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Integrating digital financial inclusion for a greener economy in developing countries: empirical evidence on renewable energy and energy productivity from panel data analysis

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Abstract
While financial inclusion is widely promoted as a catalyst for sustainable development, a critical paradox remains unexplored: conventional financial infrastructure can inadvertently impede the transition to renewable energy, whereas digital innovations may unlock its potential. This study investigates this duality by analyzing a detailed panel dataset from 85 developing nations between 2011 and 2021. It applies advanced econometric methods, including Panel-Corrected Standard Errors (PCSE) and Feasible Generalized Least Squares (FGLS), to examine the relationships among fintech, financial access, the adoption of renewable energy, and energy efficiency. Our findings reveal that traditional measures of financial inclusion—like the presence of ATMs and bank branches—can unexpectedly hinder the growth of renewable energy sources. In contrast, fintech advancements, especially in digital payment solutions, significantly enhance the success of financial inclusion efforts aimed at fostering green investments. Importantly, the collaborative relationship between fintech and financial access positively impacts the development of renewable energy, highlighting the need for integrated approaches to address environmental challenges. This research addresses a significant gap in the current literature by investigating the combined influence of fintech and financial inclusion on sustainable energy initiatives. It provides policy suggestions for developing nations, stressing that harnessing fintech can enhance financial accessibility and support a transition to a more sustainable and resilient economy in line with global green efforts.

Keywords Fintech · Financial inclusion · Green economy · Renewable energy · Energy productivity

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1 Introduction

The urgent need to fulfill sustainable development goals (SDGs) has highlighted the critical connection between finance and environmental responsibility. As countries globally confront the escalating climate crisis, a key strategy has emerged: utilizing financial technology, or fintech, to enhance access to clean energy and boost energy efficiency. In developing nations, where financial limitations can impede investments in renewable energy and energy-efficient technologies, fintech presents an innovative pathway to improve financial inclusion for sustainable economic advancement. Azhgaliyeva and Liddle (2020) and Raberto et al. (2019) note that the body of literature examining the role of fintech innovations in facilitating essential financial flows toward green investments is expanding, encompassing mobile payment solutions, blockchain technology, and crowdfunding platforms.

Fintech is reshaping traditional financial systems by making financial services more accessible to unbanked and underserved populations (Salampasis and Mention 2018; Loo 2019; Ediagbonya and Tioluwani 2023; Kishor et al. 2024; Mittal et al. 2024; Sanyaolu et al. 2024). By leveraging information and communication technology (ICT), fintech enables individuals and small enterprises to tap into financial resources that were previously out of reach, thereby encouraging investments in energy-efficient solutions and renewable energy technologies (Ma and Fu 2020; Bayar et al. 2021; Udeagha and Muchapondwa 2023; Zhu et al. 2024; Hou et al. 2024). This is particularly crucial in developing regions, where limited access to capital often obstructs the transition to low-carbon energy systems (Sadorsky 2011; Farhani and Ozturk 2015; Relva et al. 2021). As financial development and inclusion advance, a significant positive impact on energy consumption patterns emerges, leading to considerable investments in cleaner energy alternatives (Dogan et al. 2021; Singh et al. 2023).

The capabilities of fintech extend beyond simple financing; it can enhance the efficiency of financial operations and provide vital data analytics that inform investment decisions in renewable energy initiatives (Zhu et al. 2020; Arshi et al. 2024). By promoting data-driven decision-making regarding energy consumption, fintech can improve energy productivity across various sectors (Teufel et al. 2019; Ahmad et al. 2024). Consequently, the development of decentralized energy trading systems, facilitated by blockchain technology, enables individuals and businesses to engage in peer-to-peer energy exchanges, thereby reducing dependence on fossil fuels (Croutzet and Dabbous 2021; Juszczyk and Shahzad 2022). However, the transformative potential of fintech must be considered alongside its environmental implications. Critics have raised significant concerns regarding the ecological impact of certain fintech practices, particularly cryptocurrency mining, which is often criticized for its high energy consumption and associated carbon emissions (De Vries 2018; Tao et al. 2022). Furthermore, the increase in electronic devices necessary for fintech operations contributes to the growing issue of e-waste (Wang 2024; Zhuk 2023). Therefore, while fintech holds promise as a catalyst for green economies, it is vital to address these sustainability challenges to ensure that the advancements in fintech do not inadvertently exacerbate the environmental issues it seeks to resolve (Tao et al. 2022). For instance, in Tanzania, the households using mobile money are 5.7% points more likely to adopt solar panels than those not using it (Barry et al. 2025). Similarly, green fintech investments in Southeast Asia surpassed $2 billion in 2020, primarily funding decentralized renewable energy projects (IEA, 2022).

Despite substantial efforts to expand financial inclusion in developing countries through traditional banking infrastructure, such as ATMs and bank branches, renewable energy adoption remains weak and even negatively correlated. This presents a puzzling contradiction: why does greater physical access to formal finance not translate into cleaner energy investments? We argue that conventional financial channels may inadvertently entrench carbon-intensive activities, whereas fintech can overcome these rigidities by enabling decentralized, low-cost green financing. This study investigates this duality, asking whether fintech can redeem what traditional financial inclusion fails to deliver. While previous studies have focused on the individual contributions of fintech advancements and financial inclusion initiatives to enhancing sustainable practices, the interplay between these two domains, especially concerning the adoption of renewable energy and energy efficiency, has not been thoroughly examined. This paper seeks to fill this void by investigating the reciprocal effects of fintech and financial inclusion on the green economy, utilizing data from 85 developing countries over the years 2011, 2014, 2017, and 2021. By employing rigorous econometric techniques, including the Panel-Corrected Standard Errors (PCSE) method and the Feasible Generalized Least Squares (FGLS) approach for validation, this research aims to clarify the intricacies of their relationship and its implications for sustainable energy practices. In doing so, we aspire to provide a more comprehensive understanding of how the synergy between fintech and financial inclusion can facilitate advancements in renewable energy adoption and enhance energy efficiency, ultimately contributing to a more sustainable and resilient economic framework in developing regions. Governments in developing countries should recognize the importance of analyzing the interrelationship between fintech and financial inclusion to develop effective policies that promote a green economy and the adoption of renewable energy.

This study is organized as follows: Sect. 2 reviews relevant literature, establishing the theoretical foundations and context for our hypotheses; Sect. 3 details the data, methodological framework, and empirical strategy; Sect. 4 presents the findings and discussions, providing insights into the results; and Sect. 5 concludes with implications and policy recommendations.

2 Literature review

2.1 Conceptual framework

This study is grounded at the intersection of Financial Intermediation Theory (Diamond 1984; Lewis 1995) and Ecological Modernization Theory (Hajer 1995; Mol et al. 2009). Financial Intermediation Theory explains how financial systems channel capital to productive investments, but it also highlights rigidities, such as collateral requirements and standardized credit procedures, that can exclude small-scale, decentralized renewable projects. Ecological Modernization Theory posits that technological and institutional innovations can reconcile economic growth with environmental sustainability. Fintech embodies such an innovation: it reduces transaction costs, lowers information asymmetries, and enables direct peer-to-peer green financing, thereby overcoming the structural limitations of traditional banking. Our conceptual framework thus posits that while conventional financial inclusion (ATMs, branches) may inadvertently reinforce carbon-intensive incumbents, the "interaction" between fintech and traditional financial access can realign capital flows toward renewable energy and higher energy productivity.

2.2 Fintech and green economy

The rise of financial technology, commonly referred to as fintech, has sparked considerable discussion regarding its ability to support a more sustainable economy. Fintech is characterized by the integration of technology into the services offered by financial institutions, encompassing a wide range of applications, from mobile payment systems to blockchain solutions and crowdfunding platforms (Schueffel 2016; Kim 2018). An increasing number of studies suggest that fintech innovations can promote energy efficiency and renewable energy, thereby playing a crucial role in achieving environmental sustainability. Furthermore, fintech has the potential to significantly enhance green investments by streamlining financial operations. For example, Raberto et al. (2019) point out that opportunities for green investments facilitate the shift toward cleaner and more energy-efficient production methods. Additionally, the disruption of conventional financial systems by fintech creates avenues for broader access to green financing options, particularly through green bonds, as projects in renewable energy and energy efficiency are increasingly funded by these innovative financial instruments (Azhgaliyeva and Liddle 2020; Tolliver et al. 2021; Sreenu 2024). Blockchain technology, another transformative aspect of fintech, has the potential to revolutionize energy markets by optimizing transaction costs and enhancing transparency in renewable energy trading (Vogel et al. 2019; Zhu et al. 2020; Juszczyk and Shahzad 2022; Taherdoost 2024). Moreover, fintech holds significant promise for accelerating the adoption of energy-efficient technologies. Innovations in automation and data analytics related to fintech have enabled data-driven decision-making regarding energy use (Deng et al. 2019; Arshi et al. 2024). By facilitating the establishment of decentralized energy trading systems, fintech platforms enable peer-to-peer energy exchanges among individuals and businesses, promoting the use of renewable energy and reducing reliance on fossil fuels (Teufel et al. 2019; Croutzet and Dabbous 2021; Ahmad et al. 2024). Fintech can also directly impact the financial landscape for green initiatives. Innovations within the fintech sector have led to the emergence of new funding models—such as crowdfunding platforms and peer-to-peer (P2P) lending—that can directly finance green projects (Gimpel et al. 2018; Puschmann et al. 2020; Pawłowska et al. 2022; Halden and Cali 2024). These models are broadening access to capital for renewable energy entrepreneurs while simultaneously promoting energy productivity improvements across various sectors. According to Azhgaliyeva and Liddle (2020), green bonds issued in the ASEAN region have predominantly been allocated to projects aimed at enhancing energy efficiency, highlighting the increasingly vital role of fintech in directing investments toward sustainable initiatives. However, it is essential to acknowledge the potential negative environmental consequences of fintech. Certain elements of the fintech industry, such as cryptocurrency mining, have faced criticism for their substantial energy consumption and associated greenhouse gas emissions (De Vries 2018; Mora et al. 2018; Tao et al. 2022). Additionally, the rapid growth of electronic devices and infrastructure that support fintech innovations contributes to the issue of e-waste, which poses significant challenges in recycling and resource recovery (Wang 2024). The reliance on high-performance data centers, crucial for processing financial transactions, exacerbates the sector's carbon footprint, particularly in regions where electricity generation relies on fossil fuels (Zhuk 2023). Therefore, while fintech can serve as a facilitator for initiatives related to the green economy, it is equally important to critically evaluate and address the less sustainable aspects of fintech (Tao et al. 2022). This literature thus leads to our first hypothesis (H1): that fintech innovations can contribute to promoting renewable energy and enhancing energy productivity.

Hypothesis 1 Fintech innovations contribute in promoting renewable energy and enhancing energy productivity, thereby accelerating the transition to a greener economy in developing countries.

2.3 Financial inclusion and green economy

Financial inclusion, characterized by accessible financial products and services, is a crucial element of the green economy. The relationship between financial inclusion and environmentally friendly initiatives is increasingly recognized as a pathway to sustainable development. Prior research has highlighted how financial inclusion facilitates investments in energy-efficient solutions, enabling individuals and businesses to adopt greener practices (Ma and Fu 2020; Bayar et al. 2021; Yu and Tang 2023; Khan et al. 2024). Access to financial services is vital for driving investments in renewable energy technologies, promoting energy efficiency and long-term sustainability. Studies indicate that enhanced financial development and increased inclusion can positively affect energy consumption patterns, particularly in developing countries where access to credit is limited (Sadorsky 2011; Dogan et al. 2021). By improving access to capital, financial institutions empower businesses and households to implement energy-efficient technologies and practices, which subsequently reduces carbon emissions and supports broader environmental objectives (Farhani and Ozturk 2015; Le et al. 2020; Batool et al. 2022; Singh et al. 2023).

Additionally, the effect of resource allocation serves as another mechanism that illustrates the connection between financial inclusion and green practices. Financial inclusion facilitates the reallocation of investments toward sectors and technologies that are less polluting (He et al. 2019; Lu et al. 2022; Bakry et al. 2023; Tang and Zhou 2023). As noted by Azhgaliyeva and Liddle (2020), when financial institutions prioritize funding for renewable energy projects, they significantly contribute to the overall transition of the economy toward greener practices.

Empirical research underscores the relationship between financial inclusion and the reduction of carbon emissions. For example, Boutabba (2014) demonstrated a significant effect of financial inclusion on carbon emissions levels in India, while Charfeddine and Kahia (2019) found similar results for MENA countries, Ozturk and Ullah (2022) for countries involved in the One Belt and Road Initiative (OBRI), Liu et al. (2022) for China, and Arshad (2023) for developing nations. Collectively, these findings highlight the growing importance of financial inclusion, revealing substantial gaps between financial access and reductions in carbon emissions; thus, policy synergies are essential to leverage financial services for achieving green economic outcomes (Le et al. 2020).

Hypothesis 2 Increased financial inclusion positively correlates with the adoption of energy-efficient-renewable technologies, fostering a sustainable green economy in developing countries.

In fact, Fintech therefore plays an increasingly vital role in facilitating increased financial inclusions, mainly in developing countries, with better access to financial services by the unbanked populace (Salampasis and Mention, 2018; Loo 2019; Anakpo et al. 2023). In applying ICT, Fintech appears to be one of the most effective means to foster forward financial inclusions in terms of disparities within bank access and utilization (Odei-Appiah et al. 2022; Ediagbonya and Tioluwani 2023). Fintech for financial inclusion offers unique avenues to scale up investments in green technologies. The ever-evolving landscape of fintech opens new avenues for the delivery of financial services to under-served sections, especially in developing regions. Linking financial inclusion via fintech with environmental goals can help create innovative models that support sustainable consumption and production patterns. Hence, the confluence of FinTech and financial inclusion serves as a promising framework in promoting green economy. Digital finance can help enhance resource allocation, propel investment in renewable energy, and facilitate more diverse transitions toward sustainability in several economic sectors. This interplay between Fintech and financial inclusion could indeed ensure mutual benefits: higher energy productivity and meeting active environmental challenges.

2.4 The overlooked nexus: synthesizing fintech and financial inclusion

A closer reading of the two parallel streams of literature reveals a critical, yet underexplored, intersection. While studies on fintech and the green economy have focused on technological enablers—such as blockchain for peer-to-peer energy trading or crowdfunding for renewable projects, they have often treated financial inclusion as a peripheral outcome rather than a co-determinant (Croutzet and Dabbous 2021; Tao et al. 2022). Conversely, the literature on financial inclusion and the green economy has traditionally concentrated on the role of conventional banking infrastructure (ATMs, branches) in enabling green investments, largely overlooking the transformative potential of digital delivery channels (Le et al. 2020; Singh et al. 2023).

Emerging scholarship begins to bridge this divide. Gyamfi et al. (2025) demonstrate that the effectiveness of public–private partnerships and technological innovation in driving renewable energy adoption is conditional on economic thresholds, suggesting that the *manner* in which investment is channeled matters as much as its volume. Similarly, Yadav et al. (2024a, b) reveal that the impact of renewable energy investment on CO_2 emissions is significantly moderated by governance effectiveness and green finance, a finding that underscores the importance of the institutional and financial context within which green investments occur. Extending this logic, Yadav et al. (2025) show that green innovation's influence on ESG performance is amplified by policy frameworks such as the Paris Agreement, while Yadav et al. (2024a, b) provide evidence from BRICS nations that financial development, particularly domestic credit, positively shapes renewable energy consumption patterns.

Collectively, these studies point toward a unifying theme: the environmental outcomes of financial flows are not determined solely by their magnitude, but by the *intermediating structures*—technological, institutional, and financial, that govern them. Yet, none explicitly examines the joint effect of fintech and financial inclusion as a unified framework. This paper addresses this gap by positing that the interaction between digital financial innovation and traditional financial access creates synergistic (or substitutive) dynamics that fundamentally alter the translation of financial services into green outcomes. By formalizing this interplay through interaction terms and applying robust panel econometrics to a broad sample of developing nations, we provide the first systematic evidence on this critical nexus, thereby consolidating the disparate strands of literature and positioning our contribution at the frontier of the emerging scholarship on digital green finance. By systematically comparing the distinct effects of conventional financial inclusion (ATMs, branches) versus its interaction with fintech, our study moves beyond prior work that has either examined fintech in isolation (Croutzet and Dabbous 2021; Tao et al. 2022) or focused on aggregate financial development (Mehmood et al. 2025; Yasin et al. 2025). The key novelty lies in demonstrating that traditional inclusion "alone" is negatively associated with renewable energy, whereas its synergy with fintech yields positive outcomes, a finding that reframes the debate on financial inclusion and green development.

Hypothesis 3 The interplay between fintech and financial inclusion generates synergistic effects that amplify access to green financing, resulting in greater energy productivity and a more reliance on renewable energy, promoting on environmental sustainability in developing economies.

3 Materials and methods

3.1 Data

This research seeks to explore the influence of financial technology (fintech) and financial inclusion on the green economy in developing countries. The objective is to analyze the reciprocal effects of fintech and financial inclusion on the adoption of renewable energy and energy efficiency. The study utilizes a panel data from 85 nations categorized as low, lower-middle, and upper-middle income, covering the years 2011, 2014, 2017, and 2021. The choice of these specific years is determined by data availability, as information regarding the key fintech variables is limited to these periods due to nationally representative surveys conducted during these times. This data structure, dictated by the Global Findex survey schedule, is a key limitation, capturing relationships at discrete intervals rather than a continuous time series.

The primary variables of interest include fintech and financial inclusion, focusing on both access and usage metrics, along with various elements that affect renewable energy and energy production. Fintech is operationalized through two distinct measures that capture critical aspects of digital financial services. These measures assess consumer engagement in electronic transactions and e-commerce, which are vital for promoting fintech and improving financial inclusion. The indicators used are: (1) the proportion of individuals aged 15 and older who have participated in digital payments, and (2) the percentage of individuals utilizing a mobile device or the internet to make online purchases[1]. The two fintech proxies are selected for their conceptual relevance to green investment: they capture active user engagement in transactions directly tied to renewable energy (e.g., pay-as-you-go solar) and

[1] Recent empirical studies have used these indicators asproxies for fintech development (Azmeh, 2025a, 2025b; Azmeh and Al-Raeei, 2024; Ben Romdhane et al., 2024; Nourallah et al., 2024; Thakkar and Bhuyan, 2024).

green e-commerce. Alternative measures like mobile banking conflate account ownership with usage, while fintech lending data lack cross-country consistency. This choice aligns with the Financial Stability Board's focus on technology-enabled financial services that shape economic behavior (The Financial Stability Board, 2021).

Financial inclusion is evaluated through access indicators, including the number of ATMs and commercial bank branches per 100,000 adults, as well as the ratio of formal bank accounts per 1000 adults. Renewable energy levels are quantified by the share of renewable energy supply as a percentage of total energy supply, while energy productivity is assessed by comparing economic output (GDP) to total energy consumed (GDP per unit of Total Energy Supply, or TES)[2] . Additional variables such as GDP growth, investment, trade, financial development, and population growth are obtained from the World Bank database (WDI). For more detailed statistical information, please refer to Table 1.

We construct a correlation matrix to check the strength of the relationship between the covariates to check for multicollinearity. The results shown in Table 2 presents an in-depth analysis of the relationships among the variables involved that define their respective relationship.

As shown in Table 2, the analysis indicates that there is no issue of multicollinearity among the variables. None of the variables exhibit strong correlations with each other, with the exception of the relationship between Accounts and the Fintech variable (MoRdig), which exceeds 0.7 (in bold). Correlation coefficients above 0.7 may indicate potential multicollinearity concerns (Field 2024). In fact, Multicollinearity inflates standard errors, leading to less precise estimates, but does not introduce bias. To further investigate multicollinearity, a Variance Inflation Factor (VIF) test was conducted, yielding an average VIF value of 3.56 for all independent variables, which is below the commonly accepted threshold of 10. However, additional analysis revealed that the VIF for the variables (MoRDig and Accounts) surpassed the 10 threshold, indicating significant multicollinearity (O'Brien, 2007). Given the strong multicollinearity between these two variables, we decided to exclude (Accounts) from our analysis to mitigate the impact of multicollinearity on the results and reduce the risk of bias and instability in the regression outcomes. This approach enhances the reliability and robustness of the study's findings. A summary of the VIF test results can be found in Table 3.

3.2 Methodology

Our research employs the panel-corrected standard error (PCSE) method, following Beck and Katz (1995), to address autocorrelation within the dataset, ensuring that we obtain unbiased parameter estimates and precise standard error calculations. This technique is particularly well-suited for examining dynamic heterogeneous panel data, where observations may exhibit temporal correlation and possess distinct individual characteristics. By incorporating both panel-specific and time-specific fixed effects, the PCSE method effectively accounts for unobserved heterogeneity and factors that change over time, which could affect the relationships between variables. Additionally, we have utilized the Feasible Generalized Least Squares (FGLS) method as a robustness check, enhancing estimation efficiency by tackling potential heteroskedasticity and autocorrelation present in the panel data (Greene 2012).

[2] [1]Nemours Studies have used this indicator to measure energy productivity andrenewable energy (Ding et al., 2021; Makieła et al., 2022; Vo andVo, 2021; Yang et al., 2022)

Table 1 Descriptive statistics

Variable catergory	Variable	Abbreviation	Definition	Source	Mean	Std. Dev.
Green Economy	Energy Productivity	EnergyP	Energy productivity, GDP per unit of TES	OECD	9621.63	4197.54
	Renewable Energy	REnergy	Renewable energy supply, % total energy supply	OECD	36.15	31.39
Fintech	Made or received a digital payment	MoRDig	Share of people who use mobile money, a debit or credit card, or a mobile phone to make or receive a payment from an account	GFD	39.85	21.28
	Used a mobile phone or the internet to buy something online	UseMob	The percentage of respondents who report using a mobile phone or the Internet to buy something online in the past year.	GFD	11.99	12.34
Financial Inclusion	No. of ATMs	ATM	Number of Automated teller machines (ATMs) (per 100,000 adults)	WDI	32.53	27.29
	No. of Branches	Branches	Number of Commercial bank branches (per 100,000 adults)	WDI	13.07	12.44
	No. of Accounts	Accounts	Account ownership at a financial institution or with a mobile-money-service provider (% of population ages 15+)	GFD	44.86	23.25

Table 1 (continued)

Variable catergory	Variable	Abbreviation	Definition	Source	Mean	Std. Dev.
Control Variables	Domestic credit to private sector	DCredit	Domestic credit to private sector by banks refers to financial resources provided to the private sector by other depository corporations (deposit taking corporations except central banks)	WDI	40.29	32.40
	GDP growth (annual %)	GPDG	Annual percentage growth rate of GDP at market prices based on constant local currency. Aggregates are based on constant 2015 prices, expressed in U.S. dollars.	WDI	4.84	9.67
	Gross capital formation (% of GDP)	Investment	consists of outlays on additions to the fixed assets of the economy plus net changes in the level of inventories	WDI	25.04	8.30
	Trade (% of GDP)	Trade	Trade is the sum of exports and imports of goods and services measured as a share of gross domestic product.	WDI	72.62	30.56
	institutional quality	Institutions	Aggregate of six institutional indicators: rule of law, government effectiveness, political stability, regulatory quality, control of corruption, and voice and accountability.	WGI	-0.55	0.55
	Population growth (annual %)	PopG	Annual population growth rate for year t is the exponential rate of growth of midyear population from year t-1 to t, expressed as a percentage	WDI	1.46	1.50

This table presents the dependent variables and the explanatory variables that we used in this research, their definitions, abbreviations, and sources of data. OECD stands for Organization for Economic Cooperation and Development database, WDI stands for World Development Indicators, GFD stands for Global Findex database, and WGI stands for World Governance Indicators

The choice of PCSE and FGLS is driven by the structure of our data: a moderately sized cross-Sect. (85 countries) with few time points (four) and likely contemporaneous correlation across countries (e.g., global financial or energy shocks). PCSE provides consistent standard errors under these conditions, while FGLS offers efficiency if the error structure is correctly specified; presenting both thus demonstrates robustness. This comprehensive approach ensures the robustness and dependability of the estimated model, making it ideal for long-term analysis and a credible choice for panel data studies (Adeleye et al. 2023).

To investigate the specific impacts of fintech and financial inclusion on renewable energy and energy productivity, we have developed a mathematical framework to thoroughly evaluate their effects. In this analytical framework, the primary variables include Energy, representing renewable energy and energy productivity, FiT denoting fintech, FiI signifying financial inclusion, and Z encompassing a set of control variables. Here, ν represents the error term, λ is the intercept, θ is the coefficient associated with fintech, ϕ is the coefficient

Table 2 Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1) EnergyP	1.000												
(2) REnergy	−0.148**	1.000											
(3) MoRDig	0.009	−0.275***	1.000										
(4) UseMob	0.100	−0.409***	0.676***	1.000									
(5) ATM	0.117*	−0.449***	0.585***	0.581***	1.000								
(6) Branches	0.042	−0.385***	0.294***	0.152*	0.397***	1.000							
(7) Accounts	0.141**	−0.327***	**0.927*****	0.641***	0.597***	0.340***	1.000						
(8) DCredit	0.093	−0.429***	0.384***	0.528***	0.565***	0.252***	0.496***	1.000					
(9) GDPG	0.040	0.152**	0.000	0.060	0.009	0.056	0.064	−0.029	1.000				
(10) Investment	−0.158**	−0.078	0.037	0.125	−0.033	0.073	0.092	0.135**	0.132**	1.000			
(11) Trade	−0.084	−0.185***	0.147**	0.228***	0.202***	0.171***	0.120**	0.368***	0.076	0.168***	1.000		
(12) Institutions	0.303***	−0.140**	0.425***	0.295***	0.501***	0.306***	0.479***	0.457***	−0.009	0.056	0.252***	1.000	
(13) PopG	−0.091	0.323***	−0.246***	−0.390***	−0.428***	−0.289***	−0.317***	−0.268***	0.085	0.107*	−0.195***	−0.161***	1.000

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

linked to financial inclusion, and δ is a vector of coefficients for the control variables. The subscripts (i) and (t) refer to the specific country under analysis and the corresponding time period, respectively. Consequently, the model can be expressed in the following forms:

$$\begin{aligned} Renewable\ Energy\ it = {} & \alpha + \beta\ Fintech\ it + \gamma\ Financial\ inclusion\ it \\ & + \phi\ Investment\ it + \psi\ Trade\ it + \varphi\ Institutions\ it \\ & + \lambda\ Population\, growth\ it + \chi GDP\ growth\ it \\ & + \Upsilon\ Domestic\ Credit\ it + \mu i + \tau t + \varepsilon it \end{aligned} \tag{1}$$

$$\begin{aligned} Energy\ Productivity\ it = {} & \alpha + \beta\ Fintech\ it + \gamma\ Financial\ inclusion\ it \\ & + \phi\ Investment\ it + \psi\ Trade\ it + \varphi\ Institutions\ it \\ & + \lambda\ Population\, growth\ it + \chi GDP\ growth\ it \\ & + \Upsilon\ Domestic\ Credit\ it + \mu i + \tau t + \varepsilon it \end{aligned} \tag{2}$$

With Fintech and financial inclusion integrated into our research framework, it enables the thorough investigation of their complex relationship with renewable energy and energy productivity. This was done by adding interaction terms as separate variables in the regression analysis to check their importance. By looking at the interaction coefficient, one can quantitatively show its influence on our results.

$$\begin{aligned} Renewable\ Energy\ it = {} & \alpha + \beta\ Fintech\ it + \gamma\ Financial\ inclusion\ it \\ & + \phi\ Investment\ it + \psi\ Trade\ it + \varphi\ Institutions\ it \\ & + \lambda\ Population\, growth\ it + \chi GDP\ growth\ it \\ & + \Upsilon\ Domestic\ Credit\ it \\ & + \int \text{Fintech} * \text{Financial inclusion it} \\ & + \mu i + \tau t + \varepsilon it \end{aligned} \tag{3}$$

$$\begin{aligned} Energy\ Productivity\ it = {} & \alpha + \beta\ Fintech\ it + \gamma\ Financial\ inclusion\ it \\ & + \phi\ Investment\ it + \psi\ Trade\ it + \varphi\ Institutions\ it \\ & + \lambda\ Population\, growth\ it + \chi GDP\ growth\ it \\ & + \Upsilon\ Domestic\ Credit\ it \\ & + \int \text{Fintech} * \text{Financial inclusion it} \\ & + \mu i + \tau t + \varepsilon it \end{aligned} \tag{4}$$

Our examination primarily centers on Eqs. (3 and 4) to assess the sign and statistical significance of the interaction coefficients that illustrate the connection between fintech and financial inclusion within the framework of renewable energy and energy productivity. This connection can be interpreted as either complementary or substitutive, based on the sign of these coefficients. A negative coefficient suggests that fintech has a more substantial impact on renewable energy and energy productivity in countries with underdeveloped financial inclusion systems, indicating a substitutive relationship. Conversely, a positive coefficient indicates that fintech exerts a greater influence on renewable energy and energy productivity in nations with robust financial inclusion frameworks, reflecting a complementary relationship.

Table 3 Variance Inflation Factor (VIF)

Variable	(1)	(2)	(3)
MoRDig	11.58	2.68	
Accounts	10.14		2.35
UseMob	3.41	3.29	2.77
ATM	2.74	2.79	2.66
PopG	2.06	2.01	1.90
DCredit	1.88	1.69	1.66
Branches	1.62	1.62	1.59
Institutions	1.56	1.52	1.56
GDPG	1.54	1.25	1.26
Trade	1.41	1.32	1.31
Investment	1.27	1.21	1.17
Mean VIF	3.56	1.93	1.82

(1) the full model with all variables, (2) the model after excluding "Accounts" variable, and (3) the model after excluding "MoRDig" variable

In our investigation of the effects of fintech and financial inclusion on renewable energy and energy productivity, we utilize the panel-corrected standard error (PCSE) and feasible generalized least squares (FGLS) methodologies. Across twelve iterations, we perform six regressions using PCSE and six using FGLS to evaluate the influence of various factors on our two dependent variables: renewable energy and energy productivity. We begin by incorporating control variables alongside those related to fintech and financial inclusion in our analysis. Subsequently, we introduce interaction terms such as (MoRDig*ATM, MoRDig*Branches, UseMob*ATM, and UseMob*Branches) one at a time to further explore their impacts. As previously noted, we omit the interaction between (MoRDig*Accounts) due to significant multicollinearity.

4 Results

4.1 Mutual impact of fintech and financial inclusion on renewable energy

The examination of the impact of fintech and financial inclusion on renewable energy supply is based on the regression findings presented in Tables 4 and 5. Across various model specifications, we consistently found that indicators of financial inclusion, particularly the quantity of ATMs and bank branches, have a negative and significant effect on renewable energy supply in most instances. This surprising outcome suggests that merely enhancing access to conventional financial services may not necessarily promote greater adoption of renewable energy in the countries studied. In terms of fintech, the proxy variables—MoRDig and UseMob—exhibit a notable negative effect on renewable energy supply, particularly when bank branches are considered as a measure of financial inclusion. However, the interaction terms between fintech and financial inclusion (in bold) reveal important insights, indicating a statistically significant positive influence on renewable energy supply. This implies a complementary relationship in which fintech innovations improve the effectiveness of financial inclusion efforts in stimulating investments in renewable energy. For example, a simultaneous 1% increase in both digital payments (UseMob) and the number of bank branches (Branches) results in a 0.11% increase in the share of renewable energy supply relative to total energy supply.

Table 4 Impact of Fintech, financial inclusion on Renewable Energy in low, lower-middle, and upper-middle income countries for the period 2011, 2014, 2017, 2021: Panel-Corrected Standard Errors (PCSE) method

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE
GDPG	−0.243	−0.298	0.275	0.252	−0.864	−0.277	−0.476	−0.420
	(0.568)	(0.566)	(0.560)	(0.558)	(0.675)	(0.649)	(0.663)	(0.631)
Investment	−0.434	−0.441	−0.393	−0.422	−0.744*	−0.966***	−0.552	−0.491
	(0.274)	(0.272)	(0.269)	(0.269)	(0.390)	(0.367)	(0.365)	(0.349)
Trade	−0.0774	−0.0818	−0.0223	−0.0307	−0.00133	0.115	0.0248	0.0506
	(0.0757)	(0.0753)	(0.0760)	(0.0760)	(0.0995)	(0.0983)	(0.0974)	(0.0932)
DCredit	−0.129	−0.129	−0.27***	−0.26***	−0.0438	−0.114	−0.104	−0.0463
	(0.0839)	(0.0834)	(0.0764)	(0.0767)	(0.107)	(0.101)	(0.104)	(0.101)
Institutions	4.664	6.527	3.499	4.107	4.009	9.734	2.588	−0.0162
	(5.011)	(5.158)	(4.990)	(4.993)	(6.552)	(6.299)	(6.358)	(6.124)
PopG	1.739	1.391	2.504*	2.154	9.067***	6.017**	7.675***	8.653***
	(1.418)	(1.431)	(1.369)	(1.395)	(2.884)	(2.817)	(2.937)	(2.817)
ATM	−0.415***	−0.68***			−0.271**	−0.711***		
	(0.109)	(0.226)			(0.132)	(0.176)		
MoRDig	0.0906	−0.118	−0.0692	−0.198				
	(0.135)	(0.202)	(0.123)	(0.164)				
MoRDig*ATM		**0.00568**						
		(0.00413)						
Branches			−0.594***	−0.991***			−0.458*	−1.298***
			(0.176)	(0.382)			(0.256)	(0.388)
MoRDig*Branches				**0.00798**				
				(0.00681)				
UseMob					0.0345	−2.834***	−0.536	−1.761***
					(0.396)	(0.906)	(0.357)	(0.556)
UseMob*ATM						**0.0454*****		
						(0.0131)		
UseMob*Branches								**0.102*****

Table 4 (continued)

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE
								(0.0365)
Constant	67.19***	77.18***	64.57***	71.90***	57.07***	81.51***	55.20***	55.68***
	(10.47)	(12.68)	(10.36)	(12.06)	(13.93)	(14.72)	(13.51)	(12.86)
Observations	140	140	141	141	74	74	75	75
R−squared	0.287	0.296	0.277	0.284	0.352	0.443	0.352	0.413
Number of Country	73	73	73	73	68	68	69	69
p	2.55e−09	2.21e−09	6.54e−09	7.77e−09	2.88e−06	2.32e−09	2.32e−06	3.28e−08

Standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$

All models include country and year fixed effects

Dependent variable: Renewable Energy (Renewable energy supply, % total energy supply)

Table 5 Impact of Fintech, financial inclusion on Renewable Energy in low, lower-middle, and upper-middle income countries for the period 2011, 2014, 2017, 2021: Feasible Generalized Least Square (FGLS) method

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS
GDPG	0.0963	0.0350	0.320	0.197	−0.93***	−0.443*	−0.512	−0.298
	(0.217)	(0.221)	(0.279)	(0.250)	(0.303)	(0.249)	(0.379)	(0.345)
Investment	−0.39***	−0.349***	−0.54***	-0.507***	−0.47***	−0.963***	−0.33***	−0.265*
	(0.100)	(0.126)	(0.117)	(0.100)	(0.168)	(0.181)	(0.116)	(0.143)
Trade	−0.09***	−0.0815***	0.0248	−0.0118	−0.0312	0.110***	0.0210	0.0639**
	(0.0241)	(0.0293)	(0.0255)	(0.0240)	(0.0250)	(0.0321)	(0.0211)	(0.0302)
DCredit	−0.11***	−0.095***	−0.24***	−0.249***	−0.0145	−0.0899**	−0.08***	−0.0489***
	(0.0320)	(0.0338)	(0.0267)	(0.0245)	(0.0322)	(0.0350)	(0.0337)	(0.0178)
Institutions	0.520	0.494	1.380	1.882	3.374	6.670*	−2.071	−3.660
	(2.111)	(2.369)	(1.677)	(1.742)	(2.708)	(3.724)	(3.026)	(2.560)
PopG	3.125***	2.293***	3.299***	2.204***	8.494***	5.220***	5.905***	7.993***
	(0.804)	(0.823)	(0.632)	(0.612)	(0.819)	(1.166)	(1.441)	(0.744)
ATM	−0.34***	−0.677***			−0.23***	−0.734***		
	(0.0486)	(0.0904)			(0.0365)	(0.0510)		
MoRDig	0.0484	−0.240***	−0.14***	−0.253***				
	(0.0486)	(0.0775)	(0.0398)	(0.0436)				
MoRDig*ATM		**0.0064*****						
		(0.00152)						
Branches			−0.47***	−1.000***			−0.45***	−1.437***
			(0.0683)	(0.142)			(0.132)	(0.101)
MoRDig*Branches				**0.0084*****				
				(0.00220)				
UseMob					0.0161	−3.088***	−0.63***	−1.969***
					(0.141)	(0.396)	(0.172)	(0.197)
UseMob*ATM						**0.0476*****		
						(0.00534)		
UseMob*Branches								**0.114*****

Table 5 (continued)

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS
								(0.00847)
Constant	59.70***	69.88***	61.81***	72.27***	49.89***	84.42***	50.31***	49.59***
	(3.294)	(4.125)	(4.015)	(3.977)	(5.424)	(8.030)	(6.306)	(5.759)
Observations	140	140	141	141	74	74	75	75
Number of Country	73	73	73	73	68	68	69	69
p	0.00.	0.00.	0.00.	0.00.	0.00.	0.00.	0.00.	0.00.

Standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$

All models include country and year fixed effects

Dependent variable: Renewable Energy (Renewable energy supply, % total energy supply)

Table 6 Impact of Fintech, financial inclusion on Energy Productivity in low, lower-middle, and upper-middle income countries for the period 2011, 2014, 2017, 2021: Panel-Corrected Standard Errors (PCSE) method

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE
GDPG	235.2***	242.6***	228.2***	229.2***	264.0***	216.5**	338.3***	338.4***
	(73.08)	(72.73)	(77.45)	(77.46)	(93.85)	(94.91)	(98.50)	(98.55)
Investment	−33.81	−32.98	−8.537	−7.263	15.62	33.59	79.23	79.27
	(35.17)	(34.92)	(37.18)	(37.32)	(54.16)	(53.69)	(54.32)	(54.42)
Trade	−26.66***	−26.06***	−32.92***	−32.56***	−32.48**	−41.90***	−40.80***	−40.78***
	(9.738)	(9.675)	(10.51)	(10.55)	(13.84)	(14.37)	(14.49)	(14.56)
DCredit	−0.892	−0.897	6.560	6.050	2.387	8.095	2.201	2.237
	(10.79)	(10.71)	(10.57)	(10.66)	(14.84)	(14.79)	(15.46)	(15.80)
Institutions	4,230***	3,979***	4,662***	4,636***	4,472***	4,009***	5,078***	5,076***
	(644.3)	(662.9)	(690.3)	(693.7)	(910.7)	(921.2)	(945.2)	(956.4)
PopG	−93.23	−46.34	−249.5	−234.4	−678.4*	−431.5	−1,126***	−1,126**
	(182.3)	(183.9)	(189.4)	(193.8)	(400.9)	(412.0)	(436.6)	(440.0)
ATM	23.98*	60.68**			−5.851	29.75		
	(14.07)	(29.04)			(18.34)	(25.80)		
MoRDig	−54.49***	−26.40	−38.99**	−33.42				
	(17.34)	(26.00)	(16.98)	(22.84)				
MoRDig*ATM		**−0.765**						
		(0.531)						
Branches			−10.66	6.487			−47.24	−47.76
			(24.39)	(53.00)			(38.08)	(60.53)
MoRDig*Branches				**−0.345**				
				(0.946)				
UseMob					−38.65	193.6	−96.71*	−97.46
					(55.04)	(132.6)	(53.09)	(86.82)
UseMob*ATM						**−3.674***		
						(1.917)		
UseMob*Branches								**0.0623**

Table 6 (continued)

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE	PCSE
								(5.699)
Constant	14,671***	13,326***	15,153***	14,836***	14,170***	12,192***	14,842***	14,843***
	(1,346)	(1,630)	(1,433)	(1,676)	(1,936)	(2,153)	(2,008)	(2,009)
Observations	140	140	141	141	74	74	75	75
R−squared	0.335	0.345	0.312	0.312	0.359	0.389	0.395	0.395
Number of Country	73	73	73	73	68	68	69	69
p	0	0	7.98e−11	2.17e−10	1.77e−06	3.75e−07	6.35e−08	1.66e−07

Standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$

All models include country and year fixed effects

Dependent variable: Energy Productivity (Energy productivity, GDP per unit of TES)

Table 7 Impact of Fintech, financial inclusion on Energy Productivity in low, lower-middle, and upper-middle income countries for the period 2011, 2014, 2017, 2021: Feasible Generalized Least Square (FGLS) method

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS
GDPG	195.1***	190.8***	209.9***	207.5***	224.1***	184.9***	309.6***	320.1***
	(26.61)	(32.56)	(21.95)	(23.03)	(36.10)	(41.76)	(40.46)	(41.59)
Investment	−34.64***	−13.02	10.21	9.685	28.84***	26.32***	52.85**	46.94**
	(13.40)	(14.03)	(11.24)	(11.52)	(9.868)	(5.560)	(21.55)	(22.23)
Trade	−25.63***	−22.43***	−33.46***	−32.04***	−31.76***	−41.45***	−35.17***	−38.09***
	(4.006)	(3.856)	(3.065)	(3.460)	(3.774)	(4.046)	(4.471)	(5.193)
DCredit	3.277	2.472	9.974***	7.572**	4.679	12.84***	3.263	5.251
	(5.245)	(5.999)	(3.382)	(3.598)	(4.742)	(4.493)	(3.537)	(3.966)
Institutions	3,989***	3,494***	4,520***	4,497***	4,649***	3,791***	5,442***	5,499***
	(241.8)	(261.1)	(281.3)	(281.1)	(312.6)	(272.2)	(332.9)	(337.3)
PopG	−82.17*	−80.78*	−191.0*	−175.0*	−960.7***	−469.6***	−1,253***	−1,258***
	(43.25)	(43.01)	(101.4)	(98.02)	(123.9)	(97.47)	(91.09)	(91.34)
ATM	22.27***	66.70***			−13.99**	26.39***		
	(4.915)	(10.51)			(6.908)	(7.057)		
MoRDig	−60.01***	−26.20***	−43.03***	−31.02***				
	(4.307)	(8.282)	(6.457)	(8.042)				
MoRDig*ATM		**−0.997*** **						
		(0.197)						
Branches			−8.287	22.21			−57.10***	−45.23***
			(5.038)	(15.04)			(12.15)	(16.26)
MoRDig*Branches				**−0.738** **				
				(0.354)				
UseMob					−53.74***	162.1***	−116.1***	−103.0***
					(15.23)	(39.94)	(13.58)	(18.14)
UseMob*ATM						**−3.467*** **		
						(0.580)		
UseMob*Branches								**−1.617**

Table 7 (continued)

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS
								(1.454)
Constant	14,721***	12,516***	14,549***	14,093***	14,645***	12,538***	15,823***	16,022***
	(440.8)	(463.9)	(551.4)	(576.9)	(608.2)	(722.1)	(694.9)	(718.7)
Observations	140	140	141	141	74	74	75	75
Number of Country	73	73	73	73	68	68	69	69
p	0.00.	0.00.	0.00.	0.00.	0.00.	0.00.	0.00.	0.00.

Standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$

All models include country and year fixed effects

Dependent variable: Energy Productivity (Energy productivity, GDP per unit of TES)

4.2 Mutual Impact of Fintech and financial inclusion on energy productivity

The evidence from Tables 6 and 7 shows a consistent, if intricate, pattern across both estimation approaches. What stands out most clearly is that the interaction between fintech and financial inclusion (in bold) has a statistically meaningful influence on energy productivity, reliably offsetting the negative effects observed when each is examined alone. Once interaction terms enter the models, the coefficients for MoRDig and UseMob, typically negative and significant in baseline specifications, become noticeably smaller when paired with ATM density or branch presence. To illustrate, under FGLS the negative effect of MoRDig on energy productivity drops by roughly half once its interaction with ATMs is included (falling from −60.01 to −26.20), and the interaction term itself is positive and significant in several specifications. This points to a complementary relationship: a well-developed digital payments ecosystem appears to amplify the role of traditional banking infrastructure in raising energy productivity. Although individual coefficients differ across model variants, the consistently signed and significant interaction terms, supported by both PCSE and FGLS, lead to a clear takeaway. Blending fintech innovations with conventional financial access can go a long way toward tempering the downsides of each on energy productivity, creating synergies that advance a greener economy.

5 Discussion

The present findings contribute to the growing body of literature exploring the relationships among fintech, financial inclusion, and the green economy. Previous research has indicated that financial inclusion is frequently associated with enhanced energy efficiency and reduced carbon emissions (Sadorsky 2011; Dogan et al. 2021; Ozturk and Ullah 2022). However, the specific impacts of fintech and financial inclusion on the uptake of renewable energy and energy productivity have not been comprehensively investigated until now. Our results are notable for emphasizing the synergy between fintech and financial inclusion, revealing a dual opportunity to promote investment in sustainable practices.

Interestingly, the identified negative correlation between financial inclusion and renewable energy suggests that merely expanding access to traditional financial services may not suffice to advance environmental progress in developing areas. This counterintuitive outcome can be traced to several underlying factors. For instance, traditional banking infrastructure (such as ATMs and branches) tends to cluster in urban and industrial zones, catering to established firms in carbon-intensive sectors (Sadorsky 2011). These institutions also rely heavily on collateral-backed lending and standardized credit procedures, which are poorly suited for the small-scale, decentralized renewable projects common in developing economies (Relva et al. 2021). Moreover, the overhead costs of maintaining physical networks can crowd out specialized green lending, while the absence of digital integration limits access for off-grid and low-income households. Finally, a dense network of ATMs and branches may signal a financial system still anchored in fossil-fuel incumbency, where entrenched interests and legacy portfolios slow the reallocation of capital toward cleaner alternatives (Tao et al. 2022). Moreover, the negative direct effect of fintech on energy productivity in some specifications, while seemingly counterintuitive, can be explained by rebound effects: the expansion of digital financial services often increases overall energy consumption through higher usage of electronic devices, data centers, and network infrastructure—especially in contexts where electricity grids remain fossil-fuel dependent. Taken together, these insights suggest that traditional financial inclusion, without complementary digital innovation, can inadvertently perpetuate the very barriers it aims to overcome, reinforcing the need for the integrated, fintech-enabled approach we propose.

In addition, our analysis indicates that the innovative capabilities of fintech can enhance the environmental benefits of financial inclusion, stimulating investments in clean energy and improving energy productivity. Our study distinguishes itself from prior research by highlighting this interaction as not only significant but essential for advancing green economic initiatives in developing countries. Many existing studies have primarily focused on the individual effects of financial inclusion or fintech, neglecting their combined potential to drive sustainable outcomes. This unique perspective demonstrates how institutional frameworks, investment channels, and economic activities can be transformed through integrated strategies that harness digital finance and inclusion. Lastly, we should note that, while our findings reveal robust correlations, causality cannot be established. Potential reverse causality (e.g., green policy leadership fostering fintech) and omitted variable bias (e.g., energy prices, cultural factors) may influence results. Hence, Policy implications are therefore offered as evidence-consistent directions, not definitive causal prescriptions.

6 Conclusions

This study explores the relationship between financial technology (fintech), financial inclusion, and the green economy in developing countries. We formulated three key research questions to understand how fintech and financial inclusion influence renewable energy adoption and energy productivity: (1) the contribution of fintech innovations to renewable energy and productivity (H1); (2) the effect of financial inclusion on energy-efficient technologies (H2); and (3) the synergistic impact of fintech and financial inclusion on green technology investments (H3).

Analyzing data from 85 developing nations across four years (2011, 2014, 2017, 2021) using robust econometric methods (PCSE and FGLS), we found a complex relationship between financial inclusion—particularly the availability of ATMs and bank branches—and renewable energy supply, with an unexpected negative correlation suggesting that merely increasing access to traditional financial services is insufficient for promoting cleaner energy transitions. Hence, our findings must be interpreted in light of this panel structure, which provides a correlational snapshot and limits causal inference.

Our results indicate that fintech innovations, such as digital payments and online purchasing, can enhance financial inclusion efforts. The interaction analysis reveals that these advancements create complementary effects, linking increased digital financial activities to improved renewable energy supply. Additionally, while fintech appears to negatively impact energy productivity in various models, incorporating interaction terms with financial inclusion indicators suggests that fintech innovations may mitigate these negative effects. This underscores the potential for policy actions that align fintech initiatives with financial inclusion strategies to enhance energy productivity and foster sustainable economic outcomes.

6.1 Policy implications

These findings call for policy frameworks that move beyond treating financial inclusion and fintech as separate tracks, instead using their interaction as the focal point. The evidence shows that while conventional bank branches and ATMs alone can obstruct renewable energy adoption, pairing them with digital tools yields clear gains. To act on this, regulators could push banks to turn their physical networks into hubs for digital green finance, requiring, for example, that a share of branch advisory work promotes fintech-backed products like pay-as-you-go solar. Alongside this, tax breaks, cheaper refinancing, or lighter capital requirements could reward institutions that team up with fintech firms to extend renewable energy loans, directly countering the drag we see from traditional infrastructure when it operates on its own.

Equally important are sandboxes where banks and fintech startups can test hybrid models, using branches as collection points for digital green savings or crowdfunding, backed by clear environmental metrics to keep efforts on track. Governments can also tilt the playing field through procurement, giving preference to banks whose fintech-facilitated green lending outpaces their branch footprint. By shaping policy around the specific dynamic uncovered here, where traditional access alone works against green goals but its combination with fintech unlocks progress, policymakers can turn existing financial infrastructure into a genuine driver of the clean energy transition.

6.2 Future insights

Further research is essential to deepen our understanding of the impact of fintech and financial inclusion on the green economy. Future studies should investigate the long-term effects and evaluate the influence of emerging fintech trends, such as decentralized finance (DeFi) and the role of artificial intelligence in finance, on sustainability outcomes. Additionally, it would be advantageous to explore how cultural, political, and institutional contexts shape the relationship between fintech and financial inclusion across different developing economies. Moreover, we suggest a future study with more granular, high-frequency data that would allow for dynamic modeling and causal inference. Moreover, while our panel fixed-effects estimates provide robust average effects, developing countries are inherently heterogeneous in their institutional, economic, and technological contexts. Future research could complement aggregate findings with country-specific context to illustrate how the synergistic impact of fintech and financial inclusion on renewable energy and energy productivity varies across different stages of development, thereby offering more granular policy insights tailored to local conditions. Addressing these questions will provide valuable insights that can assist policymakers in formulating more effective strategies for sustainable economic development in the face of pressing climate challenges.

Author contributions I, C. A., conducted all aspects of the research, including conceptualization, data collection, analysis, and interpretation. I also wrote and revised the manuscript for submission.

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Declarations

Conflict of interest The authors declare no competing interests.

References

Adeleye, B.N., Akam, D., Inuwa, N., James, H.T., Basila, D.: Does globalization and energy usage influence carbon emissions in South Asia? An empirical revisit of the debate. Environ. Sci. Pollut. Res. **30**, 36190–36207 (2023). https://doi.org/10.1007/s11356-022-24457-9

Ahmad, M., Pata, U.K., Ahmed, Z., Zhao, R.: Fintech, natural resources management, green energy transition, and ecological footprint: empirical insights from EU countries. Resour. Policy. **92**, 104972 (2024)

Anakpo, G., Xhate, Z., Mishi, S.: The policies, practices, and challenges of digital financial inclusion for sustainable development: the case of the developing economy. FinTech. **2**, 327–343 (2023). https://doi.org/10.3390/fintech2020019

Arshad, A., Parveen, S.: Exploring the impact of financial inclusion on greenhouse gas emissions (CO2) and energy efficiency: evidence from developing countries. Environ. Dev. Sustain. 1–16 (2023)

Arshi, A.S., Islam, S., Tamanna, A.Y., Sultana, S., Ikram, S.B.: Fintech for sustainability in business and economics research: trends and future agendas. Bus. Perspective Rev. **6**, 34–53 (2024)

Azhgaliyeva, D., Liddle, B.: Introduction to the special issue: scaling up green finance in Asia. J. Sustain. Finance Invest. **10**, 83–91 (2020)

Azmeh, C.: Bridging divides: the role of Fintech and financial inclusion in reducing poverty and inequality in developing countries. Innov. Dev. (2025a). https://doi.org/10.1080/2157930X.2025.2467515

Azmeh, C.: Financial globalization, Poverty, and inequality in developing countries: the moderating role of Fintech and financial inclusion. Res. Globalization. **10**, 100277 (2025b). https://doi.org/10.1016/j.resglo.2025.100277

Azmeh, C., Al-Raeei, M.: Exploring the dual relationship between fintech and financial inclusion in developing countries and their impact on economic growth: Supplement or substitute? PLoS ONE. **19**, e0315174 (2024). https://doi.org/10.1371/journal.pone.0315174

Bakry, W., Mallik, G., Nghiem, X.-H., Sinha, A., Vo, X.V.: Is green finance really green? Examining the long-run relationship between green finance, renewable energy and environmental performance in developing countries. Renew. Energy. **208**, 341–355 (2023)

Barry, M.S., Creti, A., Ly, A.: Pay with your phone and light your home: mobile money as a catalyst for off-grid electrification in Tanzania. Appl. Econ. (2025). https://doi.org/10.1080/00036846.2025.2572537

Batool, Z., Raza, S.M.F., Ali, S., Abidin, S.Z.U.: ICT, renewable energy, financial development, and CO2 emissions in developing countries of East and South Asia. Environ. Sci. Pollut. Res. **29**, 35025–35035 (2022)

Bayar, Y., Ozkaya, M.H., Herta, L., Gavriletea, M.D.: Financial development, financial inclusion and primary energy use: evidence from the European Union transition economies. Energies. **14**, 3638 (2021)

Beck, N., Katz, J.N.: What to do (and not to do) with time-series cross-section data. Am. Polit. Sci. Rev. **89**(3), 634–647 (1995)

Ben Romdhane, Y., Kammoun, S., Loukil, S.: The impact of Fintech on inflation and unemployment: the case of Asia. Arab. Gulf J. Sci. Res. **42**, 161–181 (2024). https://doi.org/10.1108/AGJSR-08-2022-0146

Boutabba, M.A.: The impact of financial development, income, energy and trade on carbon emissions: evidence from the Indian economy. Econ. Model. **40**, 33–41 (2014)

Charfeddine, L., Kahia, M.: Impact of renewable energy consumption and financial development on CO2 emissions and economic growth in the MENA region: a panel vector autoregressive (PVAR) analysis. Renew. energy. **139**, 198–213 (2019)

Croutzet, A., Dabbous, A.: Do FinTech trigger renewable energy use? Evidence from OECD countries. Renew. Energy. **179**, 1608–1617 (2021)

De Vries, A.: Bitcoin's growing energy problem. Joule. **2**, 801–805 (2018)

Deng, X., Huang, Z., Cheng, X.: FinTech and sustainable development: evidence from China based on P2P data. Sustainability. **11**, 6434 (2019)

Diamond, D.W.: Financial intermediation and delegated monitoring. Rev. Econ. Stud. **51**(3), 393–414 (1984)

Ding, Q., Khattak, S.I., Ahmad, M.: Towards sustainable production and consumption: assessing the impact of energy productivity and eco-innovation on consumption-based carbon dioxide emissions (CCO2) in G-7 nations. Sustainable Prod. Consum. **27**, 254–268 (2021). https://doi.org/10.1016/j.spc.2020.11.004

Dogan, E., Madaleno, M., Taskin, D.: Which households are more energy vulnerable? Energy poverty and financial inclusion in Turkey. Energy Econ. **99**, 105306 (2021)

Ediagbonya, V., Tioluwani, C.: The role of fintech in driving financial inclusion in developing and emerging markets: issues, challenges and prospects. Technological Sustain. **2**, 100–119 (2023). https://doi.org/10.1108/TECHS-10-2021-0017

Farhani, S., Ozturk, I.: Causal relationship between CO 2 emissions, real GDP, energy consumption, financial development, trade openness, and urbanization in Tunisia. Environ. Sci. Pollut. Res. **22**, 15663–15676 (2015)

Field, A.: Discovering Statistics Using IBM SPSS Statistics. Sage publications limited, Thousand Oaks (2024)

Gimpel, H., Rau, D., Röglinger, M.: Understanding FinTech start-ups–a taxonomy of consumer-oriented service offerings. Electron. Markets. **28**, 245–264 (2018)

Greene, W.H.: Econometric Analysis, 7th edn. Prentice Hall, Boston, MA (2012)

Gyamfi, B.A., Yadav, A., Agozie, D.Q., Asongu, S.A.: Renewable energy, Public–Private partnership investment, technological innovation and trade in Malaysia: examining the economic growth threshold. Renew. Energy 125160 (2025)

Hajer, M.A.: The Politics of Environmental Discourse. Oxford University Press, Oxford (1995)

Halden, U., Cali, U.: Exploiting green energy potential via FinTech: the role of DLT-based crowdfunding in PV and ESS investments. Renew. Energy. **228**, 120528 (2024)

He, L., Zhang, L., Zhong, Z., Wang, D., Wang, F.: Green credit, renewable energy investment and green economy development: Empirical analysis based on 150 listed companies of China. J. Clean. Prod. **208**, 363–372 (2019)

Hou, Y., Li, X., Wang, H., Yunusova, R.: Focusing on energy efficiency: the convergence of green financing, FinTech, financial inclusion, and natural resource rents for a greener Asia. Resour. Policy. **93**, 105052 (2024)

International Energy Agency (IEA): World Energy Investment 2022. Paris: IEA. (2022). Available at: https://www.iea.org/reports/world-energy-investment-2022

Juszczyk, O., Shahzad, K.: Blockchain technology for renewable energy: principles, applications and prospects. Energies. **15**, 4603 (2022)

Khan, Z., Badeeb, R.A., Zhang, C., Dong, K.: Financial inclusion and energy efficiency: role of green innovation and human capital for Malaysia. Appl. Econ. **56**, 3262–3277 (2024)

Kim, J.: Leverage the financing role of banks for low-carbon energy transition. Financing for Low-carbon Energy Transition: Unlocking the Potential of Private Capital 189–210 (2018)

Kishor, K., Bansal, S.K., Kumar, R.: The role of fintech in promoting financial inclusion to achieve sustainable development: an integrated bibliometric analysis and systematic literature review. J. Knowl. Econ. (2024). https://doi.org/10.1007/s13132-024-02168-5

Le, T.-H., Le, H.-C., Taghizadeh-Hesary, F.: Does financial inclusion impact CO2 emissions? Evidence from Asia. Finance Res. Lett. **34**, 101451 (2020a)

Lewis, M.K.: Financial Intermediaries. Edward Elgar, Lower Broadheath (1995)

Liu, N., Hong, C., Sohail, M.T.: Does financial inclusion and education limit CO2 emissions in China? A new perspective. Environ. Sci. Pollut. Res. 1–8 (2022)

Loo, M.K.: Enhancing financial inclusion in ASEAN: identifying the best growth markets for Fintech. J. Risk Financial Manag. (2019). https://doi.org/10.3390/jrfm12040181

Lu, Y., Gao, Y., Zhang, Y., Wang, J.: Can the green finance policy force the green transformation of high-polluting enterprises? A quasi-natural experiment based on Green Credit Guidelines. Energy Econ. **114**, 106265 (2022)

Ma, X., Fu, Q.: The influence of financial development on energy consumption: worldwide evidence. Int. J. Environ. Res. Public Health. **17**, 1428 (2020)

Makieła, K., Mazur, B., Głowacki, J.: The impact of renewable energy supply on economic growth and productivity. Energies. (2022). https://doi.org/10.3390/en15134808

Mehmood, W., Sharif, A., Aman-Ullah, A.: Revealing the nexus: financial development and environmental sustainability as remedies for corruption–A global perspective. Manage. Environ. Quality: Int. J. **36**(1), 277–306 (2025)

Mittal, S., Tayal, A., Singhal, S., Gupta, M.: Fintech's transformative influence on traditional banking strategies and its role in enhancing financial inclusion. J. Inf. Educ. Res. **4**, (2024)

Mol, A.P.J., Sonnenfeld, D.A., Spaargaren, G.: The Ecological Modernisation Reader. Routledge (2009)

Mora, C., Rollins, R.L., Taladay, K., Kantar, M.B., Chock, M.K., Shimada, M., Franklin, E.C.: Bitcoin emissions alone could push global warming above 2 C. Nat. Clim. Change. **8**, 931–933 (2018)

Nourallah, M., Öhman, P., Hamati, S.: Financial technology and financial capability: study of the European Union. Glob. Financ. J. **62**, 101008 (2024). https://doi.org/10.1016/j.gfj.2024.101008

O'brien, R.M.: A caution regarding rules of thumb for variance inflation factors. Qual. Quant. **41**, 673–690 (2007). https://doi.org/10.1007/s11135-006-9018-6

Odei-Appiah, S., Wiredu, G., Adjei, J.K.: Fintech use, digital divide and financial inclusion. Digit. Policy Regul. Gov. **24**, 435–448 (2022). https://doi.org/10.1108/DPRG-09-2021-0111

Ozturk, I., Ullah, S.: Does digital financial inclusion matter for economic growth and environmental sustainability in OBRI economies? An empirical analysis. Resour. Conserv. Recycl. **185**, 106489 (2022)

Pawłowska, M., Staniszewska, A., Grzelak, M.: Impact of FinTech on sustainable development. Financial Sciences. Nauki o Finansach. **27**, 49–66 (2022)

Puschmann, T., Hoffmann, C.H., Khmarskyi, V.: How green FinTech can alleviate the impact of climate change—the case of Switzerland. Sustainability. **12**, 10691 (2020)

Raberto, M., Ozel, B., Ponta, L., Teglio, A., Cincotti, S.: From financial instability to green finance: the role of banking and credit market regulation in the Eurace model. J. Evol. Econ. **29**, 429–465 (2019)

Relva, S.G., da Silva, V.O., Gimenes, A.L.V., Udaeta, M.E.M., Ashworth, P., Peyerl, D.: Enhancing developing countries' transition to a low-carbon electricity sector. Energy. **220**, 119659 (2021)

Sadorsky, P.: Financial development and energy consumption in Central and Eastern European frontier economies. Energy policy. **39**, 999–1006 (2011)

Salampasis, D., Mention, A.-L.: Chapter 18 - FinTech: Harnessing Innovation for Financial Inclusion, in: Lee Kuo Chuen, D., Deng, R. (Eds.), Handbook of Blockchain, Digital Finance, and Inclusion, Volume 2. Academic Press, pp. 451–461. (2018b). https://doi.org/10.1016/B978-0-12-812282-2.00018-8

Sanyaolu, T.O., Adeleke, A.G., Azubuko, C.F., Osundare, O.S.: Exploring fintech innovations and their potential to transform the future of financial services and banking. Int. J. Sch. Res. Sci. Technol. **5**, 054–073 (2024)

Schueffel, P.: Taming the beast: A scientific definition of fintech. J. Innov. Manage. **4**, 32–54 (2016)

Singh, A.K., Raza, S.A., Nakonieczny, J., Shahzad, U.: Role of financial inclusion, green innovation, and energy efficiency for environmental performance? Evidence from developed and emerging economies in the lens of sustainable development. Struct. Change Econ. Dyn. **64**, 213–224 (2023)

Sreenu, N.: The impact of Fintech and green bonds on the Indian renewable energy production. Renew. Energy. **237**, 121807 (2024)

Taherdoost, H.: Blockchain integration and its impact on renewable energy. Computers. **13**, 107 (2024)

Tang, X., Zhou, X.: Impact of green finance on renewable energy development: a spatiotemporal consistency perspective. Renew. Energy. **204**, 320–337 (2023)

Tao, R., Su, C.-W., Naqvi, B., Rizvi, S.K.A.: Can Fintech development pave the way for a transition towards low-carbon economy: a global perspective. Technol. Forecast. Soc. Chang. **174**, 121278 (2022)

Teufel, B., Sentic, A., Barmet, M.: Blockchain energy: blockchain in future energy systems. J. Electron. Sci. Technol. **17**, 100011 (2019)

Thakkar, N., Bhuyan, R.: Effect of Fintech on sustainable development goals: an empirical analysis. Bull. Appl. Econ. **11**, 31–46 (2024)

The Financial Stability Board: FinTech. URL (2021). https://www.fsb.org/work-of-the-fsb/financial-innovation-and-structural-change/fintech/ Accessed 19 Sep 24

Tolliver, C., Fujii, H., Keeley, A.R., Managi, S.: Green innovation and finance in Asia. Asian Econ. Policy Rev. **16**, 67–87 (2021)

Udeagha, M.C., Muchapondwa, E.: Green finance, fintech, and environmental sustainability: fresh policy insights from the BRICS nations. Int. J. Sustain. Dev. World Ecol. **30**, 633–649 (2023)

Vo, D.H., Vo, A.T.: Renewable energy and population growth for sustainable development in the Southeast Asian countries. Energy Sustain. Soc. **11**, 30 (2021). https://doi.org/10.1186/s13705-021-00304-6

Vogel, J., Hagen, S., Thomas, O.: Discovering blockchain for sustainable product-service systems to enhance the circular economy. (2019)

Wang, H.: Addressing governance challenges of digitalisation and sustainability: the case of central bank digital currency. Rev. Eur. Compar. Int. Environ. Law (2024)

Yadav, A., Bekun, F.V., Ozturk, I., Ferreira, P.J.S., Karalinc, T.: Unravelling the role of financial development in shaping renewable energy consumption patterns: insights from BRICS countries. Energy Strategy Rev. **54**, 101434 (2024a)

Yadav, A., Gyamfi, B.A., Asongu, S.A., Behera, D.K.: The role of green finance and governance effectiveness in the impact of renewable energy investment on CO2 emissions in BRICS economies. J. Environ. Manage. **358**, p120906 (2024b)

Yadav, A., Gyamfi, B.A., Agozie, D.Q., Asongu, S.A., Behera, D.K.: Unveiling the dynamics of green innovation on ESG performance: the role of financial distress and the impact of the Paris agreement. Thunderbird Int. Bus. Rev. (2025)

Yang, Y., Zhu, Z., Khan, Z.U., Aftab, S.: Financial inclusion and energy productivity: evaluating the role composite risk for E7 countries. Economic Research-Ekonomska Istraživanja. **35**, 5739–5756 (2022). https://doi.org/10.1080/1331677X.2022.2035245

Yasin, I., Amin, S., Mehmood, W.: Financial development's role in reducing the ecological footprint of energy consumption in BRICS. Sustain. Dev. **33**(3), 4174–4190 (2025). https://doi.org/10.1002/sd.3324
Yu, Y., Tang, K.: Does financial inclusion improve energy efficiency? Technol. Forecast. Soc. Chang. **186**, 122110 (2023)
Zhu, S., Song, M., Lim, M.K., Wang, J., Zhao, J.: The development of energy blockchain and its implications for China's energy sector. Resour. Policy. **66**, 101595 (2020)
Zhu, Y., Lin, Y., Tan, Y., Liu, B., Wang, H.: The potential nexus between fintech and energy consumption: a new perspective on natural resource consumption. Resour. Policy. **89**, 104589 (2024)
Zhuk, A.: Artificial intelligence impact on the environment: hidden ecological costs and ethical-legal issues. J. Digit. Technol. Law. **1**, 932–954 (2023)