable energy consumed. Surprisingly, inflation presents a positive impact on renewable energy consumption. In Africa, where the majority of people rely on fossil fuels, inflation may hike the prices of traditional energy sources such as coal, fossil fuels, and natural gas. As the price of these conventional energy sources rises, individuals and organisations may be more interested in renewable energy sources, which are seen to be cheaper than conventional energy sources, thereby leading to high renewable energy consumption.

4.3. The nonlinear relationship between digital economy, financial development and renewable energy

Another notable contribution of this study is the consideration of the nonlinearities between digital economy, financial development and renewable energy consumption, which is discussed in this sub-section. The dynamic panel threshold estimation technique is employed in this situation to ascertain whether there are appreciable differences in the parameters across different regimes [76,77]. This is based on the argument that the influence of the digital economy and financial development on renewable energy in the context of economic globalisation and growing digitalisation may exhibit varying effects, contingent upon the degree of development of these factors exhibited by individual nations [9,23]. As a result, this study examines the possibility of nonlinearity in the relationship. The study performed a nonlinearity test which was evaluated at 100 bootstrap replications and trimmed by the default 0.4 rates. The results from Tables 4 and 5 report that the bootstrap *p*-value for linearity is significant at 1 %, which implies nonlinearities in the relationship. Hence, we reject the null hypothesis of no threshold effects. Thus, the model can be split into two – an upper regime and a lower regime, which reports the coefficient estimates when the values fall below or above the threshold indicator.

The results from Table 4 report the threshold effect of the digital economy on renewable energy. The empirical evidence presents a negative relationship when the digital economy lies in the lower regime and a significant positive impact when it falls in the upper regime, implying a nonlinear (u-shaped) relationship. This indicates that the use of renewable energy increases with growth in the digital economy. As narrated by the ecological transition and the diffusion of innovation theory, the adoption and usage of digital technologies expand the information available, which is crucial for individuals and organisations to make more sustainable decisions [37], particularly in energy systems, which involve a range of energy conversion, transmission, and consumption processes [38]. In Africa, where energy use and consumption is a challenge, integrating digital technologies in the production of smart grid technologies and solar offers the potential to improve sustainable energy production and installation of renewable energy sources. Thus, mature and sophisticated digital technologies contribute to the efficiency and optimisation of sustainable energy use. In other words, a strong digital economy will facilitate and ensure a better integration of renewable energy sources into the existing energy infrastructure in Africa. The importance of a digital economy in energy transition is supported by Dong et al. [73], who state that a digitally advanced economy reduces the vulnerability of energy and improves renewable energy consumption. Kahia et al. [39] add that improvement in environmental quality can be attributed to the use of renewable energy sources and technological developments. Khan et al. [47] bolster this claim by asserting that technologically advanced economies, particularly

Table 4
Threshold effect of digital economy on energy transition.

	(1)	(2)
Variables	Lower Regime	Upper Regime
Renewable Energy (−1)	0.810***	1.259***
	(0.164)	(0.265)
Economic Growth	4.628***	−12.14***
	(1.561)	(2.644)
Foreign Direct Investment	−0.015	0.080
	(0.045)	(0.079)
Inflation	0.024***	−0.087
	(0.007)	(0.084)
Labour Force	0.631**	0.526**
	(0.276)	(0.246)
Threshold Variable (Digital Economy)	−0.049	0.171**
	(0.0751)	(0.082)
Post-estimations		
Threshold Point (r)	1.773***	
	(0.369)	
95 % Confidence Interval	[−4.456–0.910]	
Linearity Test	0.000	
Observation	47	

Note: The values in parentheses are the standard errors; the significant values are represented as 1 %(***), 5 %(**) and 10 % (*).

Table 5
Threshold effect of financial development on energy transition.

	(1)	(2)
Variables	Lower Regime	Upper Regime
Renewable Energy (−1)	0.544***	0.0648***
	(0.074)	(0.021)
Economic Growth	−4.11***	1.648
	(0.932)	(2.224)
Foreign Direct Investment	−0.035	0.791**
	(0.024)	(0.343)
Inflation	0.0140	−0.098*
	(0.018)	(0.057)
Labour Force	0.273	−0.257*
	(0.242)	(0.151)
Threshold Variable (Financial Development)	−0.764**	1.113***
	(0.234)	(0.345)
Post-estimations		
Threshold Point (r)	4.290***	
	(0.530)	
95 % Confidence Interval	[0.251–5.329]	
Linearity Test	0.000	
Observation	47	

Note: The values in parentheses are the standard errors; the significant values are represented as 1 %(***), 5 %(**) and 10 % (*).

blockchain technology, are a major force behind renewable energy, contributing to developing an intelligent, low-carbon, decentralised, and effective energy system. Feng et al. [9] further expound that in the early stages of the digital economy, there may be a more considerable need to spend on traditional energy in order to build and improve digital infrastructure. As the extent of the digital economy increases, early-stage accumulation may result in economies of scale and a cleaner and sustainable environment, which will promote the use of renewable energy sources. The study, therefore, postulates that an advanced digital economy is essential to achieving sustainable energy use and consumption. Hence, African countries must commit enough resources to digitalisation.

The nonlinear relationship between financial development and the use of renewable energy is presented in Table 5 below. We note that the impact of financial development on renewable energy has a negative effect at lower levels, exhibiting an inverse and a significant impact. The result suggests that the consumption of renewable energy is weakened by low financial development. On the other hand, a significant positive relationship was found at the upper level, affirming the importance of financial development on renewable energy. For instance, the financial sector makes a substantial contribution to monitoring energy emissions by encouraging digitalisation and technological innovation in the energy supply industry to reduce emissions [53]. Hence, a well-functioning financial system is essential to accelerating the transition to renewable energy [63]. This aligns with Yu et al. [23], who said an increase in financial development enhances renewable energy consumption and vice versa. Similarly, Sun et al. [20] state that renewable energy consumption rises significantly in response to increases in financial development. In Africa, financial development has led to the growth of mobile banking, microfinance institutions and innovative financial services. More so, financial support from institutions such as Power Africa provides funds to off-grid companies, increasing access to clean energy production. These developments also offer financial support for off-grid energy for local solar energy and other renewable energy projects in Kenya, Nigeria, and Uganda, improving energy access. More so, financial developments promote public-private partnerships that support innovation and renewable energy projects. For instance, this partnership has helped in advancing renewable energy projects in countries such as Ethiopia and Egypt, contributing to sustainable energy production. Hence, by leveraging the strengths of the financial markets, investors, entrepreneurs, and governments can unleash the potential of renewable energy as a fundamental component of worldwide energy systems. The reason is that higher financial development frequently corresponds to more accessible opportuinities for funding for renewable energy initiatives [61]. Hence, renewable energy developers have access to a greater range of financing choices, such as loans, equity investments, and project finance, which help promote adopting renewable energy technology as financial markets grow more complex and inclusive.

4.4. Robustness analysis

Our findings in the previous sections are cross-validated through robustness analysis. Thus, we employ clean fuels and technologies as an alternative measure for renewable energy. Clean energy accounts for the share of renewables in a country's total energy consumption. This is an encompassing term that covers not just energy from renewable sources but also techniques and technology that greatly reduce or completely remove toxic emissions and their negative effects on the environment [2]. The estimated results in Table 6 confirm the validity of our findings by indicating that financial development and the digital economy promote the use of renewable energy sources. Further, the results confirm that the interaction between digital economy and financial development is significantly positive. More so, the threshold results in Tables 7 and 8 retain their impacts and direction at the different thresholds, detailing that an improved digital economy and robust financial system are essential for the growth of renewable energy sources [9,11,20]. This shows that the results obtained in the previous sections are reliable, affirming the validity of the regression results.

5. Conclusion and policy implications

5.1. Conclusion

The accelerating energy transition to renewable energy sources and encouraging sustainable environmental practices have become imperative. This is enshrined in SDG 7 and is essential to achieving net zero emissions by 2050, as presented at COP26. This requires significant effort and resources. Digitalisation and financial development are seen to be significant driving forces of the global economic operation, revolutionising the activities of every economy, including sustainable energy sources. To this end, this study contributes to knowledge by delving into the synergy and nonlinearities between financial development, the digital economy and the consumption of renewable energy. Specifically, it explored the direct and threshold levels at which digital economy and financial development influence renewable energy consumption. Also, it examined the intervening role of financial development in the relationship between the digital economy and renewable energy consumption. The results were examined using the dynamic panel threshold and the GMM estimations employing a panel of 47 African countries between 2006 and 2019.

The regression findings indicate the existence of a positive relationship between the digital economy and financial development, demonstrating that the digital infrastructure of an economy is crucial to renewable energy use and consumption. In other words, the presence of digital technologies is essential to drive the energy transition towards renewable energy sources. Hence, governments, institutions and stakeholders should ensure the integration of digital technologies into renewable energy sources to develop green technologies for sustainable energy consumption. Also, the empirical evidence presents that financial development significantly and positively affects renewable energy consumption, which means that the financial structure of an economy, including its institutions and markets, is essential to the growth in renewable energy consumption. Additionally, the findings from the interaction term indicate that financial development is a prerequisite for the development of the digital economy and its effect on the use of renewable energy. This suggests that a well-functioning financial system will boost the digital economy's development, ultimately influencing renewable energy. Thus, given a robust financial system, African countries will be able to support the digitisation process and production

Table 6
System GMM results for digital economy, financial development and renewable energy.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
VARIABLES	Clean	Clean	Clean	Clean	Clean	Clean	Clean	Clean	Clean	Clean	Clean	Clean	Clean	Clean
Clean Energy (−1)	1.060***	1.064***	0.941***	1.019***	0.864***	0.962***	0.960***	0.956***	0.965***	0.979***	0.760***	0.879***	1.091***	1.083***
	(0.039)	(0.067)	(0.061)	(0.009)	(0.177)	(0.084)	(0.209)	(0.121)	(0.089)	(0.111)	(0.114)	(0.070)	(0.120)	(0.124)
Fixed Broadband	0.329**													
	(0.159)													
Telephone		−0.101												
		(0.200)												
Mobile			0.040											
			(0.370)											
Internet Use				0.027***										
				(0.008)										
Medium and high-tech					0.121									
					(0.159)									
ICT export						−0.055								
						(0.559)								
ICT import							0.042							
							(0.857)							
Services value added								0.007						
								(0.006)						
Secure internet									0.011					
									(0.010)					
Compulsory education										−0.150				
										(0.220)				
Digital Economy											0.028		0.017	0.022
											(0.026)		(0.015)	(0.019)
Fin. Dev												0.034**	0.029	0.032*
												(0.018)	(0.004)	(0.021)
Dig. Eco*Fin Dev.														0.041**
														(0.022)
Net Effect														0.049**
Economic Growth	−0.636	−0.279	1.703	0.045	3.052	1.695	1.458	1.188	1.474	1.237	5.438**	2.775*	−0.505	−0.362
	(0.804)	(1.049)	(1.342)	(0.133)	(3.262)	(1.488)	(3.749)	(1.858)	(1.601)	(1.972)	(2.600)	(1.600)	(1.871)	(2.156)
FDI	0.005	0.011	−0.006	−0.001	−0.002	0.001	−0.004	0.015	0.009	0.003	−0.001	0.001	0.011	0.010
	(0.015)	(0.029)	(0.017)	(0.005)	(0.032)	(0.020)	(0.040)	(0.043)	(0.025)	(0.037)	(0.018)	(0.015)	(0.049)	(0.050)
Labour Force	0.024	0.024	−0.012	0.009	−0.093	0.015	0.001	0.008	0.019	0.014			0.025	0.024
	(0.023)	(0.047)	(0.050)	(0.008)	(0.131)	(0.075)	(0.171)	(0.120)	(0.075)	(0.096)			(0.082)	(0.080)
Inflation	0.001	0.004	0.007	−0.002	0.012	0.001	−0.002	0.009	0.009	0.006	0.030	0.017	0.003	0.003
	(0.008)	(0.013)	(0.011)	(0.004)	(0.034)	(0.025)	(0.038)	(0.022)	(0.014)	(0.020)	(0.028)	(0.026)	(0.023)	(0.023)
Observations	607	607	604	607	607	607	607	607	607	607	604	607	604	604
Time/Country Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
No. of id/instruments	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/12	47/11	47/12
AR(1)	0.808	0.129	0.261	0.008	0.648	0.702	0.751	0.258	0.191	0.156	0.410	0.420	0.538	0.517
AR(2)	0.010	0.144	0.717	0.021	0.560	0.882	0.881	0.858	0.971	0.353	0.707	0.625	0.346	0.423
Hansen	0.170	0.225	0.266	0.001	0.900	0.451	0.617	0.414	0.314	0.524	0.980	0.832	0.701	0.697

Note: The values in parentheses are the standard errors; the significant values are represented as 1 %(***), 5 %(**) and 10 % (*); while foreign direct investment is represented as FDI; Dig. Eco represents the digital economy, and Fin. Dev. represents financial development.

Table 7
Threshold effect of digital economy on clean energy.

Variables	(1) Lower Regime	(2) Upper Regime
Clean Energy (−1)	0.988***	0.608**
	(0.0231)	(0.356)
Economic Growth	0.529***	−0.525***
	(0.148)	(0.197)
Foreign Direct Investment	−0.094	0.192**
	(0.067)	(0.094)
Inflation	0.055	−0.063
	(0.047)	(0.049)
Labour Force	0.051**	−0.057
	(0.024)	(0.079)
Threshold Variable (Digital Economy)	−6.107***	6.332***
	(1.801)	(1.872)
Post estimations		
Threshold Point (r)	0.208***	
	(0.018)	
95 % Confidence Interval	[−0.015–0.673]	
Linearity Test	0.000	
Observation	47	

Note: The values in parentheses are the standard errors; the significant values are represented as 1 %(***), 5 %(**) and 10 % (*).

Table 8
Threshold effect of financial development on clean energy.

Variables	(1) Lower Regime	(2) Upper Regime
Clean Energy (−1)	1.013***	0.713*
	(0.0109)	(0.421)
Economic Growth	0.390***	−0.998***
	(0.106)	(0.108)
Foreign Direct Investment	0.011	−0.013*
	(0.007)	(0.007)
Inflation	−0.013*	−0.017
	(0.005)	(0.016)
Labour Force	0.049***	−0.028***
	(0.014)	(0.011)
Threshold Variable (Financial Development)	1.197	2.141**
	(0.761)	(0.831)
Post estimations		
Threshold Point (r)	0.283***	
	(0.067)	
95 % Confidence Interval	[0.152–0.816]	
Linearity Test	0.000	
Observation	47	

Note: The values in parentheses are the standard errors; the significant values are represented as 1 %(***), 5 %(**) and 10 % (*).

of renewable energy technologies. Furthermore, the study found non-linearities in the relationship in the form of a U-shaped relationship, demonstrating that advanced levels of financial development and the digital economy increase the consumption of renewable energy. In other words, the use of renewable energy increases with growth in the financial system and advancement in a digital economy. Given that renewable energy thrives in a strong digital environment and financial system, it will be important to develop these factors to create opportunities for the energy transition process. Thus, a strong digital environment and financial system are required to achieve sustainable energy consumption.

5.2. Policy implications

The paper yields several policy implications. Given that the results emphasise the significant role of the digital economy in renewable energy in Africa, there is a need to create a favourable regulatory framework that encourages the development of digital technologies and includes the use of these technologies in the production of sustainable energy solutions. Given this, African countries must prioritise creating and reforming policies to foster digitally advanced economies. They must encourage the use of digital infrastructure such as fixed broadband, fixed telephones, and ICT goods, leading to the support of renewable energy sources. This will promote energy trade patterns that support environmental sustainability and benefit the individuals and the economy at large. For instance, ICT may alter technical operations in a variety of ways, improve adaptability to centralised energy systems and encourage the rapid growth of renewable and distributed energy sources. Furthermore, African countries must strengthen international corporations with developed countries to help develop advanced technologies and facilitate the digital transition process.

Considering the substantial influence of the digital economy at higher levels, the study recommends that policymakers exert more effort in this area by promoting digitalisation domestically and globally. Such policies must ensure significant investment to expand the growth and application of digital technologies. For example, governments need to apply and build technology like smart grids and electric vehicles in the energy sector and increase the number of renewable energy charging stations. Again, to ensure the growth and use of digital technologies, governments must incorporate digital literacy and skills programs in the educational system. These measures will contribute greatly to the digital transformation agenda, which presents significant potential for producing and using renewable energy. More so, countries should also build a digital power strategy that involves aiding energy corporations in their endeavours to augment digital innovation. Governments also need to support the development of digital infrastructure and encourage the broad use of the internet. This can be done by ensuring that better frameworks are created to incentivise the use of digital tools in the renewable energy sector, like predictive analytics, in order to boost productivity and encourage the creation of advanced technologies. The development of the digital economy will ultimately improve the consumption of renewable energy sources. Governments may expedite the shift towards the use of renewable energy sources by harmonising policy objectives with the integration of digital and renewable energy advances.

It is also important to highlight that the advancement of the digital economy cannot be possible without a developed financial system. Thus, the digitalisation process requires a significant amount of financial resources in order to ensure that renewable energy sources are produced speedily. Hence, policies relating to the use of renewable energy should consider interventions that promote access to financial resources to support the digitalisation process, particularly green technologies. By creating a sustainable financial environment for digitalisation and renewable energy, policymakers can drive innovation, minimise greenhouse gas emissions, and accelerate the transition towards sustainable energy, which might present several opportunities for growth and development. Also, policymakers should place a high premium on investments in digital infrastructure that foster collaboration among digital firms and the renewable energy industry. Although the level of renewable energy sources in Africa is minimal, it is possible that creating a strong digital environment and financial system will facilitate its production and use. In this regard, countries with low financial development need to develop policies to enhance the scope of financial development by promoting financial institutions and markets and fostering its integration with the digital economy, such as internet connectivity and ICT infrastructure. Companies should also embrace online financial services platforms, increase the scope of microfinance offerings, and devote more resources to developing sustainable and energy-efficient technology.

5.3. Limitations and future research

While this research provides valuable insights, several constraints must be considered for further studies. First, the study was limited to only African countries; hence, this could be extended to other continents to contribute to the discussion on global policymaking. Another limitation of the study is its inability to estimate multiple threshold levels using the chosen technique; hence, scholars could consider this avenue to capture the underlying complexities in the model. Also, the study used renewable energy and clean energy as proxies of energy transition, which could be made more comprehensive by incorporating other variables in future studies. More so, the study could further be disaggregated into the income levels to determine its differential impacts. Further, scholars could use other proxies, such as green financing, as proxies for financial development. It will also be worthwhile to consider green technology indicators, such as solar, wind, etc., as proxies for digitalisation. It will also be interesting to take into account a country-specific analysis of the relationship explored. These initiatives will broaden our knowledge and help shape more specialised policy responses tailored to the needs of the individual nations to solve climate-related issues.

CRediT authorship contribution statement

Sylvester Senyo Horvey: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jones Odei-Mensah:** Writing – review & editing, Validation, Supervision. **Tankiso Moloi:** Writing – review & editing. **Godfred A. Bokpin:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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