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Research article

The effect of eco-friendly and financial technologies on renewable energy growth in emerging economies

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ABSTRACT

Successfully integrating renewable energy sources depends on eco-friendliness, financial technology, and economic growth (GDP). This paper examines the dynamic effect of innovative financial and green technology on renewable energy for 38 emerging economies from 2006 to 2021. Using the dynamic First-difference Generalized Method of Moments (FD-GMM) model, the analysis identifies a critical GDP threshold of 1831.772 US dollars, significant at the 1 % confidence level. Below this threshold, GDP negatively affects green energy adoption, while above it, GDP positively influences the shift to greener energy, supporting the predicted U-shaped relationship in the data. The results conclude that eco-friendly and financial technology positively and significantly influence renewable energy adoption, where the dynamics and barriers to adopting eco-friendly and financial technologies in emerging countries may differ from those in developed nations. Based on the findings, relevant energy policies have been recommended for energy stakeholders, Tech firms and decision-makers.

1. Introduction

Growing reliance on conventional energy sources has become a big worry, hindering efforts to achieve environmental sustainability, combat climate change, and promote renewable energy [1–3]. In 2022, renewable sources accounted for 30.2 % of worldwide energy production, as reported by Ref. [4]. The dismal statistics emphasize the urgent necessity for a global transition to renewable energy (RE) sources to alleviate the negative impacts on the environment and lessen the continued pressure on our planet's ecological equilibrium. This study highlights the effect of eco-friendly and financial technology on greener energy.

In this context, green patents and eco-friendly technologies play a crucial role in advancing renewable energy by promoting innovation, cutting costs, and enhancing efficiency in the industry [5,6]. Renewable energy technology, such as solar panels and wind

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turbines, reduces renewable energy production costs, improving its competitiveness with traditional fossil fuels [7,8]. Furthermore, the increased efficiency of these technologies allows for a more effective transformation of natural resources into energy, expanding the use of renewable sources [9]. Moreover, the increase in green patents indicates to officials and investors the feasibility and promise of renewable energy, drawing in favorable policies and financial backing and hastening the expansion of the industry [10].

The rapid expansion of the fintech sector, valued at USD 550 billion, significantly contributes to the progress of the renewable energy industry, especially in areas with high emissions [11]. Financial technology creative financing methods, including crowdfunding and peer-to-peer lending, make capital more accessible, allowing investors of all sizes to support renewable energy initiatives. In this pursuit, blockchain technology in fintech enables efficient and transparent energy trading, promoting peer-to-peer transactions that encourage renewable projects [12,13]. Moreover, the statement underscores the significance of natural resources and advocates for sustainable living by utilizing digitalization to minimize carbon emissions. This is achieved by decreasing the need for physical bank branches and travel through online financial transfers, positively impacting the environment [14,15]. For example, NRGcoin is a financial technology that connects cryptocurrencies to renewable energy. It utilizes blockchain technology to compensate users with one NRGcoin for each kilowatt-hour of renewable energy they contribute to the grid. Users can exchange or use these currencies for their renewable energy usage, where one NRGcoin is equivalent to 1 kW-hour, regardless of market electricity rates. The decentralized system encourages renewable energy, provides a reliable incentive against policy changes, and enables cost-effective, instantaneous energy transactions.

The convergence of financial technology (fintech) with eco-friendly technology in renewable energy is an emerging topic focused on transforming energy production, delivery, and consumption through innovation and investment. Fin tech's purpose in this scenario is to offer the financial framework and resources needed to support, exchange, and oversee renewable energy projects effectively. This synergy enhances access to money for green energy projects, provides creative investment opportunities in renewable resources, and promotes the adoption of renewable energy technologies by improving their financial feasibility and accessibility. Therefore, Fin tech uses advanced technologies such as machine learning and artificial intelligence, including digital assistants and mobile applications [16]. Fintech develops technological advancements using effective, convenient, and accessible financial services [17]. We assess the effects of financial and eco-friendly technology on RE use, considering GDP, population, and the Foreign Direct Investment (FDI) in the 38 developing economies from 2006 to 2021, making several contributions. This study addresses a significant gap in the worldwide academic discussion by highlighting the absence of research that concentrates on the particular effects seen in emerging nations. The proposal suggests shifting focus from analyzing wealthy nations and large energy producers, as previous investigations have already thoroughly identified the primary sources of emissions in these areas [18,19]. This selection provides many advantages for examining the impact of financial technology in several geographical and economic settings. The research explores the significant influence of fintech over time and its changing impact on environmental sustainability. The research is notable for identifying distinct obstacles and opportunities encountered by emerging markets, providing valuable insights into the finance, technology, and renewable energy sectors within the academic realm. It emphasizes the significance of creating creative financial technology solutions customized to the particular requirements of these markets. These innovations are crucial in improving financial inclusion, advocating for environmentally friendly technologies, and boosting the use of renewable energy sources. Secondly, our research greatly enhances policy discussions focused on attaining the Sustainable Development Goals (SDGs). Our study emphasizes the importance of green investments in building solid infrastructures, which can help advance the goals of Sustainable Development Goal 9.

Furthermore, our emphasis on investing in clean energy highlights their crucial contribution to accomplishing the objectives of Sustainable Development Goal 7 by reducing the effects of climate change. This method focuses on Sustainable Development Goal 13 by directly tackling climate change issues and offers a comprehensive plan to manage environmental challenges through renewable energy consumption, saving and investment. Third, our research utilizes a unique econometric method that involves a non-linear model to account for both asymmetric dynamics and unobserved differences across individuals. Our methodology goes beyond standard models by using a dynamic panel data model that includes an endogenous threshold variable and regressors, following the approach presented by Ref. [20]. This model recognizes the potential endogeneity in both the threshold variable and the regressors. This study consists of five sections. The first section presents an introduction, and the second is a literature review. The third section also provides information about data and methods, and the fourth reports the findings. Finally, the fifth section includes a conclusion.

2. Review literature

Green innovation includes many efforts and technological progress focused on improving environmental sustainability. This involves advancing energy storage options, like cutting-edge battery technology and pumped hydro storage systems, as discussed in the studies by Refs. [21,22]. These advancements are essential for enhancing the effectiveness and dependability of renewable energy sources, showcasing the various strategies in green technology to tackle energy storage obstacles. Another essential aspect of green innovation is incorporating smart grid technology, which allows for more efficient energy distribution [23]. They suggested that integrating green technologies, including renewable energy sources and energy-saving innovations, reduces energy intensity significantly. This body of work underscores the critical role of sustainable technological solutions in achieving energy efficiency and environmental preservation.

Eco-friendly tech involves developing and putting into reality new ecologically sustainable ideas, technologies, and practices that can be applied across different industries, such as renewable energy [24–26]. According to Ref. [27], environmentally sustainable technologies are an important intermediary, demonstrating that green innovations significantly impact RE consumption in select Latin American countries. From 1994 to 2018, an assessment of the effects of environmental technology and economic growth on REC was conducted across 29 nations within the Organisation for Economic Co-operation and Development (OECD), using the panel cointegration technique [28]. argue that economic growth environmental, and technological advancements positively impact renewable energy [29].conduct further research into the effects of economic growth and environmental technology on REC within the G-7 countries over the same period, revealing that environmental levies, technological innovations, and economic proliferation all positively correlate with RE. This discussion expands to examine the relationship between economic growth, financial development, and green innovation in the top ten OECD countries about REC from 1994 to 2019, using both the panel Autoregressive Distributed Lag (ARDL) and Non-linear Autoregressive Distributed Lag (NARDL) methodologies [30]. Finally, the findings show that, over time, Gross Domestic Product (GDP) has little influence on RE, whereas financial development and green innovation have a significant impact. Pata et al. [31] used the Autoregressive Distributed Lag (ARDL) model to examine the effects of economic growth, biomass energy utilization, and financial development on CO2 emissions in the United States from 1965 to 2018. Their analysis confirmed the validity of the Environmental Kuznets Curve (EKC), which suggests that an increase in wealth can incrementally improve the load capacity factor (LCF), implying that the United States' economic growth has facilitated technological advancements and increased ecological awareness, both of which have the potential to reduce environmental degradation. In a parallel study [32], investigated the effects of renewable energy consumption (REC), non-renewable energy use, investments, energy innovation, and the acquisition of green patents on environmental sustainability in the United States from 1980 to 2015. Their findings supported the EKC hypothesis and the loading capacity curve theory, but there was one significant difference: non-renewable energy consumption was linked to an increased Ecological Footprint, indicating a decrease in the load capacity factor associated with non-renewable energy use. In contrast, renewable energy consumption was found to have a positive effect, increasing the load capacity factor and thus contributing to environmental sustainability.

There is a consensus for the reduction of the effect of fintech on renewable energy and enhancing sustainable economic development (ED) by increasing access to climate-friendly financing and improving environmental quality [33–36]. [37] Considering new developments and growing economic complexities, explore how the fintech industry affects China's transition to renewable energy. An examination of industry data from 2005 to 2010 argues that the fintech industry significantly impacts China's transition to sustainable energy sources, especially on a small scale. Fintech tools have helped companies shift from coal-based energy to more eco-friendly options. The study emphasizes that innovations and economic complexity within firms, as demonstrated by their export activities, play a significant role in creating a positive connection between fintech adoption and energy transition in China. Alexandre Croutzet [18] examined how financial technology affects RE, focusing on NRGcoin and blockchain-based renewable energy certificates to demonstrate how FinTech enables financial transactions in this field. They used a balanced panel of 21 OECD nations from 2005 to 2018, applying the fixed-effects estimator with Driscoll-Kraay standard errors for empirical analysis. The findings demonstrated a strong correlation between the advancement of FinTech and the utilization of renewable energy, indicating FinTech's capability to improve the adoption of renewable energy sources [38]. studied the impact of the fintech sector on the shift to pro-environmental power in a panel of 91 emerging territories from 2000 to 2020. The findings indicate that fintech has a favorable impact on the energy transition process in the areas studied. The authors recommend that policy-makers leverage the beneficial effects of the fintech industry to expedite the energy transition, particularly in middle-income regions.

Regardless of the economic growth and RE, the relationship is still a complex and important topic. There is significant academic interest in this field, with a general agreement that shifting to renewable energy sources is crucial for advancing economic development despite multiple complexities and subtleties [39–41]. Research has shown that investing a portion of GDP in renewable energy initiatives through fiscal policies and public expenditure can lead to long-term economic benefits [42,43]. The benefits mentioned are improved energy security, decreased reliance on imported fuels, and alleviating the negative impacts of fossil fuel price fluctuations on national economies [44,45]. The renewable energy sector is recognized for its ability to generate employment opportunities at a higher rate than traditional fossil fuel-based energy sectors on a per-unit-of-energy-produced basis. The connection between green energy and economic growth faces obstacles, including the substantial upfront investment needed to develop renewable energy infrastructure and the sporadic nature of some renewable energy sources, necessitating substantial investments in energy storage technologies and grid modernization [46,47].

Furthermore, the available body of literature suggests that several factors specific to each country influence the relationship between green energy and economic growth. For instance, studies conducted by Ref. [48] in China and [49], in the USA have highlighted the importance of factors such as economic development and regional considerations, including the Middle East and North Africa (MENA) countries [50], Sub-Saharan Africa (SSA) [51], and the OECD countries [52,53]. The existing energy infrastructure and policy framework also play a significant role in shaping this nexus, as emphasized by Ref. [54]. Furthermore [55], examined the determinants of renewable energy consumption in emerging BRICS economies. The study finds that financial development and technological innovations have positive and significant roles in enhancing renewable energy consumption in these countries.

2.1. Research gap

Based on the findings outlined above, we note the following gaps in the literature: 1) It is evident that the literature evidence that eco-friendly and financial technology positively and significantly influence renewable energy adoption in developed countries, G7, OCED, and BRICS. However, emerging economies may encounter several barriers to introducing and effectively implementing eco-friendly and financial technologies. These could include infrastructural constraints, institutional weaknesses, limited access to financial resources, or technological gaps. Additionally, the impact of these technologies on renewable energy adoption may be influenced by specific features of emerging economies, such as economic structure, energy policies, or sociocultural factors. Conceqacly, this study focused on the emerging countries. This novel focus allows insights into potential barriers, opportunities and policy recommendations tailored to the unique needs of these nations in sustainable energy transitions. 2) Existing studies have revealed few studies assessing threshold GDP per capita that can affect RE adoption, considering eco-friendly tech and fintech in developed countries. However, we could not find any study in the respective domain that assesses emerging countries, identifying a critical GDP threshold of 1831.772 US dollars.

3. Data and methodology

3.1. Data

3.1.1. Methodology

The EKC is a theory that suggests environmental degradation follows an inverted U-shaped curve as income levels rise [56]. Initially, as an economy grows, environmental degradation increases due to higher levels of industrial activity and resource consumption. However, once a certain income level is reached, environmental degradation decreases as societies prioritize environmental protection and invest in cleaner technologies [57,58]. In the context of the EKC, GDP is considered a threshold because it represents the income level at which a country transitions from increasing to decreasing environmental degradation. Below this threshold, the focus is often on economic growth at the expense of the environment. However, once the threshold is surpassed, societies can afford to prioritize environmental concerns and invest in sustainable practices. Thus, the FD-GMM stands out from classic threshold models, such as the Panel Threshold Regression (PTR), providing increased flexibility and adaptability. The shape of the curve can vary depending on various factors, such as the type of environmental indicator used, the stage of economic development, and the effectiveness of environmental policies. Unlike [59] model, which requires the threshold variable to be exogenous, FD-GMM allows for endogeneity in the threshold variable, which improves its ability to examine the interaction of this variable with other factors. This characteristic is critical in economic studies since such interactions are frequently complex. Furthermore, as [20] points out, DPTR abandons the homogeneity assumption for all shared variables, allowing it to represent the threshold variable's asymmetric impacts. This trait is remarkably consistent with economic theory, which frequently predicts various outcomes depending on whether variables fall above or below specified thresholds. While Hansen's model offers a static approach with a fixed-effects estimator, it is hampered by the need for variable exogeneity to provide consistency. FD-GMM overcomes this restriction by accounting for probable endogeneity in the threshold variable. This breakthrough is aided by the use of the FD-GMM, which is further backed by a linear test to establish the presence of a threshold effect and the model's non-linearity, as proved by Ref. [20] In conclusion, FD-GMM is a considerable methodological improvement over prior models, such as Hansen's PTR, providing greater flexibility, adaptability, and conformity with economic theory. Therefore, the FD-GMM model equation is given below (eq. (1)):

$$y_{it} = u_i + \beta_1' x_{it} 1(q_{it} \le \gamma) + \beta_2' x_{it} 1(q_{it} > \gamma) + \varepsilon_{it} \tag{1}$$

The data observed come from a panel that is evenly distributed as $\{y_{it}, q_{it}, x_{it}, 1 \le i \le N, 1 \le t \le T\}$. the subscript "i" represents individual, and the subscript "t" represents time. The dependent variable y_{it} i is a scalar, the threshold variable q_{it} is also a scalar, and the regressor x_{it} is a vector with k components. The slope parameters associated with different regimes are represented as β_1' and β_2'. Also $1(.)$ Serves as the index for the transition function.

Building upon the previous framework [20] introduces a further refinement to the FD-GMM model by incorporating the lagged dependent variable. y_{it}. This modification yields the following equation (eq. (2)):

$$y_{it} = (1, x_{it}')\Phi_1 1(q_{it} \le \gamma) + (1, x_{it}')\Phi_2 1(q_{it} > \gamma) + \mu_i + \varepsilon_{it} \quad i = 1, \ldots.., N;\ t = 1, \ldots\ldots., T \tag{2}$$

So that $x_{it}' = \left(y_{i,t-1}, x_{it}'\right)$ represents the independent variables and the lagged dependent variable, q_{it} represents the threshold variable, where μ_i is an unobserved individual fixed, and ε_{it} is a zero mean idiosyncratic random disturbance.

If ordinary least squares (OLS) are used to estimate this model, biased regression coefficients will result in two cases [60].

- The coefficient of the unobserved state fixed effects, μ_i is statistically significant.
- There is a correlation between the independent variables and μ_i.

To alleviate these issues, we adopt the methodology of [61] by applying a first-difference transformation, yielding the following equation (3) [20]:

$$\Delta y_{it} = \beta' \Delta x_{it} + \delta' X_{it}' 1_{it}(\gamma) + \Delta \varepsilon_{it} \tag{3}$$

Where Δ represents first differences and $\underset{k1\times 1}{\beta} = \left(\Phi_{12}, \ldots, \Phi_{1,k1+1}\right)'$, as $\underset{(k1+1)\times 1}{\delta} = \Phi_2 - \Phi_1$, and we also have equation (4):

$$\underset{2\times(1+k1)}{X} = \begin{pmatrix} (1, x_{it}') \\ (1, x_{i,t-1}') \end{pmatrix} \text{ and } \underset{2\times 1}{1_{it}(\gamma)} = \begin{pmatrix} I(q_{it} \le \gamma) \\ -I(q_{it} > \gamma) \end{pmatrix} \tag{4}$$

3.2. CD test

Before employing the FD-GMM, this study employs econometric methods, including CSD Test (Cross-Sectional Dependence) and

Slope heterogeneity tests. The CD is widely used for detecting cross-sectional dependence in panel data. The M. Hashem Pesaran CD test [62–64], constitutes an evaluation method for CS in unbalanced panel data. This test is particularly useful for assessing the presence of CS, with [63] offering a straightforward method to ascertain its existence in panel datasets.

In panel data analysis, it is imperative to employ robust tests that account for cross-sectional dependence (CD) and slope heterogeneity (SH), especially in unbalanced panels spanning prolonged periods. The [64]test offers a more robust approach by compensating for CD in unbalanced panels. This study presents the CD test and subsequently employs the CS-ARDL technique, considering the significant differences across cities within countries. The CD test statistic proposed by Ref. [65] is summarized in equation (5):

$$\mathrm{CD} = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}\right) \rightarrow N(0,1) \tag{5}$$

3.3. Slope heterogeneity test

Slope heterogeneity (SH) must be addressed, as panel units may exhibit varying slopes. The [66,67] tests can accommodate this issue. The [66] test is a fixed-effects model-based procedure that examines the relationship between individual slope estimates and their respective means to detect SH across subjects. Alternatively, the [67] test analyzes the estimated slope coefficients and their standard errors to identify SH, applicable to both fixed and random effects models. The accuracy and reliability of these tests are crucial for panel data analysis outcomes. This study dynamically investigates the SH issue as per equation (6):

$$\widetilde{\Delta}_{ASH} = \Bigg(\left(\frac{2k(T-k-1}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - 2k\right) \tag{6}$$

$\Delta_{\tilde{A}SH}$ and $\Delta_{S\tilde{}H}$ divulge the adjusted delta tide and delta tide, respectively.

3.3.1. Cointegration test

Cointegration tests are vital for determining long-run relationships among non-stationary variables in panel data analysis. The Westerlund [68] test is based on the relationship between the long-run and short-run variance of non-stationary series.

3.3.2. Quantile regression

This study will use the QR to robust the DF-GMM results [69]. proposed the panel QR in 2015 to analyze the independent influence of dependent variables in various market scenarios. Unlike standard regression models, which can only estimate the average effect and do not account for changing market conditions, QR can provide more robust findings by addressing difficulties including heteroskedasticity, skewness, multicollinearity, and structural breaks [70–73].

3.3.3. Data

This study examines the effect of eco-friendly technologies, financial technology, GDP, population and FDI on renewable energy from 2006 to 2021 in 38 developing countries. The choice of this specific period is motivated by the increasing global focus on sustainable energy sources and the proliferation of eco-friendly and financial technologies during this timeframe. Additionally, this period captures the diverse trajectories of renewable energy adoption and the varying levels of technological advancement across developing nations. Regarding the sample of 38 developing countries, this selection was made to provide a comprehensive representation of economies at different stages of economic development and with varying degrees of renewable energy penetration. Developing countries were chosen as they often face unique challenges and opportunities in transitioning towards sustainable energy sources, making them a relevant and insightful context for this study. The specific countries were carefully selected to ensure a diverse geographical spread and account for data availability, energy policies, and economic conditions. Table 1 and Fig. 1 represent the data description and trend, respectively. Equation (7) shows the model:

Table 1

Data description.

Data	Measures	Source
Green energy or renewable energy	% of total energy	Footprint Network (2024) www.footprintnetwork.org
Economic growth	US $ GDP per capita	WDI (2024)
Eco-friendly Tech	% patent on environment technologies	OCED (2024) https://data.oecd.org/envpolicy/patents-on-environment-technologies.htm
Population	Urban population % of the total population	WDI (2024)
Financial technology	Index	[74–76]
FDI	Net flow as % of GDP	WDI (2024)

Source: authors' elaboration

$$RE_{it} = \psi_0 + \psi_1 GDP_{it} + +\psi_2 EF_{it} + \psi_3 FITCH_{it} + \psi_4 FDI_{it} + \psi_5 POP_{it} + \vartheta_{it} \tag{7}$$

Where RE is greener energy, GDP is economic growth, FINT is Fintech credit, EF represents Eco-friendly technology., and POP is the population. Moreover, ψ_1 to ψ_5 are the coefficients. Finally, ϑ_{it} represents the error term. Based on the literature, the sign of the fintech and EF coefficient is expected to be positive, $\psi_{2,3} = \text{FINT} > 0,$ and the coefficient of economic growth variable to be positive at the threshold level and negative before, $\psi_1 = \text{GDP} > 0$. Moreover, there is an anticipated positive link between FDI and RE. The sign of the population coefficient is expected to be negative, $\psi_5 = \text{POP} < 0$. Table 1 and Fig. 1 represent the data description and trend, respectively.

4. Empirical findings

4.1. Descriptive statistics

By analyzing the statistical summary, we can gain valuable insights into the distributions and variabilities of crucial variables like greener energy, GDP, FDI, eco-friendly technology, financial technology, and population, focusing on the mean, median, minimum, maximum Skewness, Kurtosis, Jarque-Bera values (Table 2). The high mean values for greener energy and population are evidenced by 32.9 % and 35.7 %, respectively, a wide range of data points, reflecting diversity from countries excelling in sustainable energy to those

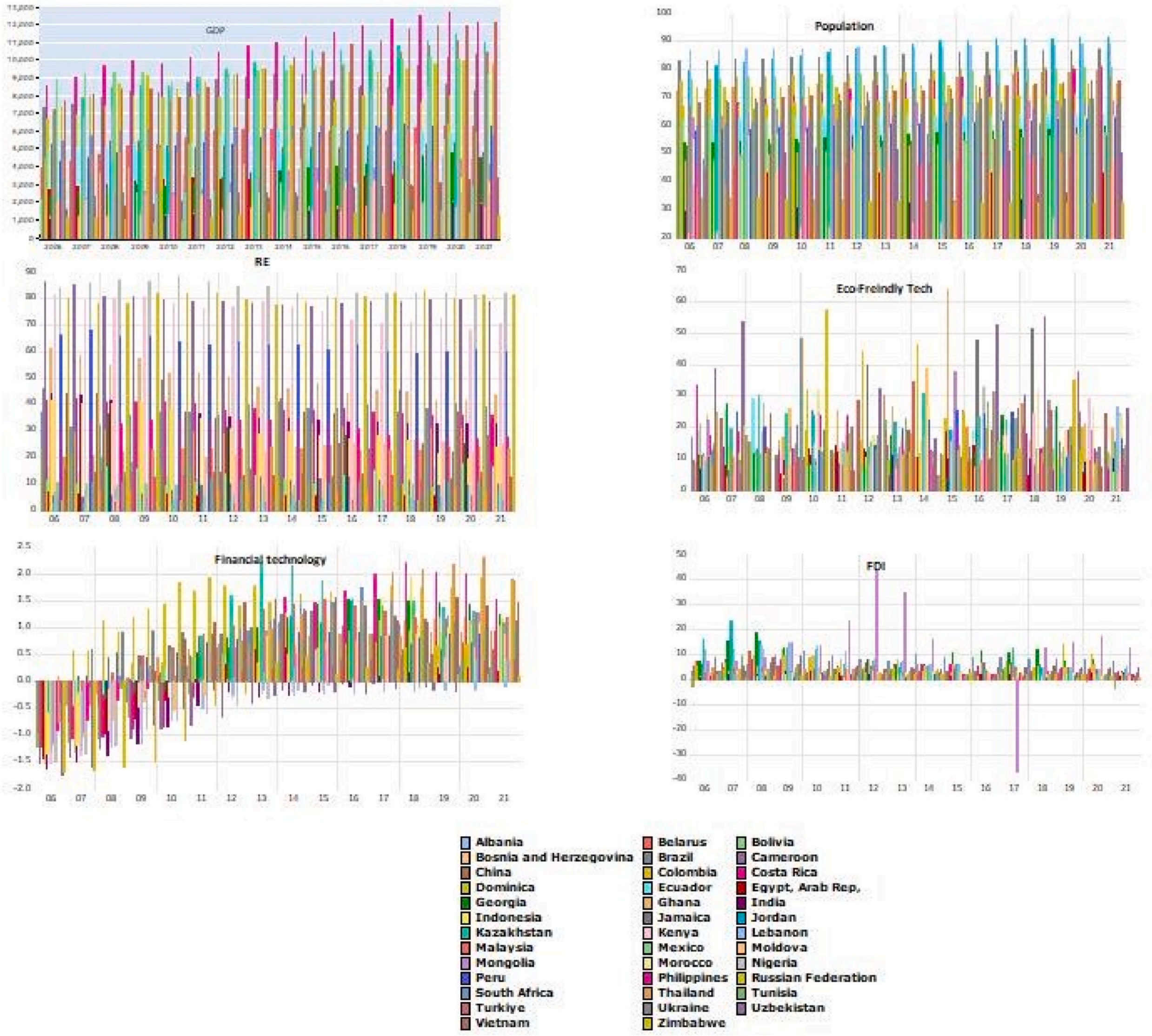

Fig. 1. Data trend of the variables.

with large populations. The standard deviation reflects the diversity in greener energy, GDP, and population metrics, indicating substantial variations and emphasizing the differences between countries. Moreover, the results exhibit positive skewness in GDP and FDI, where most data are concentrated towards the lower end of the scale, with fewer very high values extending the distribution's tail to the right. On the contrary, the near-zero skewness of eco-friendly technology and population suggests more symmetric distributions. This symmetry in eco-friendly technology implies that progress and applications are distributed evenly across the panel data without any dominant extreme outliers. Variables with high kurtosis, such as FDI, indicate the presence of heavy tails and a prominent peak, suggesting a greater chance of encountering extreme values. The distribution of FDI, characterized by its high kurtosis, indicates a broad range of investment levels and highlights the substantial influence of outliers or extreme investment occurrences that deviate significantly from the average. The Jarque-Bera test results highlight significant deviations from normality for most variables, except for eco-friendly technology. The deviation, supported by low p-values, affirms that the distributions of these variables are significantly non-normal, with notable skewness and kurtosis influencing their distinct shapes.

The correlation coefficients presented in Table (3) indicate statistically significant associations, at a significance level of 1 %, between the explanatory variables eco-friendly, fin tech, FDI, GDP and population, and the dependent variable RE.

The correlation analysis in the dataset shows moderate to slight negative relationships between greener energy and other key variables. Greener energy shows a moderate negative correlation with GDP (−0.444) and population (−0.443), suggesting that as economic output and population size increase, there is a tendency for less focus on greener energy solutions. A moderate negative correlation of −0.469 between eco-friendly technology and greener energy metrics suggests that progress in eco-friendly technology does not always align with advancements in greener energy, possibly due to varying priorities in the sustainability field. The negative correlation of −0.308 with financial technology suggests that regions or sectors at the forefront of fintech innovations may not necessarily be the same ones performing well in green energy initiatives. The negative correlation coefficient of −0.143 between FDI and greener energy metrics indicates a minimal but adverse relationship, highlighting the intricate interplay between investment patterns and the adoption of sustainable energy.

4.2. CSD test results

The scaled LM test developed by Refs. [63,65,77] support the hypothesis of CS-D in the remainder, suggesting that CS-D exists among the grouped countries, indicating that the variables in middle-income countries are affected by shared unobserved factors or simultaneous shocks. Including causal structures in data analysis is crucial for producing dependable and precise estimates for data modelling and analytical processes (Table 4).

Table 5 displays the results of two SHT tests: the test created by Pesaran and Yamagata in 2008. The tests produce statistically significant results beyond the 1 % level, offering strong evidence to reject the null hypothesis of slope uniformity. It is crucial to acknowledge the presence of SHT, which suggests that the relationship between variables shows significant variation among different groups or categories. Recognizing this diversity is essential for researchers, as it requires creating statistical models and methodologies that effectively represent the varied relationships and interactions between variables in different groups. This method improves the accuracy and dependability of the analysis, making it easier to comprehend the complex patterns and implications present in the data.

4.3. Multicollinearity finding

We conducted a multicollinearity examination to ascertain the absence of multicollinearity and mitigate the potential for omitted variable bias. The test results presented in Table 6 indicate no significant concerns regarding multicollinearity, as evidenced by the lack of substantial coefficients for individual variables.

4.4. Cointegration test

Having established the cross-sectional dependence and unit root properties, we investigate the existence of a long-run equilibrium relationship among the relevant variables. Table 7 presents the cointegration relationship using the Westerlund [68] test, which is appropriately suited to account for cross-sectional dependence in the panel data.

Table (2)
Statistical characteristics of variables.

	Greener Energy	GDP	FDI	Eco-friendly technology	Financial technology	Population
Mean	32,95581	4166,593	4,154295	−0,324	0,258446	53,75238
Median	29,52000	3773,422	2,868337	−0,312	0,328972	54,37900
Maximum	90,92000	13341,60	43,91211	1,254254	2,302815	91,62600
Minimum	0,060000	617,9405	−37,173	−1810	−1740	17,74200
Std. Dev.	24,52016	2724,035	4,603329	0,511801	0,840696	18,51876
Skewness	0,623233	0,855356	1,858611	−0,026	−0,224	−0,052
Kurtosis	2,438825	3,073833	20,54401	3,088242	2,472133	2,143951
Jarque-Bera	83,38598	130,8400	14351,85	0,466745	21,39149	33,19198
Probability	0,000	0,000	0,000	0.791859	0.000023	0,000
Observations	607	607	607	607	607	607

Table (3)
Correlation matrix.

	Greener Energy	GDP	FDI	Eco-friendly technology	financial technology	Population	INDU
Greener Energy	1	−0,444	−0,143	−0,469	−0,308	−0,443	−0,109
GDP	−0,444	1	0,095	0,485	0,373	0,600	0,149
FDI	−0,143	0,095	1	0,082	−0,017	0,026	−0,052
Eco-friendly technology	−0,469	0,485	0,082	1	0,309	0,243	0,077
financial technology	−0,308	0,373	−0,017	0,309	1	0,377	0,190
Population	−0,443	0,600	0,026	0,243	0,377	1	0,210

Table 4
Results of the CSD.

Test	Test statistics	p-value
Breusch-Pagan LM	6759.758	0.0000
Pesaran scaled LM	76.91059	0.0000
Pesaran CD	6.562262	0.0000

Note: 0.000 indicates statistical significance at 1 % level.

Table 5
Slope homogeneity.

	Statistics	p-value
Δ	−4.245	0.000
Δ adj	−7.324	0.000

4.5. FD-GMM model for short panels estimation

The FD-GMM results in Table 8 strongly support the hypothesis being studied. The model shows a clear change in the connection between GDP and the dependent variable, greener energy. A negative coefficient marks this change for GDP before a certain threshold level and a positive coefficient after that level. The threshold value identified is 1831.772, showing statistical significance at a 1 % confidence level. Below a certain GDP threshold, known as the low regime, GDP has a negative impact on the adoption of greener energy with high confidence. Above a particular economic benchmark, GDP positively and significantly impacts transitioning to greener energy, confirming the U-shaped trajectory predicted for the regression function. This pattern highlights the non-linear relationship between economic growth and environmental sustainability, with around 76 % of the observed data falling into the upper regime. The study aligns with previous findings [39–41], which collectively noted a significant change in the impact of GDP on environmental sustainability across various economic strata. Non-linearities emphasize the importance of considering economic thresholds when creating and assessing environmental policies and sustainability measures. The FD-GMM results show that financial technology plays a significant and positive role in promoting environmental sustainability, with a coefficient of 1.467 [37]. concluded that fintech positively impacts efficiency, green finance, transparency, and reducing carbon footprints through blockchain technology. The analysis shows that a 1 % rise in eco-friendly technology is associated with a 3.17 % increase in greener energy, supporting the conclusions of [21,22]. The model indicates that FDI and urbanization at advanced economic stages have negative environmental impacts, as shown by coefficients like −0.251 for population and −0.100 for FDI.

4.6. Robustness test

The results of the quantile regression analysis show that higher GDP levels are initially linked to lower, greener energy usage, as indicated by the negative coefficients for GDP across all quantiles, as presented in Table 9. The positive coefficients for GDP squared suggest a U-shaped relationship, indicating that once a certain GDP level is reached, further increases in GDP result in greater utilization of greener energy, potentially aligning with the environmental Kuznets curve hypothesis. Initially, economic growth has a

Table 6
Multicollinearity test results.

Variable	VIF	1/VIF
GDP	2.10	0.475964
Population	1.77	0.563804
Eco-friendly technology	1.34	0.745072
Financial technology	1.24	0.803321
FDI	1.05	0.955131
Mean VIF		1.50

Table 7
Westerlund test.

	Value statistics	p-value
Westerlund	−1.815**	0.036**

Note: 0.05 indicates statistical significance at 5 % level.

Table 8
FD-GMM model estimation results.

	Coefficient	Probability
Financial technology	1.467	0.000
Eco-friendly technology	3.718	0.000
FDI	−0.100	0.000
Population	−0.251	0.000
GDP	−0.034	0.000
Threshold	1831.772	0.000
Upper regime (%)	76	
Linearity (p-value)	0.00	

negative impact on the adoption of greener energy. However, this effect becomes positive as economies expand and invest more resources in environmental protection. The FDI generally have a negative effect across different levels of quantiles, except at the highest level where it loses significance, indicating that the FDI may not always promote the transition to greener energy, possibly because of a focus on immediate economic benefits rather than sustainable strategies. The correlation with eco-friendly technology is remarkable; it is positive at lower levels of greener energy usage, suggesting an initial increase in the adoption of green energy, but becomes notably negative at higher levels of green energy adoption. This may suggest decreasing benefits or possible adverse impacts of environmentally friendly technology as it becomes more widely adopted, possibly due to technological, economic, or infrastructural constraints. The varied effects of financial technology on greener energy usage, with negative coefficients at lower and higher quantiles but insignificant impacts around the median, indicate a nuanced relationship that could either support or impede adoption in various scenarios. The consistently negative and significant coefficients for population across all quantiles emphasize the strain that a growing population puts on greener energy resources, pointing to a universal challenge in expanding greener energy adoption as population levels rise. The analysis using QR validates the results of FD-GMM.

5. Conclusions and policy implications

This study examined the influence of eco-friendly and FinTech on RE in 38 emerging economies from 2006 to 2021. The quantile regression study shows a U-shaped correlation between GDP and green energy usage, suggesting that increased GDP first reduces but later boosts green energy consumption, which is in line with the environmental Kuznets curve theory. The impact of economic expansion on green energy transitions from negative to positive as economies expand. FDI typically hurts the transition to green energy, as it often prioritizes short-term economic benefits over sustainability. Eco-friendly technology initially has a favorable impact on adopting green energy, but this effect turns negative at increasing levels, indicating difficulties in achieving universal adoption. The impact of financial technology varies, with negative and inconsequential effects observed at different quantiles, while population increase continuously negatively influences green energy resources. The results, backed by FD-GMM, demonstrate the intricate elements that impact the transition to more environmentally friendly energy sources.

Our analysis reveals numerous policy implications for players in the renewable energy sector and policymakers in the energy field. The statement supports the idea of governments acknowledging the inherent capacity of fintech to accelerate investments in environmental sustainability. Legal frameworks should be established to support and encourage fintech solutions focused on renewable energy projects and sustainability endeavors. Integrating fintech apps with current environmental standards could improve their effectiveness. Governments must establish robust intellectual property rights (IPR) for green technologies to provide effective legal safeguards and encourage innovation. Implementing incentive programs such as tax incentives, grants, and subsidies for research in green technology is essential for reducing financial obstacles and fostering an innovative environment. Encouraging the sharing of green technology through methods such as open-source platforms and international technology exchange agreements can significantly speed up worldwide sustainability endeavors. Incorporating green patents into public procurement rules promotes market expansion for sustainable innovations and demonstrates a robust governmental dedication to environmental stewardship. Facilitating partnerships across the corporate sector, academia, and government can enhance the advancement and utilization of green technologies. Using more renewable energy, nations can reduce their reliance on fossil fuels like petroleum and natural gas. This can help minimize the negative effects of non-renewable energy consumption on productivity and human health. Utilizing cleaner, renewable energy sources like solar, wind, and hydropower offers a chance to reduce these negative impacts. Promoting education and knowledge about fintech's impact on the energy transition is essential to increase public and business involvement, ultimately securing broad support and acceptance of these projects. Our research recognizes limitations, such as a restricted dataset and lack of data on numerous crucial variables. The study did not investigate the immediate and long-lasting effects of the predictors on the outcome variable. Future

Table 9
Quantile regression results.

	Quantile	Coefficient	Std. Error	t-Statistic	Prob.
GDP	0.100	−0.005962	0.001212	−4.919071	0.0000
	0.200	−0.005829	0.000944	−6.175609	0.0000
	0.300	−0.006452	0.000789	−8.180337	0.0000
	0.400	−0.006770	0.000819	−8.269758	0.0000
	0.500	−0.006600	0.001020	−6.470901	0.0000
	0.600	−0.005739	0.001412	−4.065354	0.0001
	0.700	−0.004452	0.001668	−2.669078	0.0077
	0.800	−0.003818	0.001292	−2.956453	0.0032
	0.900	−0.006068	0.001256	−4.830090	0.0000
GDP_2	0.100	4.03E-07	8.72E-08	4.617493	0.0000
	0.200	4.02E-07	7.14E-08	5.626941	0.0000
	0.300	4.30E-07	6.27E-08	6.848440	0.0000
	0.400	4.50E-07	6.72E-08	6.698412	0.0000
	0.500	4.32E-07	8.87E-08	4.869966	0.0000
	0.600	3.75E-07	1.24E-07	3.027795	0.0025
	0.700	3.96E-07	1.01E-07	3.920144	0.0001
	0.800	3.68E-07	9.13E-08	4.029781	0.0001
	0.900	4.95E-07	1.05E-07	4.734491	0.0000
FDI	0.100	−0.234223	0.144884	−1.616631	0.1063
	0.200	−0.383125	0.112022	−3.420096	0.0006
	0.300	−0.387323	0.099031	−3.911118	0.0001
	0.400	−0.422237	0.107976	−3.910487	0.0001
	0.500	−0.502884	0.125358	−4.011579	0.0001
	0.600	−0.365382	0.178768	−2.043893	0.0412
	0.700	−0.800473	0.181436	−4.411882	0.0000
	0.800	−0.996807	0.210297	−4.740005	0.0000
	0.900	−0.507048	0.506304	−1.001470	0.3168
Ecofireldy technology	0.100	4.593591	1.564446	2.936241	0.0034
	0.200	1.257641	1.228820	1.023454	0.3063
	0.300	−1.544846	1.045327	−1.477859	0.1397
	0.400	−2.905510	1.174598	−2.473621	0.0135
	0.500	−6.255030	1.856611	−3.369057	0.0008
	0.600	−12.63660	3.004395	−4.206037	0.0000
	0.700	−23.10226	2.769224	−8.342504	0.0000
	0.800	−26.58170	1.828616	−14.53652	0.0000
	0.900	−27.13991	2.485504	−10.91928	0.0000
Financial technoogy	0.100	−1.567574	1.139682	−1.375449	0.1693
	0.200	−2.851014	0.761138	−3.745725	0.0002
	0.300	−2.468145	0.838763	−2.942601	0.0033
	0.400	−2.145081	0.909567	−2.358355	0.0185
	0.500	−0.940147	1.018663	−0.922922	0.3563
	0.600	−0.064649	0.941307	−0.068680	0.9453
	0.700	−0.699700	1.079758	−0.648015	0.5171
	0.800	−3.264905	0.873668	−3.737009	0.0002
	0.900	−2.396956	0.982106	−2.440629	0.0148
Population	0.100	−0.249219	0.049889	−4.995421	0.0000
	0.200	−0.369856	0.030545	−12.10861	0.0000
	0.300	−0.390368	0.030794	−12.67676	0.0000
	0.400	−0.405322	0.037289	−10.86972	0.0000
	0.500	−0.408381	0.047041	−8.681304	0.0000
	0.600	−0.415918	0.054127	−7.684108	0.0000
	0.700	−0.377376	0.053464	−7.058519	0.0000
	0.800	−0.281433	0.054820	−5.133811	0.0000
	0.900	−0.210925	0.076145	−2.770058	0.0057
C	0.100	48.22639	5.439500	8.865961	0.0000
	0.200	63.74185	3.461106	18.41661	0.0000
	0.300	69.15426	3.373381	20.49999	0.0000
	0.400	72.23823	3.575967	20.20103	0.0000
	0.500	75.06811	5.081080	14.77405	0.0000
	0.600	72.23472	6.733856	10.72710	0.0000
	0.700	71.89081	5.977512	12.02688	0.0000
	0.800	69.77992	4.217421	16.54564	0.0000
	0.900	73.33322	4.065158	18.03945	0.0000

research could overcome these shortcomings by using different approaches for mean-based estimation to analyze these effects thoroughly.

Data availability statement

Data are publicly available and the data sources were specified in Table 1. Moreover, the data are available from corresponding author on reasonable request.

CRediT authorship contribution statement

Hind Alofaysan: Writing – original draft, Investigation. **Magdalena Radulescu:** Writing – original draft, Investigation, Data curation, Conceptualization. **Daniel Balsalobre-Lorente:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Kamel Si Mohammed:** Writing – original draft, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Magdalena Radulescu: Associate Editor of Heliyon journal Daniel Balsalobre-Lorente: Associate Editor of Heliyon journal If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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