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The Role of Financial Development and Financial Technology in Driving Renewable Energy Technologies: Evidence from Developed and Developing Countries

Majid Aghaei[a]*, Mahdieh Rezagholizadeh[a]

[a] Department of Economics, Faculty of Economics and administrative sciences, University of Mazandaran, P. O. Box: 47416-95447, Babolsar, Mazandaran, Iran.

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ABSTRACT

The transition to renewable energy technologies (RETs) is crucial for mitigating greenhouse gas emissions and advancing sustainable development. This study investigates the role of financial development (FD) and financial technology (FinTech) in fostering RET deployment across developed and developing economies, while also assessing the moderating effect of FinTech on the FD–RET nexus. Using annual panel data from 2000 to 2022 and applying robust econometric techniques, namely Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS), the analysis reveals that FD exerts a significant positive influence on RET deployment in both groups of countries. FinTech directly promotes RET adoption, and in developed economies, it further amplifies the effectiveness of FD through the interaction effect. By contrast, in developing economies, institutional weaknesses and structural barriers constrain FinTech's ability to reinforce the role of FD. Moreover, real GDP per capita, population growth, and energy prices emerge as additional drivers of RET deployment, although the effect of energy prices remains muted in contexts with fossil fuel subsidies. Overall, the findings highlight the importance of strong financial markets, effective regulatory frameworks, and institutional quality in facilitating clean energy transitions, providing actionable policy insights for accelerating renewable energy adoption worldwide.

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1. INTRODUCTION

Over the course of the twentieth century, fluctuations in oil prices have posed both opportunities and challenges for the global economy. The persistent growth in fossil fuel consumption has raised profound concerns regarding energy security and environmental sustainability. On the one hand, the detrimental consequences of fossil fuel dependency, most notably greenhouse gas emissions and their contribution to global warming, have become increasingly alarming. On the other hand, the potential benefits of transitioning to renewable energy systems, particularly their capacity to enhance energy security and reduce environmental pressures, have encouraged policymakers to design new strategies and seek innovative solutions (Bhattacharya et al., 2017; Charfeddine & Kahia, 2019). Among the various policy responses, the promotion and large-scale adoption of renewable energy technologies (RETs) have been highlighted as a critical pathway toward sustainable development. These technologies are widely recognized for their ability to mitigate environmental degradation, accommodate rising global energy demand, and provide an alternative to the limitations inherent in conventional fossil fuels (Paramati et al., 2016; Kim & Park, 2016).

Despite the widely acknowledged importance of renewable energy in addressing climate change, its contribution to the global energy mix remains relatively modest. This is particularly true in developing economies, where financial and institutional barriers constrain large-scale deployment. One of the primary obstacles to the large-scale deployment of renewable energy technologies lies in their substantial upfront capital requirements, which render the mobilization of adequate financial resources a persistent challenge. The renewable energy sector is inherently capital-intensive, with significant initial expenditures associated with infrastructure development, technological equipment, and energy conversion processes, which demand considerable investments before power generation can even commence (Zhang et al., 2013; Ji & Zhang, 2019). Furthermore, renewable energy projects are frequently characterized by relatively low rates of return and extended payback horizons, placing them in the category of high-risk investments that necessitate sustained financial commitment and strong support from financial institutions and markets (Kim & Park, 2016).

In this scenario, financial development (FD) plays a pivotal role in mobilizing resources toward the advancement of renewable energy technologies. By enhancing financial diversification, liquidity, and allocative efficiency, FD can help mitigate investment risks while mobilizing the large-scale capital flows required for renewable energy deployment

*Corresponding Author's Email: M.aghaei@umz.ac.ir (M. Aghaei)
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(Paramati et al., 2016). In this context, financial technology (FinTech) has emerged as a transformative force in channelling financial resources towards the development of renewable energy technologies. Unlike traditional financial development which relies heavily on the depth and maturity of financial markets, FinTech leverages digital innovation to reduce transaction costs, expand access to finance, and improve risk management in renewable investments. Digital banking, crowdfunding platforms, peer-to-peer lending, and blockchain-based financing provide new avenues for mobilizing capital and overcoming the challenges of high costs and long payback periods in renewable energy projects (Osmani & Ebrahimi, 2025). However, the effectiveness of FinTech in supporting renewable energy projects differs significantly between developed and developing countries. While advanced economies benefit from strong digital infrastructure and regulatory frameworks that enable FinTech adoption, many developing countries still face barriers such as limited internet penetration, lack of digital literacy, and weak institutional capacity. These limitations reduce their ability to leverage FinTech for mobilizing investments in the renewable energy sector. Therefore, the advancement and diffusion of FinTech solutions are essential for bridging the financing gap and accelerating the deployment of renewable energy technologies worldwide. (Gyimah & Bonzo, 2025).

FinTech can influence the deployment of renewable energy technologies both directly and indirectly. On the one hand, it facilitates direct investment in green projects through innovative financial mechanisms. On the other hand, it can also play a moderating role by strengthening the relationship between financial development and renewable energy technologies, as it enhances the capacity of financial systems to mobilize resources, diversify risks, and improve the accessibility of green finance. Despite the growing importance of FinTech, limited research has examined its role as a moderating factor in the link between financial development and renewable energy technology deployment. Most previous studies have focused separately on the impact of FD or FinTech on sustainable energy, overlooking the potential interaction between the two. This gap motivates the present study, which aims to investigate whether FinTech enhances the effectiveness of FD in promoting renewable energy technologies.

Accordingly, this study explores the moderating role of FinTech in the relationship between FD and RET deployment across developed and developing country groups. The remaining research parts are arranged as follows: Section 2 reviews the theoretical foundations and the relationship between FD and RETs, with a focus on FinTech. Section 3 presents the data and methodology. Section 4 discusses the empirical results, and Section 5 concludes with policy implications.

2. Literature review

2.1. Financial Development and Renewable Energy Technology

One of the most important strategies for achieving energy diversification, environmental protection, sustainable development, and addressing the challenge of climate change is the energy transition. However, this transition requires not only advanced technologies but also substantial financial resources. In the path toward carbon neutrality, financing green projects plays a pivotal role in the expansion and adoption of renewable energy. Financial development can influence the growth of renewable energy through two main channels: the level effect, which enhances investors' access to financial resources, and the efficiency effect, which, by increasing asset liquidity and investment diversification, enables the financing of riskier and more innovative projects. In this sense, financial development can serve as a driving force for the adoption of renewable energy. Moreover, the expansion of financial markets and their attractiveness to foreign direct investment provide opportunities for investment in advanced technologies and the construction of green energy infrastructure. Nevertheless, some studies have cautioned that financial development may also lead to irrational investment flows into low-value sectors, thereby hindering renewable energy development and misallocating resources. (Osmani & Ebrahimi, 2025).

Financial development (FD) plays a crucial role in mobilizing real financial resources to support high-efficiency activities, such as the installation of renewable energy technologies (RETs) by banks. Financing renewable energy projects typically involves a combination of debt (loans) and equity (ownership) investments. Loans, being generally less risky than stocks, are often preferred by renewable energy developers for project financing. Banks, due to their cohesive and systematic approach to collecting and analyzing information, are able to allocate resources more efficiently by selecting robust companies and capable managers. Thus, the development of efficient credit markets reduces adverse selection and ensures that resources are appropriately allocated (Greenwood & Jovanovic, 1990). By fostering long-term relationships, banks can lower the cost of acquiring information and monitor the operations of companies and their principals more effectively (Levine, 1997). Banks also encourage corporate executives to manage businesses in the best interest of creditors, serving as effective supervisors and reducing the overall cost of surveillance, as monitoring is carried out by banks rather than by all investors (Diamond, 1984).

Given the significant capital requirements of renewable energy projects, a well-developed financial system can identify these projects and allocate the necessary resources accordingly. Conversely, in less-developed credit markets, banks often lack the expertise to effectively collect and analyze information about individuals, leading to inefficient resource allocation and limited acceptance of innovative RET projects (Greenwood & Jovanovic, 1990). Banks in these markets face challenges in consistently channeling financial resources to renewable energy projects, resulting in higher financing costs for loans. In addition, banks may struggle to effectively monitor managers' performance due to the high costs associated with acquiring creditors' information (Levine, 1997). Consequently, investors and financiers in these markets face constraints in employing effective risk management tools like hedging.

In less-developed financial markets, the lack of adequate diversification instruments and hedging options makes it difficult for the renewable energy sector to attract efficient financing (Kim & Park, 2018; Levine, 2005). High liquidity risks in these markets make innovative and long-term projects less attractive (Kim & Park, 2018). On the other hand, well-developed financial markets facilitate easier access to finance for high-investment projects, including those in renewable energy (Kim & Park, 2016). These markets enable efficient resource allocation and effective surveillance of managers, particularly when credit markets function effectively

(Greenwood & Jovanovic, 1990). Banks in these markets can allocate funds more effectively to renewable energy projects, reducing costs associated with misinformation. Moreover, financial development stimulates banking activities and attracts foreign direct investment, contributing to economic growth and increased energy demand (Gaies et al., 2019).

Several studies have explored the relationship between FD and RET. Fei et al. (2011) suggested that FD plays a positive and significant role in the development of renewable energy, particularly in the hydropower sector. Tang et al. (2012) examined the role of financing in renewable energy infrastructure and found that a significant portion of the initial costs of renewable energy projects could be recovered through revenue from the sale of carbon bonds after ten years. Dogan and Seker (2016) investigated the impact of real production, renewable energy, and FD on carbon emissions. Their findings indicate that increasing the consumption of renewable energy, along with FD, leads to a reduction in carbon emissions, whereas an increase in non-renewable energy consumption results in higher emissions. Kim and Park (2016) analyzed the role of FD in relation to RET and found that countries with well-developed financial markets experience greater development in the renewable energy sector due to easier access to foreign financing. Gaies et al. (2019) examined whether FD affects the deployment of renewable energy projects, finding a long-term positive and significant relationship between FD and renewable energy development. Pata (2018) assessed the impact of renewable energy consumption, FD, urbanization, and income level on greenhouse gas emissions, revealing that while urbanization, economic growth, and FD contribute to environmental degradation, the use of renewable energy does not significantly affect emissions. Kim and Park (2018) studied the effect of clean mechanisms on the development of renewable energy, considering the level of FD in various countries. Their findings suggest that countries with less flexible financial markets have limited access to debt and asset financing for renewable projects. Paramati et al. (2016) proposed that production, foreign direct investment flows, and stock market development have a positive and significant effect on clean energy. Overall, the development of stock markets facilitates the acquisition of available assets for clean energy projects and enables investors to manage high levels of risk and return. Charfeddine and Kahia (2019) estimated the impact of renewable energy consumption, FD, greenhouse gas emissions, and economic growth, showing that renewable energy and FD have minimal effects on economic growth. Moreover, in MENA countries, FD's impact on the renewable energy sector was observed to be weak in terms of environmental development and improvement. Ji and Zhang (2019) analyzed the role of the capital market in China's renewable energy sectors and found that FD contributed to the growth of renewable energy. He Liu et al. (2019) examined the effect of green FD on the effective investment in renewable energy, considering short-term and long-term bank loans in 141 Chinese enterprises. Their results indicated that green FD in China has a negative impact on bank loans in general, hindering the improvement of effective investment in renewable energy. Yang et al. (2019) surveyed the role of government green fiscal policies in the flow of renewable energy capital, finding that the green credit policy is positively and significantly related to the development of renewable energy enterprises. As carbon tax rates and externalities increase, assets and capital flow towards renewable energy companies. He Zhang et al. (2019) studied the importance of renewable energy investment in the green economy, finding that investment in renewable energy does not have a significant effect on the green economy index. However, improving pollution control costs and industrial structure enhances the development of the green economy. Anton and Nucu (2020) examined the role of FD in renewable energy consumption in EU member states, finding that financial development, including the banking sector, bond market, and capital market, has a positive effect on renewable energy consumption.

2.1.1. Financial Technology and Renewable Energy Technology

The advancement of financial technology (FinTech) plays a pivotal role in accelerating the development of renewable energy technologies by bridging the gap between financial resources and technological innovation. Building on the endogenous growth hypothesis proposed by Romer (1990), which underscores the importance of innovation in driving industrial productivity and renewable energy adoption, FinTech provides novel mechanisms to mobilize and allocate capital more efficiently. Through digital platforms, crowdfunding, blockchain-based green bonds, and peer-to-peer lending, FinTech enhances access to finance for renewable energy projects, particularly those requiring sophisticated technologies such as advanced wind turbines, biomass conversion, or solar innovations. By lowering transaction costs, improving transparency, and diversifying investment opportunities, FinTech reduces barriers to financing green technologies, thereby fostering innovation and accelerating the diffusion of clean energy. Moreover, in economies with higher technological sophistication and economic complexity, FinTech can act as a complementary driver, enabling firms to channel resources into innovative projects that enhance both energy efficiency and environmental sustainability. Nonetheless, similar to broader discussions on technology and economic complexity, the impacts of FinTech may vary across countries and sectors, suggesting the need for further investigation into its asymmetric effects on different types of renewable energy technologies (Dogan et al., 2025).

Recent research has highlighted the growing importance of financial technology (FinTech) as a transformative force in promoting renewable energy and sustainable development. FinTech leverages digital innovations such as blockchain, peer-to-peer lending, crowdfunding, and artificial intelligence to reduce transaction costs, enhance transparency, and broaden access to green finance (Karakosta & Psarras, 2021; Gyimah & Bonzo, 2025). For instance, digital green bonds and blockchain-enabled financing have improved the efficiency and traceability of capital flows toward renewable energy projects, while gamified platforms, like Ant Group's Ant Forest initiative, incentivize low-carbon behaviors and direct investments in environmental projects (Gyimah & Bonzo, 2025; Malamas et al., 2023). These innovations demonstrate that FinTech not only facilitates direct investment in renewable energy but also shapes environmentally conscious behavior among investors and consumers, reinforcing the transition towards a low-carbon economy (Chueca Vergara & Ferruz Agudo, 2021; Gyimah & Bonzo, 2025). Importantly, FinTech can interact with traditional financial development to amplify its effects on RET deployment. By enhancing the capacity of financial systems to mobilize resources, diversify risks, and improve the accessibility of green finance, FinTech can strengthen the relationship between FD and renewable energy development, particularly in contexts where conventional financial markets are mature and well-regulated (Osmani & Ebrahimi, 2025; Gyimah & Bonzo, 2025). Conversely, in developing economies with weak digital infrastructure, limited regulatory frameworks, and low financial literacy, FinTech's moderating effect may be constrained or even weaken the effectiveness of FD (Glemarec et al., 2024). This highlights the need to examine both direct and interactive effects of FinTech alongside FD when assessing determinants of renewable energy deployment.

A thorough review of existing studies reveals a notable gap in comprehensively exploring the relationship between financial development (FD) and the deployment of renewable energy technologies (RET) while considering role of financial technology. Despite the growing recognition of FinTech, existing literature has largely focused on its conceptual role or isolated effects on green finance, with limited empirical evidence on how FinTech interacts with FD to drive renewable energy adoption (David et al., 2022; Javaid et al., 2022). Most studies examine developed economies where digital infrastructure is robust, while the practical challenges and opportunities in developing countries, particularly in Africa and other low-income regions, remain underexplored (Wieczorek, 2018; Mir & Qadri, 2014). Furthermore, prior studies often overlook the differential impacts of financial and technological innovations on specific renewable energy technologies, such as solar, wind, and renewable electricity, which may have varying capital requirements, technological complexities, and risk profiles (Sharma et al., 2021).

Therefore, this study addresses these gaps by investigating how FinTech moderates the relationship between FD and RET deployment across two groups of developed and developing countries. By integrating empirical evidence on digital finance, green bonds, and blockchain-enabled financing mechanisms, the study contributes to a deeper understanding of the conditions under which financial development and technological innovation synergistically promote renewable energy adoption. This approach provides policymakers with insights into tailoring financial and technological interventions according to country-specific infrastructural and institutional capacities, ultimately facilitating a more effective and equitable energy transition.

3. METHODOLOGY

3.1. Empirical model and the data

This study investigates the impact of financial development (FD) on the deployment of renewable energy technologies (RETs), with particular attention to the moderating role of financial technology (FinTech). The analysis distinguishes between developed and developing countries, classified according to the World Bank's country income group indicators. The sample covers the period 2000–2022, allowing for a comprehensive examination of long-term dynamics across diverse economies. The empirical strategy relies on panel data econometric models to capture both the direct effects of FD on RET deployment and the interactive effects of FinTech. By incorporating the interaction term between FD and FinTech, the model evaluates whether FinTech amplifies or dampens the effectiveness of FD in fostering renewable energy technologies, depending on the level of digital and financial infrastructure. The baseline empirical model is specified as follows:

$$\begin{aligned} \ln RET_{it} = \beta_0 + \beta_{1i}\ln FD_{it} + \beta_{2i}\ln FT_{it} + \beta_{3i}\ln GDP_{it} \\ + \beta_{4i}\ln POP_{it} + \beta_{5i}\ln CPI_{it} \\ + \beta_{6i}\ln (FD * FT)_{it} + \varepsilon_{it} \end{aligned} \quad (1)$$

for i = 1.2, … , I and t = 1.2, … , T

In the empirical model, RET_{it} denotes the installed capacity of Renewable Energy Technologies (RET), measured as the annual addition to power generation capacity. This definition is consistent with the approaches adopted by Kim and Park (2016) and Dong (2012).

FD_{it} represents the Financial Development Index, as reported by the World Bank. This index comprehensively evaluates the functioning of financial systems through three key dimensions: (i) financial depth, which reflects the size and liquidity of financial markets; (ii) financial access, which measures the availability of financial services to households and firms; and (iii) financial efficiency, which captures the cost-effectiveness and performance of financial institutions and markets. Given its multidimensional coverage, the index is widely considered one of the most reliable indicators of financial development.

GDP_{it} denotes the real per capita gross domestic product, representing the economic output of each country. This variable is included to assess the impact of the economic level on RET deployment.

POP_{it} represents the total population. Population growth influences renewable energy deployment by shaping energy demand patterns and providing a labor force that may support infrastructure development and electricity generation capacity.

CPI_{it} is the Consumer Price Index, which is employed as a proxy for energy prices. Since fluctuations in energy prices are rapidly transmitted to household expenditure patterns, CPI serves as a reliable indicator of relative price changes affecting energy consumption.

FT_{it} captures the role of financial technology (FinTech), which is a central focus of this study. Following Gyimah & Bonzo (2025) and Nwigwe et al. (2024), three proxies are employed to represent FinTech:

Mobile cellular subscriptions: measured as the number of active postpaid and prepaid subscriptions to public mobile telephone services that provide voice access through cellular networks. This indicator excludes subscriptions via data cards, USB modems, or private networks.

Fixed broadband subscriptions: defined as fixed high-speed Internet connections (≥ 256 kbit/s), including cable modem, DSL, fiber-to-the-home/building, and other wired broadband technologies. It excludes Internet access through mobile cellular networks but includes both residential and organizational subscriptions.

Internet users: defined as the percentage of individuals who have used the Internet from any device and location within the past three months, including computers, mobile phones, digital TVs, and gaming devices.

The use of these three proxies allows the study to capture different dimensions of FinTech penetration and its potential influence on renewable energy deployment, thereby providing a broader perspective that has often been overlooked in the existing literature. To construct a comprehensive FinTech index, these three sub-indicators are aggregated using the Principal Component Analysis (PCA) method, ensuring that the combined measure reflects the overall intensity and diffusion of FinTech adoption across countries.

The interaction term, denoted as FD_{it}* FT_{it}, is constructed to capture the moderating role of financial technology in the relationship between financial development and renewable energy technology (RET) deployment. The rationale for this variable is that while financial development (FD) provides the overall capacity for mobilizing capital and channeling resources, its effectiveness in promoting green investments may depend on the extent of financial technology (FT) penetration. FinTech can strengthen the impact of FD by expanding access to financial services, enhancing efficiency, and facilitating innovative green financing mechanisms. Conversely, in the absence of sufficient digital and technological infrastructure, the influence of FD on RET may be weakened. Therefore, the interaction term allows the model to test whether FinTech amplifies or dampens the effect of financial development on renewable energy technologies, reflecting both complementary and conditional dynamics between the two factors.

Finally, i represents the country, and β_0 captures country-specific fixed effects. All variables are transformed into their natural logarithms prior to estimation in order to account for potential non-linear relationships between the variables and to improve the accuracy of the results, as supported by Khan et al. (2019) and Ali et al. (2018). Table1 displays the introduction and source of the variables.

Table 1. Variable definition

Variables	Variable description	Source of Data
RET	Total installed capacity of renewable energy technologies, measured as annual power generation capacity additions	EIA
FD	Financial Development Index, covering financial depth, access, and efficiency	World Bank (WDI)
GDP	Gross Domestic Product at 2010 constant US dollars	World Bank (WDI)
POP	Total population (in millions)	World Bank (WDI)
CPI	Consumer Price Index, used as a proxy for energy prices	World Bank (WDI)
FD* FT	Interaction term between Financial Development and Financial Technology, designed to capture the moderating role of FinTech in strengthening or weakening the effect of financial development on renewable energy technologies	World Bank (WDI)
FT	Financial Technology Index, constructed from mobile cellular subscriptions, fixed broadband subscriptions, and internet users, aggregated through PCA	World Bank (WDI),

3.2. Estimation approach

This study explores the long-term relationships between the variables by applying cointegration tests and using suitable estimators to analyze these relationships. The choice of regression models depends on the stationarity of the time series processes involved. Conventional OLS estimation methods, such as pooled OLS, fixed effects, and dynamic panel models, often yield inconsistent and biased estimates when the time series are non-stationary and the variables exhibit cointegration (Lin and Chen, 2019). For variables that are integrated of order one, cointegration tests, like those proposed by Kao, Pedroni, and Fisher, are reliable. When evidence of cointegration and long-term relationships is found, estimation is conducted using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS). Both methods are applied in this study, and their results are compared. FMOLS and DOLS have been employed in numerous studies, including those by Merlin and Chen (2021) and Cui et al. (2022), to estimate long-run parameters. In addition, Generalized Method of Moments (GMM) estimation is utilized to validate the findings from FMOLS and DOLS.

The research focuses on a sample of developed and developing countries over the period from 2000 to 2022. Initially, the presence of cointegration or long-term relationships between the variables is assessed using the Kao and Pedroni cointegration tests. Kao (1999) utilized an extended Dickey-Fuller test to investigate cointegration in panel data, assuming homogeneous cointegration vectors across time periods (t = 1, 2..., T) and heterogeneous vectors across cross-sections (i = 1, 2..., N).

Once a long-term relationship between the variables is confirmed, these relationships are estimated using FMOLS and DOLS estimators. The FMOLS method is particularly reliable for small samples and is a non-parametric approach that addresses issues of serial correlation and heteroscedasticity in OLS estimates by applying general corrections such as the Cochrane-Orcutt and Prais-Winsten procedures. The DOLS method, introduced by Stock and Watson (1993), incorporates lags of differenced explanatory variables to correct for endogeneity and serial correlation, yielding robust estimates of the long-term relationships between variables. The application of FMOLS and DOLS ensures the reliability and efficiency of the parameter estimates, offering deeper insights into the interactions between financial development, institutional quality, and the adoption of renewable energy technologies in developing countries. Kao's methodology for the FMOLS approach involves considering the following regression:

$$\mathrm{Y_{it}} = \alpha_i + \beta_i X'_{it} + \varepsilon_{it} \quad \forall_t = 1, \dots, T \quad i = 1, \dots, N \tag{2}$$

$$\hat{\beta}_{OLS} = \left[\sum_{i=1}^{N}\sum_{t=1}^{T}(X_{it} - \bar{X}_\iota)(X_{it} - \bar{X}_\iota)'\right]^{-1}\left[\sum_{i=1}^{N}\sum_{t=1}^{T}(X_{it} - \bar{X}_\iota)(Y_{it} - \bar{Y}_\iota)\right] \tag{3}$$

considering that $\hat{\beta}_{OLS}$ is inappropriate for use in heteroscedastic and inconsistent data, Kao and Chiang (2000) utilized the FMOLS and DOLS estimators in datasets where a long-term relationship exists (Baltagi, 2005). These estimators are more suitable for dealing with heteroscedasticity and inconsistency in the data, providing more reliable and efficient parameter estimates for the long-term relationship between the variables.

$$\hat{\beta}_{FMOLS} = \left[\sum_{i=1}^{N}\sum_{t=1}^{T}(X_{it} - \bar{X}_\iota)(X_{it} - \bar{X}_\iota)'\right]^{-1}\left[\sum_{i=1}^{N}\left(\sum_{t=1}^{T}(X_{it} - \bar{X}_\iota)\,Y_{it}^{+} - T\hat{\Delta}_{\varepsilon u}^{+}\right)\right] \tag{4}$$

The dynamic ordinary least squares (DOLS) method was initially proposed by Stock and Watson (1993) as a modification of the ordinary least squares (OLS) method to estimate the relationship between variables with random trends. This method addresses the endogeneity and heteroscedasticity issues in the OLS method caused by the presence of lagged values and contemporaneous terms. DOLS is suitable for estimating balanced and unbalanced panel data, and the estimated coefficients for the DOLS estimation will be as follows:

$$\hat{\beta}_{DOLS} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\sum_{t=1}^{T} Z_{i.t}Z'_{i.t}\right)^{-1}\left(\sum_{t=1}^{T} Z_{i.t}\tilde{y}_{i.t}\right)\right] \quad (5)$$

3.3. Cross-Sectional Dependency Test

When analysing panel data, it is important to begin by evaluating the stationarity of the variables involved. To determine the most suitable unit root test, recognizing any potential interdependencies among the sections of the panel is crucial. Conventional unit root tests typically assume independence across cross-sections, an assumption that may not hold in panel data analysis, as common factors might influence all members of the panel (Henningsen & Henningsen, 2019). Overlooking cross-sectional dependencies during unit root testing can lead to inaccurate and unreliable results. Consequently, it is vital to perform cross-sectional dependence tests to detect the existence of such dependencies. In this research, the cross-sectional dependence test developed by Pesaran (2004) is applied.

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \sim N(\cdot,1)i,j \quad (6)$$

where T represents the time period; N denotes the sample size; the estimation of the cross-sectional dependence between the errors corresponding to countries i and j is denoted by ρ.

3.4. Unit Root Test

To effectively manage cross-sectional dependencies and ensure the reliability of the estimations, unit root tests are employed to assess the stationarity of the variables. There are two primary categories of unit root tests. The first-generation tests, such as the Levin, Lin, and Chu (LLC) test, the Im, Pesaran, and Shin (IPS) test, and the Maddala and Wu (MW) test, assume that cross-sectional independence exists. On the other hand, second-generation tests, which include the Pesaran (2007) Cross-Sectionally Augmented IPS (CIPS) test and the Smith et al. (2004) test, take cross-sectional dependence into account. In this study, to address cross-sectional dependence, the CIPS test developed by Pesaran (2007) is utilized. Moreover, an adapted version of the Augmented Dickey-Fuller (ADF) test, known as the adjusted ADF test (as per Charfeddine & Kahia, 2019), is also applied to further reduce issues related to cross-sectional dependence.

$$\Delta Y_{it} = \pi_i + \beta_i Y_{i,t-1} + \omega_i \bar{Y}_{t-1} + \varphi_i \Delta\bar{Y}_t + \varepsilon_{it} \quad (7)$$

$$\bar{Y}_t = \left(\frac{1}{N}\right)\sum_{i=1}^{N} Y_{it} \qquad \Delta\bar{Y}_t = \left(\frac{1}{N}\right)\sum_{i=1}^{N}\Delta Y_{it} \quad (8)$$

Pesaran's (2007) unit root test method relies on averaging the adjusted ADF statistics across the different cross-sections. This modified version of the IPS unit root test, as proposed by Pesaran (2007), can be represented as follows:

$$CIPS = \left(\frac{1}{N}\right)\sum_{i=1}^{N} CADF_i \quad (9)$$

The CADF (Cross-sectional Augmented Dickey-Fuller) test calculates the adjusted cross-sectional statistics for the Dickey-Fuller test specific to each cross-section. In this approach, the null hypothesis posits that the variables under investigation exhibit non-stationarity.

3.5. Cointegration Test

To confirm the robustness of the estimation results, it is essential to verify the existence of a long-term relationship among the variables through a cointegration test. Cointegration reflects a stable equilibrium relationship, implying that while individual variables may be nonstationary, their linear combination remains stable over time. In this research, the Westerlund (2007) cointegration test is employed. Unlike the Pedroni (2001) test, which relies on residual-based analysis, the Westerlund test adopts a structural approach and is regarded as providing higher accuracy (Charfeddine & Kahia, 2019). This test utilizes an error correction model (ECM) framework to evaluate the presence of cointegration, where the null hypothesis states that no cointegration exists among the variables.

4. RESULTS AND DISCUSSION

This study primarily investigates the impact of financial development on the deployment of renewable energy technologies (RET), measured by the installed capacity of renewable energy generation technologies. Beyond this central objective, the study also explores the role of financial technology (FinTech), examining both its direct effect and its moderating influence on the relationship between financial development and renewable energy deployment. To ensure the robustness of the empirical findings, several methodological procedures are implemented. First, the Pesaran cross-sectional dependence test is applied to detect potential cross-sectional dependence among the variables. Based on the results of this test, appropriate panel unit root tests are employed to determine the stationarity properties of the series. After establishing the integration order of the variables, panel cointegration tests are conducted to verify the existence of long-run equilibrium relationships among the key variables. Finally, the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimators are utilized to estimate the long-run coefficients and quantify both the direct and interaction effects of financial development and FinTech on renewable energy technology deployment.

4.1. Cross-Sectional Dependence

The results from the analysis of cross-sectional dependence and homogeneity are summarized in Table 2. These findings strongly refute the assumption of cross-sectional independence, indicating potential issues with residual cross-sectional connectivity in the panel data. The presence of cross-sectional dependence suggests that a shock in one country could potentially influence the economies of other member countries.

Table 2. Pesaran (2004) Cross-Section Dependence Test

Variables	developed countries	developing countries
	statistic	statistic
lnRET	58.077	66.402
	(0.00)	(0.00)
lnFD	18.315	61.667
	(0.00)	(0.00)
lnFT	32.317	48.225
	(0.00)	(0.00)
lnGDP	45.664	63.625
	(0.00)	(0.00)
lnPOP	41.38	53.15
	(0.00)	(0.00)
lnCPI	54.242	71.431
	(0.00)	(0.00)
Ln (FT*FD)	18.955	44.187
	(0.00)	(0.00)

As reported in Table 2, the Pesaran (2004) cross-sectional dependence test rejects the null hypothesis of no cross-sectional dependence at a 1% significance level for all variables. This confirms the presence of cross-sectional dependency, indicating that shocks or changes in one country are likely to affect others. Such interconnections highlight the importance of accounting for cross-sectional dependence in the estimation process to ensure robust, unbiased, and reliable empirical results.

4.2. Panel Unit Root Test (Cross-Sectional Augmented IPS (CIPS) Test)

To assess the stationarity of the variables, the study employs the Cross-Sectionally Augmented IPS (CIPS) panel unit root test developed by Pesaran (2007). The CIPS test accounts for potential cross-sectional dependence across countries, offering a more robust evaluation of unit roots in panels with interdependent observations. The results in Table 3 reveal that some variables are stationary at their levels, while others become stationary only after first differencing. Given this mixture of integration orders, it is necessary to perform panel cointegration tests to investigate the existence of long-run relationships among the variables.

Table 3. Pesaran (2007) Panel Unite Root Test

Variables	Developed countries		Developing countries	
	CIPS Statistics	Order of Integration	CIPS Statistics	Order of Integration
lnRET	-3.78***	I(1)	-4.88***	I(1)
lnFD	-4.22***	I(1)	-3.66***	I(1)
lnFT	-3.18***	I(1)	-4.28***	I(1)
lnGDP	3.64***	I(1)	-3.74***	I(1)
lnPOP	-4.46***	I(1)	-3.58***	I(0)
lnCPI	-3.45***	I(1)	-3.41***	I(0)
Ln (FT*FD)	-4.76***	I(1)	-333***	I(0)

4.3. Cointegration Test

Given that some variables are stationary at their level and others are stationary at their first-order difference, it is most appropriate to employ a second-generation cointegration test (Khan et al., 2019). This study utilizes the Westerlund (2007) cointegration test, a robust method particularly suited for panel data characterized by cross-sectional dependence (CD) (Dogan & Seker, 2016). The Westerlund test evaluates the null hypothesis of no cointegration by analyzing the error-correction dynamics both within individual cross-sections (countries) and across the entire panel. It employs a bootstrap procedure to generate a sampling distribution and constructs two group-mean and two panel-mean statistics to assess the existence of a long-term equilibrium relationship among variables while accounting for cross-sectional dependence. This test is particularly effective for panels comprising variables that exhibit a mix of stationary and non-stationary behavior. Results of the Westerlund (2007) panel cointegration test, presented in Table 4, provide strong empirical evidence of a long-run equilibrium relationship between the selected variables and the total installed capacity of Renewable Energy Technologies (RET) in both developed and developing countries. For developed countries, the Gt and Pt statistics are significant at the 10% and 5% levels, respectively, while for developing countries, both Gt and Pt exhibit significance at the 10% and 5% levels. Furthermore, the Ga and Pa statistics, though generally considered less restrictive, show significance at the 1% and 10% levels across both country groups. Collectively, these results strongly reject the null hypothesis of no cointegration across all panels, confirming the existence of a stable long-term relationship among the selected variables.

The significance of the Gt, Pt, and Pa statistics underscores their critical role in capturing enduring relationships among the variables, suggesting that these interactions persist over time and substantially influence renewable energy deployment policies and investment strategies. Consequently, these findings justify the use of long-run estimation techniques such as FMOLS and DOLS, which effectively account for the dynamic interdependencies and long-term effects among the variables. This robust empirical evidence highlights the importance of integrating both financial and technological dimensions in shaping sustainable energy development, particularly across countries that differ in their levels of financial technology advancement and financial market maturity.

Table 4. Panel Westerlund Cointegration Test

Test Statistic	Developed Countries		Developing Countries	
	Value	Z-Value	Value	Z-Value
Gt	-1.703*	4.131	-2.103*	5.221
Ga	0.428	9.387	0.568	8.217
Pt	-2.581**	8.223	-3.551**	7.333
Pa	0.289***	6.472	0.469***	5.372

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

4.4. Estimation Results and Discission

Following the confirmation of a long-term relationship among the variables through the Westerlund cointegration test, the study employs Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) to estimate the long-run coefficients. Both methods are well suited for panel data analysis, effectively addressing potential endogeneity, serial correlation, and cross-sectional dependence, thereby providing consistent and unbiased

Table 5. FMOLS and DOLS Estimation for Developing and Developed Countries

Variable	DOLS Estimation	FMOLS Estimation	Variable	DOLS Estimation	FMOLS Estimation
	Developed Countries	Developed Countries		Developing Countries	Developing Countries
Total Installed Capacity of Renewable energy Technology is Dependent Variable (LnRET)					
lnFD	0.297***	0.708***	lnFD	0.398**	0.094**
	(0.063)	(0.130)		(0.187)	(0.042)
lnFT	0.146**	0.161***	lnFT	0.479**	0.233*
	(0.058)	(0.008)		(0.206)	(0.1293)
lnGDP	0.749*	0.739***	lnGDP	0.889***	0.294***
	(0.379)	(0.011)		(0.155)	(0.039)
lnPOP	0.377	0.696***	lnPOP	0.543***	0.381***
	(1.625)	(0.041)		(0.052)	(0.098)
lnCPI	0.825***	0.782***	lnCPI	0.218	0.686
	(0.026)	(0.172)		(0.216)	(0.764)
Ln (FT*FD)	0.240***	0.497***	Ln (FT*FD)	0.847	0.779
	(0.012)	(0.142)		(0.571)	(0.651)
Constant	-0.811***	-0.713***	Constant	0.296***	0.454***
	(0.011)	(0.001)		(0.034)	(0.029)
R-squared	0.893	0.985	R-squared	0.862	0.859
Wald	499***	742***	Wald	217***	417***

estimates of long-term relationships (Phillips & Hansen, 1990; Kao & Chiang, 2000).

The standard error (SE)is reported in parenthesis. *** and ** and * denote the significance at 1%, 5%, and 10% level, respectively.

The FMOLS and DOLS estimations (Table 5) reveal that financial development (FD) exerts a positive and statistically significant effect on the deployment of renewable energy technologies (RET) in both developed and developing countries. The positive coefficients indicate that improvements in the financial development index contribute to an expansion in the installed capacity of RET, underscoring the critical role of financial systems in supporting clean energy transitions. These findings are consistent with the broader empirical literature, including studies by Paramati et al. (2016), Kim & Park (2016, 2018), Dogan & Seker (2016), Anton & Nucu (2020), and Khan et al. (2019), which also document a strong link between financial development and renewable energy adoption. In the case of developed countries, the results highlight the importance of well-functioning financial systems in mobilizing capital for renewable energy projects. Advanced financial markets are typically characterized by deeper capital bases, efficient intermediation, and greater access to diverse financing instruments, all of which facilitate investment in renewable energy infrastructure. For developing countries, financial development similarly shows a positive and significant relationship with RET deployment. However, the extent to which financial systems can channel resources into clean energy projects is often constrained by structural and institutional challenges. These include limited access to international capital markets, underdeveloped financial institutions, higher investment risks, and macroeconomic instabilities such as persistent trade deficits and low economic growth. Such barriers hinder the effectiveness of financial development in accelerating renewable energy deployment, a pattern also emphasized in Sadorsky (2010).

The empirical results also reveal that financial technology (FT) exerts a positive and statistically significant impact on the deployment of renewable energy technologies (RET) in both developed and developing countries. This finding highlights the pivotal role of FT in facilitating access to finance, reducing transaction costs, and enhancing the efficiency and transparency of financial systems. By promoting innovative financing solutions, such as digital lending platforms, crowdfunding mechanisms, and blockchain-based green finance instruments, FT lowers barriers to investment and creates new channels for mobilizing capital toward renewable energy projects. These results are consistent with the emerging literature on the transformative potential of financial innovation in accelerating the transition to clean energy (e.g., Chen & Volz, 2021; Zhan & Santos-Paulino, 2021). Beyond its direct effect, FT also plays an indirect role by strengthening the relationship between financial development (FD) and renewable energy deployment. The interaction term (FD×FT) is positive and significant for developed countries, suggesting that financial technology enhances the effectiveness of mature financial systems in channeling resources toward renewable energy investments. In these economies, advanced digital infrastructure, supportive regulatory frameworks, and high levels of financial inclusion allow FT to act as a catalyst, amplifying the impact of FD on RET deployment. By contrast, in developing countries, although the coefficient of the interaction term is positive, it remains statistically insignificant. This implies that while FT has the potential to support renewable energy deployment, its ability to enhance the role of FD is limited in contexts where financial institutions are underdeveloped, digital infrastructure is weak, and regulatory environments are fragmented. This aligns with the broader literature emphasizing that the benefits of FT materialize most strongly in markets with robust institutional frameworks and well-established financial systems. Overall, these findings underscore that FT is not only a direct driver of renewable energy deployment but also a critical enabler of the effectiveness of financial development, particularly in advanced economies. For developing countries, realizing this potential may require parallel reforms in financial markets, digital infrastructure, and governance frameworks to unlock the synergistic benefits of FT and FD for sustainable energy transitions. This result can be attributed to the institutional and structural constraints commonly present in developing economies. Regulatory immaturity and governance deficiencies have limited the capacity of FinTech to effectively mobilize financial resources for renewable energy projects (Xu et al., 2023). For example, interventions by central banks in West African states have led to the freezing of digital financial assets due to insufficient licensing and oversight of FinTech firms (Gyimah & Bonzo, 2025). Moreover, additional challenges such as political and economic instability, inadequate infrastructure, and weak environmental regulations further impede the ability of FinTech to strengthen the impact of financial development on renewable energy deployment (Gyimah et al., 2023). These findings highlight that in developing countries, the potential of FinTech to augment financial development in promoting renewable energy is constrained by contextual and institutional barriers, emphasizing the critical need for regulatory enhancement and infrastructure development to fully harness FinTech for the clean energy transition.

The estimation results indicate that real GDP per capita has a positive and statistically significant effect on the deployment of renewable energy technologies (RET) in both developed and developing countries. This finding highlights the central role of economic growth in fostering clean energy transitions. As economies expand, rising income levels increase energy demand and create the financial capacity to invest in renewable technologies, thereby reducing reliance on fossil fuels and mitigating environmental externalities. In developed countries, higher per capita income facilitates renewable energy adoption through stronger institutional frameworks, advanced technologies, and greater capital availability. In developing countries, although structural constraints remain, economic growth still enhances the fiscal and investment capacity needed to expand renewable energy capacity. These results are consistent with prior studies (Kim & Park (2016, 2018); Anton & Nucu, 2020), which emphasize that sustained economic growth is a key driver of renewable energy deployment across different stages of development.

The results show that population growth exerts a positive and statistically significant effect on the deployment of renewable energy technologies (RET) in both developed and developing countries. This outcome is consistent with the view that larger populations increase energy demand and expand the labor force available for the renewable energy sector, thereby stimulating investment and adoption of clean energy technologies. In developed countries, population growth reinforces the transition to renewable energy by enhancing skilled labor availability and creating greater societal demand for sustainable energy solutions. In developing countries, although structural challenges such as unemployment and income inequality may temper the benefits, demographic expansion still contributes positively to renewable energy deployment by widening the market base and facilitating industrial development. These findings align with economic growth theories, such as the Solow-Swan model, which emphasize the role of demographic dynamics in shaping energy demand, while also underscoring that population growth must be complemented by capital accumulation and technological progress to maximize its positive effects.

The results indicate that the Consumer Price Index (CPI), employed as a proxy for energy prices, exerts a positive and significant effect on the deployment of renewable energy technologies (RET) in developed countries, while its impact in developing countries, although positive, is statistically insignificant. This finding suggests that rising energy prices enhance the competitiveness of renewable energy relative to fossil fuels, thereby incentivizing investment in clean energy technologies. Such outcomes are consistent with prior studies, including Anton & Nucu (2020), which emphasize the role of higher energy prices in accelerating renewable energy adoption. The limited significance of CPI in developing countries can be attributed to structural factors, particularly the widespread subsidization of fossil fuel prices in regions such as the Middle East and North Africa. In these economies, artificially low energy prices weaken the relative cost advantage of renewables and reduce the incentive for economic agents to shift toward cleaner technologies. This highlights the importance of energy pricing reforms, as emphasized in the literature on sustainable energy transitions, to ensure that price signals effectively encourage the deployment of renewable energy.

5. CONCLUSIONS

This study examined the impact of financial development on the deployment of renewable energy technologies (RET) in both developed and developing countries, with particular emphasis on the direct role of financial technology (FinTech) and its moderating effect through interaction with financial development. By employing advanced econometric techniques, including FMOLS and DOLS, the findings provide robust evidence on the determinants of clean energy deployment across heterogeneous economic contexts.

The results first confirm that financial development exerts a positive and statistically significant effect on RET in both developed and developing countries. This underscores the critical role of financial markets in mobilizing capital for renewable energy projects. However, while developed countries benefit from deep and efficient financial systems that can effectively channel resources into clean energy, developing countries remain constrained by institutional weaknesses, limited access to international finance, and macroeconomic instability. These findings highlight the importance of strengthening financial markets and reducing structural barriers in developing economies to enhance their renewable energy transition. The study further demonstrates that FinTech directly fosters RET deployment by improving access to finance, reducing transaction costs, and offering innovative financing models such as digital lending, crowdfunding, and blockchain-based green instruments. Importantly, FinTech also amplifies the positive effect of financial development on RET deployment in developed countries, where robust digital infrastructure and regulatory frameworks create an enabling environment. In contrast, in developing countries, the moderating role of FinTech is insignificant, reflecting challenges such as weak governance, regulatory gaps, inadequate infrastructure, and limited financial inclusion. These insights suggest that FinTech can be a powerful enabler of green energy transitions, but its effectiveness is highly context dependent and contingent on institutional maturity.

The results also indicate that real GDP per capita and population growth significantly contribute to renewable energy deployment across both country groups. Economic growth expands the fiscal space and investment capacity for clean energy, while population growth stimulates energy demand and creates labor market dynamics favorable to renewable energy industries. Furthermore, energy prices, proxied by the CPI, positively influence RET in developed economies, reflecting the competitiveness of renewables relative to fossil fuels. However, in developing countries, this effect remains muted due to widespread fossil fuel subsidies that distort price signals and weaken incentives for clean energy adoption.

From a policy perspective, several implications arise. For developed countries, maintaining well-functioning financial markets, investing in digital infrastructure, and supporting FinTech innovation can further accelerate the green energy transition. These economies should also continue leveraging advanced regulatory frameworks to integrate digital financial tools with renewable energy financing. For developing countries, policies should prioritize strengthening institutional quality, reforming regulatory environments, and investing in digital and financial infrastructure to unlock the potential of FinTech as a complement to financial development. In addition, energy pricing reforms, coupled with targeted subsidies for renewable projects, can improve the competitiveness of clean energy.

Overall, the study demonstrates that both financial development and FinTech are indispensable drivers of renewable energy deployment. However, their effectiveness is shaped by broader economic and institutional conditions. Policymakers in developing countries must adopt a holistic approach, combining financial sector reforms, regulatory strengthening, and infrastructure investment, to ensure that FinTech can fully complement financial development in promoting renewable energy technologies. Meanwhile, developed countries should continue to integrate digital financial innovations into green finance strategies and assume leadership roles in global renewable energy cooperation. These coordinated efforts are essential to achieving sustainable energy transitions and meeting international climate and development goals.

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