



## A SPATIAL-QUANTILE-FRONTIER ANALYSIS OF FINTECH-ENERGY TRANSITION: SPILLOVERS AND DISTRIBUTIONAL EFFECTS OF FINTECH ON RENEWABLE ENERGY INVESTMENT IN DEVELOPING COUNTRIES

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### **Abstract**

*Amid growing global urgency for climate action, innovative financial mechanisms are critical for advancing renewable energy transitions in developing economies. This study investigates the role of financial technology (fintech), with a focus on foreign portfolio investment (FPI), in influencing renewable energy investment (REINV) across 54 developing countries in Africa, Asia, and Latin America from 2010 to 2023. Employing a multi-method empirical approach, comprising Spatial Durbin Models (SDM), Quantile Regression (QR), Stochastic Frontier Analysis (SFA), and Spatial Quantile Regression (SQR), the research captures spatial dependencies, distributional heterogeneity, and efficiency dynamics. The SDM results indicate that FPI significantly increases REINV both directly (1.112) and indirectly through spillover effects (0.445), supported by significant spatial autocorrelation (0.334). Economic development and institutional quality also play key roles, with GDP per capita and institutional quality exerting positive and significant direct effects. Quantile regression reveals that FPI has a stronger influence at higher quantiles of REINV, with coefficients rising from 0.745 to 1.445, highlighting distributional inequality in fintech impact. SFA results show that FPI also enhances technical efficiency (0.912), though diminishing marginal returns are evident. Greater financial depth and electricity access reduce inefficiency, while inflation worsens it. Spatial quantile regression further confirms that regional spillovers are more pronounced among high-investment countries, underscoring the role of spatial dynamics in clean energy financing. The findings suggest that fintech can be a catalyst for renewable energy growth, especially in countries with higher institutional and financial capacity. Policy recommendations include strengthening digital infrastructure, enhancing regulatory coordination, and ensuring macroeconomic stability to fully leverage fintech's potential. Future research should explore emerging fintech tools such as decentralized finance and blockchain-based green bonds.*

**Keywords:** Fintech, Renewable Energy Investment, Spatial Econometrics, Quantile Regression, Stochastic Frontier, Developing Countries

**JEL Codes:** G23, Q42, C23, O16

### **INTRODUCTION**

The transition to renewable energy is central to achieving global climate goals and the UN Sustainable Development Goals (SDGs), especially in developing regions where energy poverty remains prevalent. Financing such a transition is constrained by high upfront costs and limited access to capital (IEA, 2024). The proliferation of financial technology ("fintech") offers transformative opportunities to mobilize green finance through digital platforms, mobile lending, and cross-border investment channels. Early studies have suggested that fintech can both diversify financial instruments and reduce transaction costs, thereby alleviating investment barriers to renewable energy (Aghion et al., 2023; IMF, 2024).

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The transition to renewable energy is central to achieving global climate goals and the UN Sustainable Development Goals (SDGs), especially in developing regions where energy poverty remains prevalent. Despite its importance, many developing countries face persistent barriers to scaling renewable energy investments due to high capital intensity, policy uncertainty, and underdeveloped financial ecosystems. Financing such a transition is constrained by high upfront costs and limited access to capital (IEA, 2024).

This challenge underscores a critical problem: how can developing countries overcome financial bottlenecks to accelerate renewable energy adoption? In this context, the proliferation of financial technology (“fintech”) offers transformative opportunities to mobilize green finance through digital platforms, mobile lending, and cross-border investment channels. Early studies have suggested that fintech can both diversify financial instruments and reduce transaction costs, thereby alleviating investment barriers to renewable energy (Aghion et al., 2023; IMF, 2024).

However, empirical evidence on the extent and nature of fintech’s influence on renewable energy investment, particularly in developing countries, remains limited. Most prior research has focused either on green credit and climate finance in developed economies, often using fixed-effects models that overlook nonlinear and spatial dynamics (Bai & Lin, 2023; IMF, 2024). This narrow focus has left important questions unanswered: Do fintech tools exhibit varying levels of effectiveness across investment levels? Can fintech spillovers extend beyond national borders in shaping renewable investment patterns? Are these effects conditional on broader institutional and economic factors?

Moreover, the theoretical and empirical linkage between fintech-related variables (such as foreign portfolio investment and digital financial inclusion) and the dependent variable, being renewable energy investment, requires deeper exploration. Fintech can theoretically enhance renewable energy investment by lowering information asymmetries, expanding access to capital, and increasing the efficiency of financial intermediation. However, these relationships are likely to be heterogeneous across countries and influenced by factors such as digital infrastructure, institutional quality, and regional interconnectedness.

Quantile- and regime-based models have grown in prominence, particularly in capturing nonlinearities in fintech–green finance relationships. Turner & Nguyen (2022) applied threshold regressions in Southeast Asia and found that fintech’s positive impact on solar investment materializes only beyond certain GDP per capita and digital literacy levels. Ibrahim et al. (2024) demonstrated via panel quantiles that institutional quality acts as a binding constraint at lower tail distributions, a finding consistent with the quantile slope divergence and Chow test results, reinforcing policy relevance. However, these approaches do not adequately capture spatial spillovers or distributional heterogeneity, which are key to understanding investment patterns across countries at different economic levels.

To address these gaps, this study investigates the influence of fintech, proxied by foreign portfolio investment and digital finance inclusion, on renewable energy investment across 54 developing countries from 2010 to 2023. We employ a suite of advanced econometric methods: Spatial Durbin Models to account for geographic interdependence; quantile regression to explore heterogeneous

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effects across the RE investment distribution; and stochastic frontier analysis to measure technical efficiency.

This multi-method approach provides several distinct advantages. First, it captures both the direct and indirect spatial channels through which fintech influences renewable investments. Second, it reveals important nonlinearities and threshold effects that inform targeted policy interventions. Third, it quantifies the efficiency of fintech's conversion into actual investments, highlighting potential areas for improvement. Together, these methodological choices allow us to provide a nuanced, context-aware understanding of the fintech-renewables nexus in developing economies (He et al., 2023).

The preliminary results from spatial modeling reveal significant direct and indirect effects of fintech on renewable energy investment, suggesting that digital financial integration fosters cross-border spillovers. Quantile regression highlights greater fintech efficacy at higher quantiles of RE investments, indicating threshold effects in financial absorption capacity. Furthermore, stochastic frontier results show that fintech adoption enhances the technical efficiency of investments, especially in economies with better institutional quality and digital infrastructure. These findings are consistent with the dynamic spatial interaction observed in urban carbon efficiency studies using city-level fintech metrics (Liu et al., 2024).

The practical implications are multifold. They suggest that developing-country policymakers should not only promote fintech adoption but also coordinate regionally and invest in infrastructure upgrades to maximize spillover benefits. Policies should emphasize cross-border regulatory alignment, digital inclusivity, and macroeconomic stability. Such recommendations build on the emerging consensus that fintech platforms, when combined with sound governance, can significantly lower green capital barriers (Bai & Lin, 2023; IMF, 2024).

The remainder of this paper is organized as follows: Section 2 reviews relevant literature on fintech-enabled green financing. Section 3 describes the dataset, variables, and econometric techniques. Section 4 presents the empirical findings and discusses the policy implications. Finally, Section 5 concludes, addressing limitations and future research avenues.

## LITERATURE REVIEW

### *Conceptual Clarification*

The convergence of financial technology (fintech) and renewable energy investment represents a transformative nexus in global development discourse, especially in the Global South. In particular, the introduction of mobile money, digital lending, crowdfunding, blockchain, and AI-driven analytics has significantly expanded financial inclusion, enabling broader access to clean energy technologies. These fintech tools reduce traditional financing barriers, such as high transaction costs, limited collateral, and geographic inaccessibility, by offering more flexible, scalable, and inclusive mechanisms for energy investment.

In Sub-Saharan Africa, this convergence is most visible in the proliferation of pay-as-you-go (PAYG) solar systems. Enabled by mobile payments, these systems serve as both energy access solutions and financial instruments. Users can access solar home systems without upfront capital, using mobile payments as ongoing collateral, a model shown to facilitate not just energy adoption

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but also household financial resilience and digital inclusion. This fintech-energy synergy allows previously excluded populations to participate in green markets, with mobile finance acting as both an enabler and amplifier of clean energy access.

Beyond household-level adoption, digital credit platforms and crowdfunding mechanisms are increasingly supporting energy entrepreneurs and startups. By bypassing traditional banking institutions, these digital tools democratize capital mobilization, especially in contexts where risk perceptions or underdeveloped financial sectors typically restrict access to funding for renewable projects. Importantly, the effectiveness of such mechanisms varies widely, depending on institutional quality, governance, and macroeconomic conditions, highlighting a need to embed fintech initiatives within broader green growth strategies.

At the frontier of innovation, technologies such as blockchain-enabled peer-to-peer (P2P) energy trading, AI-backed analytics, and big data-driven ESG finance are creating new pathways for efficient and decentralized energy systems. Though still in their early stages, these emerging modalities illustrate fintech's expanding role in not only financing but also governing, distributing, and optimizing renewable energy systems. In essence, fintech functions as a multidimensional enabler: it mobilizes capital, increases the technical and allocative efficiency of green investments, and promotes the spatial diffusion of renewable energy technologies. However, its full potential is only realized when coupled with supportive policy frameworks, stable regulatory environments, and strong digital infrastructure.

### *Theoretical Review*

Several theoretical frameworks help elucidate the mechanisms and outcomes observed in the relationship between fintech and renewable energy investment, particularly within emerging and developing markets. First, financial intermediation theory provides a foundation for understanding how fintech reduces transaction costs and information asymmetries. Mobile money platforms, digital credit systems, and crowdfunding operate as new-age intermediaries that expand access to financial services and investment capital. For instance, digital lending has been shown to effectively allocate funds to energy startups, especially in middle to upper investment quantiles where absorptive capacities are higher (Ibrahim et al., 2024; Le & Nguyen, 2022). These findings align with the intermediation logic that when financing channels become more inclusive and efficient, investment in long-term infrastructure, such as solar and wind, rises. Building on this, diffusion of innovation theory (Rogers, 2003) can be applied to explain the uptake of fintech-enabled energy solutions. PAYG solar systems, which depend on mobile payments, exemplify how innovations spread through a population once financial and technological thresholds are met. The rise in solar adoption in Ghana, Kenya, and Bangladesh following mobile money penetration supports this diffusion framework, as does the role of fintech in lowering the upfront costs and behavioral risks associated with adopting new energy technologies.

Furthermore, the institutional theory of development underscores the role of governance, regulatory stability, and infrastructure in mediating fintech's impact. Empirical studies reveal that fintech's influence on renewable energy investment is significantly amplified in countries with stronger governance (Bai et al., 2024; Halkos & Polemis, 2023). This supports the theoretical claim that institutional environments shape the efficacy of technological interventions. Fintech

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interventions thrive in regulatory contexts that ensure legal stability, data protection, and transparent financial oversight, preconditions that facilitate trust and risk reduction in both domestic and international investment.

In macroeconomic terms, investment and growth theories are also relevant. Panel studies using System-GMM and stochastic frontier approaches (Adegbite et al., 2023; Bashir et al., 2022) have shown that fintech penetration enhances the efficiency and volume of renewable energy investment. These findings align with endogenous growth models that view technological and financial innovation as central to capital formation and productivity improvements. The spatial econometric findings (Sun et al., 2021; Omri et al., 2023), which demonstrate cross-border spillover effects, further resonate with new trade and capital mobility theories that emphasize regional interconnectedness and market integration.

Another emerging theoretical angle is the resource-based view (RBV) and dynamic capabilities framework, especially relevant to fintech firms and energy startups. These perspectives emphasize that firms possessing unique resources, such as proprietary digital platforms, data analytics capabilities, or blockchain protocols, can gain competitive advantage and scale rapidly. Studies documenting how blockchain improves energy transaction efficiency (Li, Boateng, & Asante, 2023) and how ESG analytics enhance investment allocation (Faruq & Chowdhury, 2025) validate the role of digital capabilities as strategic assets in the green finance ecosystem.

Finally, behavioral finance and inclusive finance theories are crucial to understanding fintech's developmental and equity impacts. These frameworks help explain how fintech tools can change user behavior, such as encouraging savings, reducing perceived risks, and supporting energy-related investments among underserved groups. The ability of fintech to reach women, rural households, and marginalized entrepreneurs (as shown in earlier studies such as Bhattacharya et al., 2020) demonstrates that beyond economic efficiency, fintech also generates social returns by broadening participation in energy markets.

In sum, the theoretical landscape surrounding fintech and renewable energy investment is both multi-layered and evolving. While foundational theories from finance, economics, and development continue to offer explanatory power, new conceptual tools are emerging to capture the complexity introduced by digital innovation, data governance, and decentralized energy systems. As fintech continues to evolve, so too will the theoretical frameworks needed to analyze its role in facilitating a just and sustainable energy transition.

### *Empirical Review*

The introduction of mobile money and fintech in Sub-Saharan Africa has been repeatedly linked to accelerated deployment of off-grid solar systems, often financed via pay-as-you-go (PAYG) schemes that use mobile payments as collateral instruments (Alstone et al., 2015; Oseni & Pollitt, 2021; Fanta & Mutsonziwa, 2024). These models not only enhance access to clean energy but also demonstrate the multifaceted returns of financial inclusion through mobile-based green investments (Chukwuma & Mensah, 2020; Bhattacharya et al., 2020). Generally, evidence from empirical converges on three key insights: (1) fintech enhances renewable energy investment through capital mobilization, increased technical efficiency, and spatial diffusion; (2) these effects are heterogeneous – stronger in more developed institutional, economic, and infrastructural

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contexts; and (3) digital finance should be embedded within broader green growth strategies to unlock its full potential.

Empirical work on digital lending platforms and crowdfunding has revealed their growing role in financing renewable energy startups. In Southeast Asia, Ibrahim et al. (2024) and Le & Nguyen (2022) used quantile regression to show digital credit effectiveness rises in mid-to-upper quantiles of energy investment, reflecting heterogeneous absorptive capacities. Complementing mobile finance, this research underscores the dual financial and developmental returns of digital lending in emerging markets. Studies from Ghana, Kenya, and beyond show that mobile money adoption correlates with higher uptake of domestic solar solutions, supporting both rural electrification and broader livelihoods (PEG Africa; M-Kopa; Banerjee & Duflo, 2017).

Numerous panel studies (Adu-Gyamfi & Boateng, 2020; Adegbite et al., 2023; Raimi et al., 2023) have leveraged fixed-effects and GMM approaches to empirically demonstrate that fintech penetration boosts renewable energy investment across Africa, Southeast Asia, and beyond. Recent spatial econometric applications (Sun et al., 2021; Omri et al., 2023) further reveal that fintech's influence is not confined nationally but spreads through regional networks, producing measurable direct and spillover effects.

Beyond spatial dynamics, research on institutional synergy finds that fintech exerts stronger renewable investment effects in high-quality governance environments (Bai et al., 2024; Halkos & Polemis, 2023). These results show digital financial inclusion amplifies green outcomes, but only within robust regulatory, macroeconomic, and infrastructure conditions. Similarly, inflation and financial depth have been identified as critical enablers in stochastic frontier models (Bashir et al., 2022; Wang & Zhao, 2023).

Cross-regional case studies, such as those in China (Zhang & Zhang, 2022), India (Kumar et al., 2023), and Latin America (Adu, Ofori, & Donkor, 2023), validate these findings in diverse socioeconomic contexts. For instance, China's fintech-led green investment has displayed strong threshold effects, while India and Brazil exhibit nonlinear responses tied to regional development levels, highlighting the importance of quantile and regime-switch models.

Recent innovations like blockchain-enabled peer-to-peer renewable energy trading (Li, Boateng, & Asante, 2023), AI-backed energy analytics (Hua et al., 2022), and big-data-driven ESG finance (Faruq & Chowdhury, 2025) are emerging as promising yet under-researched fintech tools. These advanced digital models offer the potential to both deepen and broaden the green fintech ecosystem, though empirically their adoption remains nascent.

Some studies have increasingly focused on the interplay between fintech and institutional quality in shaping green finance outcomes. Bai et al. (2024) found that governance strength amplifies the effect of fintech on renewable energy investment, concluding that "regulatory transparency and legal stability are essential for fintech-enabled green transitions" based on a panel analysis of 28 emerging economies. Mukherjee and Dutta (2020) demonstrated that alternative credit scoring, leveraging mobile data, significantly increased solar asset financing in Bangladesh, reinforcing the importance of data-driven governance as a fintech complement.

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Global cross-country panel regressions, such as Zhang and Khan (2021) in Sub-Saharan Africa and Zhou et al. (2021) across developing markets, consistently show robust associations between fintech penetration indicators (e.g., mobile money accounts, digital credit platforms) and renewable energy consumption/investment. Such studies often adopt System-GMM estimators, accounting for endogeneity and confirming long-term effect, echoing the threshold and frontier results, which reveal a combination of scale adjustments and efficiency gains.

Other regional case studies have enriched the global narrative. Ghosh and Vinod (2021) used firm-level data in India to show that digital financial services reduced investment risk premiums in small-scale solar firms. Adu et al. (2023) demonstrated that cross-border fintech investments, especially green bonds and equity from foreign investors, facilitated solar and wind investment growth, mirroring global spillover themes in Latin America. Emerging fintech modalities, such as blockchain, AI, and peer-to-peer platforms, are being empirically tested. Li, Boateng & Asante (2023) documented blockchain-enabled P2P energy trading in Ghana, noting increased investor confidence and reduction in transaction costs. Faruq & Chowdhury (2025) provided early-stage empirical evidence on big-data-driven ESG screening improving allocation efficiency, showing how fintech's analytical capabilities can inform green investment decisions.

### *Theoretical Framework*

The theoretical foundation of this study, based on the Financial Development Theory, the Technology Acceptance Model (TAM), and the Neoclassical Investment Theory, followed that, in developing countries, fintech acts as a transformative agent providing decentralized, inclusive, and digital financial services that extend credit, mobilize savings, and reduce transaction costs.

The basic investment function following this logic is given as:

$$I_t = \alpha + \beta_1 FPI_t + \beta_2 X_t + \epsilon_t \quad (1)$$

Where  $I_t$  is renewable energy investment,  $FPI_t$  is foreign portfolio investment as a fintech, and  $X_t$  is a vector of controls (GDP per capita, institutional quality). This model shows a partial adjustment model capturing short-run dynamics, with  $\beta_1 > 0$  under financial liberalization.

TAM supports the behavioral mechanisms through which digital financial technologies are adopted by firms and consumers. The model emphasizes perceived usefulness ( $PU$ ) and perceived ease of use ( $PEOU$ ) as key determinants of fintech adoption (Davis, 1989; Venkatesh & Davis, 2000). Greater adoption facilitates payment flows, digital credit scoring, and crowdfunding for decentralized renewable systems. Mathematically, fintech adoption ( $FA$ ) as a function of these beliefs can be described as:

$$FA_i = \gamma_0 + \gamma_1 PU_i + \gamma_2 PEOU_i + v_i \quad (2)$$

This behavioral foundation links with the economic model via  $FPI$ , as fintech penetration enhances the attractiveness and accessibility of investment in clean technologies.

The spatial structure of renewable energy investment is explained using a Spatial Durbin Model (SDM), acknowledging that economic activities and investments in one country are influenced by those in nearby economies (Elhorst, 2014). In this regard, the inclusion of spatial lags of the dependent and independent variables captures diffusion effects such as cross-border technology spillovers and capital flows. The formal expression of the SDM used in the empirical model is:

$$REINV = \rho WREINV + X\beta + WX\theta + \mu + \epsilon \quad (3)$$

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Where  $REINV$  is the renewable energy investment vector,  $W$  is a spatial weights matrix (based on inverse distance),  $\rho$  captures spatial dependence, and  $WX\theta$  captures spillovers from independent variables.

The stochastic frontier model draws from the production function literature, particularly the translog specification, to model technical inefficiency in renewable energy investments. Assuming that the frontier investment level is conditioned on input variables and that actual investment deviates due to inefficiency, the model is represented as:

$$\ln(REINV_i) = \alpha_0 + \alpha_1 \ln(FPI_i) + \alpha_2 \ln(GDPpc_i) + \alpha_3 \ln(IQ_i) + \frac{1}{2} \alpha_4 (\ln(FPI_i))^2 + \alpha_5 \ln(FPI_i) \ln(GDPpc_i) + v_i - u_i \quad (4)$$

Where  $v_i$  is the random error and  $u_i \geq 0$  is the inefficiency term, assumed to follow a truncated normal distribution. This allows us to examine how far countries deviate from the optimal renewable energy investment frontier given their fintech capacity and economic fundamentals.

## METHODOLOGY

The empirical analysis in this study focuses on a diverse set of developing countries across three major regions - including Sub-Saharan Africa (SSA), Asia, and Latin America and the Caribbean, selected based on data availability and relevance to fintech adoption and renewable energy investment dynamics. In SSA, countries such as Nigeria, Kenya, Ghana, Ethiopia, Tanzania, Uganda, Rwanda, Senegal, Zambia, and South Africa were included due to their rapidly growing fintech ecosystems and increasing renewable energy demands. These nations exhibit varying levels of mobile money penetration, foreign portfolio investment inflows, and renewable infrastructure development, thus suitable for spatial and efficiency analysis. In Asia, the study includes India, Bangladesh, Pakistan, Vietnam, Indonesia, the Philippines, Sri Lanka, Nepal, Cambodia, and Myanmar, which represent a broad spectrum of emerging economies with expanding fintech sectors and significant government commitments to sustainable energy transitions. They present heterogeneous institutional qualities and income levels, allowing for meaningful quantile and spatial regression analysis. In Latin America and Caribbean region is represented by countries such as Brazil, Mexico, Colombia, Peru, Bolivia, Ecuador, Guatemala, Honduras, El Salvador, and the Dominican Republic. These economies offer valuable insights due to their evolving digital finance environments and policy-driven renewable energy initiatives, especially in solar and wind technologies.

This study employs an integrated econometric framework to analyze the relationship between fintech development and renewable energy investments across developing economies. The methodological approach combines advanced spatial econometrics, quantile regression techniques, and stochastic frontier analysis to provide a comprehensive examination of both the direct and spillover effects while accounting for regional heterogeneity and efficiency considerations. This mixed-methods design aligns with recent approaches in spatial-financial research highlighting how fintech can affect environmental outcomes both directly and through systemic contagion (He et al., 2023).

The foundation of the analysis rests on a spatial Durbin model (SDM) specification, which captures the complex interdependencies between neighboring countries' fintech ecosystems and renewable investment patterns. This approach allows us to simultaneously estimate: (1) the direct

effects of domestic fintech penetration, (2) the indirect spillover effects from geographically proximate markets, and (3) the spatial autocorrelation in investment behaviors. We construct an inverse-distance spatial weights matrix with a 50-kilometer threshold, following established practices in regional energy studies, which appropriately reflects the economic gravity between neighboring developing economies. The SDM specification incorporates the endogenous spatial effects through the spatially lagged dependent variable ( $W \times REINV$ ); exogenous spatial effects via spatially lagged fintech penetration ( $W \times FPI$ ) and the spatial error correlation to control for unobserved spatial dependence. The full SDM specification is:

$$REINV_{it} = \rho WREINV_{it} + \beta_1 FPI_{it} + \beta_2 WFPI_{it} + \sum_k \delta_k X_{kit} + \mu_i + \epsilon_{it} \quad (5)$$

Where  $W$  is the inverse-distance spatial weights matrix (50km threshold), following best practices in regional energy studies (LeSage & Pace, 2009). The model decomposes total effects into direct effects, capturing the impact of local fintech development; indirect effects, i.e., spillovers from neighboring countries and total effects, combining local and spatial impacts.

Building upon the spatial analysis, the paper implement a quantile regression framework to uncover the heterogeneous impacts of fintech across different segments of renewable investment distribution. This methodological choice is particularly salient given the finding that fintech's effectiveness varies substantially between early-stage and mature renewable energy markets. The quantile approach reveals important nonlinearities that would be obscured by conventional mean-regression techniques. The model estimated is:

$$Q_{REINV}(\tau|X) = \beta_0(\tau) + \beta_1(\tau)FPI_{it} + \sum_k \delta_k(\tau)X_{kit} + \mu_i(\tau) \quad (6)$$

This approach captures the "snowball effect" where fintech's marginal utility increases with renewable market maturity (Koenker, 2005).

Combining both methods, the spatial quantile regression estimates:

$$Q_{REINV}(\tau|X) = \rho(\tau)WREINV_{it} + \beta_1(\tau)FPI_{it} + \beta_2(\tau)WFPI_{it} + \sum_k \delta_k(\tau)X_{kit} + \epsilon_{it}(\tau) \quad (7)$$

To assess the efficiency of fintech's translation into actual renewable investments, we employ stochastic frontier analysis (SFA) with a translog production function specification. This methodology enables us to distinguish between: (1) the maximum potential investment level achievable given existing fintech infrastructure (the frontier), and (2) the systematic inefficiencies that prevent countries from reaching this potential. The inefficiency model incorporates key institutional and macroeconomic factors that may facilitate or hinder this conversion process. The translog production frontier models technical efficiency:

$$\ln(REINV_{it}) = \beta_0 + \beta_1 \ln(FPI_{it}) + \beta_2 \ln(GDPpc_{it}) + \frac{1}{2} \beta_3 [\ln(FPI_{it})]^2 + \beta_4 \ln(FPI_{it}) \times \ln(GDPpc_{it}) + v_{it} - u_{it} \quad (8)$$

Where:  $v_{it} \sim N(0, \sigma_v^2)$  represents random noise;  $u_{it} \sim N^+(\mu, \sigma_u^2)$  captures inefficiency and  $\gamma = \sigma_u^2 / (\sigma_u^2 + \sigma_v^2)$ .

The econometric implementation addresses several technical. For the spatial models, we use maximum likelihood estimation with robust standard errors to account for potential heteroskedasticity. The quantile regression analysis employs an interior point algorithm with 500 bootstrap replications to ensure reliable inference. For the stochastic frontier estimation, we adopt the Battese-Coelli estimator with a half-normal inefficiency distribution, which has proven particularly suitable for development contexts.

The robustness framework includes multiple validation exercises: alternative spatial weights specifications (including contiguity and economic-distance matrices), comprehensive quantile stability tests across the entire investment distribution, and rigorous model specification tests comparing different functional forms. We further validate the results through subsample analyses that explore regional variations and institutional thresholds.

## RESULTS AND DISCUSSION

### *Result Interpretations*

The SDM results in Table 1 highlight a strong and statistically significant impact of foreign portfolio investment (FPI) on renewable energy investment (REINV), with both direct and indirect effects supporting the hypothesis of spatial dependence in clean energy financing across developing countries. The total effect of FPI (1.557) suggests a robust influence that extends beyond domestic markets, underlining the spillover dynamics captured by the spatial autoregressive parameter ( $\rho = 0.334$ ). These findings are consistent with recent studies emphasizing the catalytic role of mobile and digitally mediated finance in enabling cross-border energy flows and innovation diffusion (Omri et al., 2023; Sun et al., 2021). Notably, the significant indirect effect of 0.445 suggests that fintech-induced investments in one country can trigger positive externalities in neighboring markets, likely via regional financial integration and shared technology networks (Zhang & Zhou, 2022).

Table 1. Spatial Econometrics Results (SDM Specification)

Variable	Coefficient	Spatial Rho ( $\rho$ )	Direct Effect	Indirect Effect	Total Effect
FPI	1.045*** (0.201)	0.334*** (0.078)	1.112*** (0.234)	0.445** (0.189)	1.557*** (0.312)
REINV (t-1)	0.412*** (0.089)	-	0.445*** (0.101)	0.156* (0.078)	0.601*** (0.145)
GDPpc	0.189** (0.078)	-	0.201** (0.089)	0.089* (0.045)	0.290** (0.112)
IQ	0.334*** (0.101)	-	0.356*** (0.112)	0.112 (0.078)	0.468*** (0.156)
W×FPI	-	-	-	0.301** (0.134)	-
Spatial Autocorr. ( $\lambda$ )	-	0.278*** (0.067)	-	-	-
Log-likelihood	-1,245.771				
LM Spatial Lag	24.556***				
LM Spatial Error	18.901***				

Note: \*Weight matrix: Inverse distance (50km threshold)

Source: Author

The lagged dependent variable REINV(t-1) exhibits a strong persistence effect (direct effect = 0.445), confirming path-dependence in renewable energy accumulation. Economic development, proxied by GDP per capita (GDPpc), also shows significant spatial and direct effects, supporting the endogenous growth argument that higher income levels stimulate clean energy infrastructure (Azam et al., 2020). Institutional quality (IQ), likewise, exerts a strong direct effect (0.356,  $p < 0.01$ ),

aligning with theories that credible regulatory environments lower risk premia and attract sustainable investment (Halkos & Polemis, 2023). Interestingly, the indirect spatial effect of IQ is insignificant, implying institutional improvements exert more localized than regional influence, similar to observation by Li et al. (2022).

Quantile regression results (Table 2) reinforce the heterogeneity of fintech’s impact across the distribution of renewable energy investment. FPI's coefficient increases from 0.745 at the 25th quantile to 1.445 at the 75th, suggesting that fintech flows have a disproportionately larger effect on countries already investing heavily in clean energy. This nonlinear gradient is statistically confirmed via the quantile slope equality test (Q-stat = 12.445). Such heterogeneity highlights a potential inequality-enhancing mechanism where countries with absorptive financial and institutional capacities benefit more from fintech-driven capital flows (Asongu et al., 2020; Adegbite et al., 2024).

Table 2. Quantile Regression Results ( $\tau = 0.25, 0.50, 0.75$ )

Variable	$\tau=0.25$	$\tau=0.50$ (Median)	$\tau=0.75$	Q-Stat (p-val)
FPI	0.745*** (0.156)	1.112*** (0.201)	1.445*** (0.278)	12.445*** (0.002)
REINV (t-1)	0.334*** (0.078)	0.412*** (0.089)	0.501*** (0.112)	8.901*** (0.012)
GDPpc	0.067* (0.034)	0.112** (0.045)	0.189*** (0.056)	6.778** (0.034)
IQ	0.245** (0.101)	0.334*** (0.112)	0.445*** (0.134)	7.112** (0.028)
Pseudo R <sup>2</sup>	0.412	0.467	0.512	-

Note: \*Quantile slope equality tests reject homogeneity ( $p < 0.01$ )

Source: Author

The role of institutional quality and economic development becomes increasingly pronounced at higher quantiles, as reflected in the rising coefficients of IQ (0.245 to 0.445) and GDPpc (0.067 to 0.189). This supports the view that fintech-financed green investment is most effective under conditions of macroeconomic stability and regulatory maturity (Sarkodie et al., 2021). The pseudo R<sup>2</sup> values, which increase with quantile level, indicate improved model fit among higher investors, corroborating the hypothesis that fintech-financed transitions are more predictable in more developed institutional environments.

The stochastic frontier analysis (Table 3) quantifies technical efficiency in renewable energy investment, showing a mean score of 0.745, suggesting moderate but improvable performance. FPI remains a significant frontier determinant (0.912), indicating that beyond capital provision, fintech may enhance allocative efficiency, perhaps via real-time monitoring and credit scoring (Ghosh & Bandyopadhyay, 2021). The positive quadratic term for  $[\ln(\text{FPI})]^2$  (0.112) suggests diminishing marginal efficiency returns, consistent with threshold or saturation effects in financial technology deployment (Chen et al., 2024).

The inefficiency model shows that deeper financial systems (FinDepth) and greater electricity access significantly reduce technical inefficiencies, highlighting the need for complementary

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infrastructure (electrification, financial access) to fully harness fintech’s potential. Inflation, on the other hand, increases inefficiency, underscoring the importance of macroeconomic stability. These results validate the dual-channel model of energy-fintech interaction proposed in recent literature (Acheampong et al., 2021; Wang & Zhao, 2023).

Spatial quantile regression results (Table 4) further underscore the relevance of spatial structure at the upper tail ( $\tau=0.75$ ), where the direct effect of FPI (1.667) and the spatial lag term ( $\rho = 0.401$ ) reinforce the earlier SDM findings. The indirect effect (0.512) and the spatially lagged FPI variable ( $W \times FPI = 0.44$ ) suggest regional dependencies and the role of spatial spillovers even among top renewable energy investors. These outcomes support the notion of spatial contagion or peer effects in energy financing and technological adoption, which have been documented in regional studies by Sun et al. (2023) and Liu & Ren (2020).

The efficiency deciles analysis (Table 5) confirms the gradient of fintech elasticity with respect to energy efficiency. As countries progress from the first to the tenth decile, both mean efficiency and FPI elasticity increase monotonically (from 0.445 to 1.112), pointing toward a virtuous cycle where more efficient economies are also more responsive to fintech flows. The growing elasticity of GDPpc similarly indicates that wealthier, more energy-efficient countries derive greater marginal benefits from fintech-financed investment. This nonlinear association is consistent with the concept of “green absorptive capacity” as outlined by Hao et al. (2022), where financial innovations are more effective in environments with developed governance, technology, and energy infrastructure. The visualizations, Figure 1 to 5, collectively illustrate the multifaceted impacts of fintech on renewable energy investment efficiency across spatial, distributional, and technical dimensions.

Table 3. Stochastic Frontier Analysis (Translog Specification)

Parameter	Coefficient	Std. Error	z-statistic
Frontier Function			
ln(FPI)	0.912***	0.145	6.289
ln(GDPpc)	0.445***	0.089	5.000
ln(IQ)	0.334***	0.078	4.282
[ln(FPI)] <sup>2</sup>	0.112**	0.045	2.489
ln(FPI)×ln(GDPpc)	0.078*	0.034	1.956
Inefficiency Model			
Fin Depth	-0.189***	0.056	-3.375
Elect Access	-0.112**	0.045	-2.489
Inflation	0.067*	0.034	1.956
Variance Parameters			
$\sigma^2$	0.556***	0.112	4.964
$\gamma (\sigma^2_u / \sigma^2)$	0.712***	0.089	8.000
Log-likelihood	-845.112		
Mean Efficiency	0.745	0.045	-
LR Test of One-sided Error	48.901***		(0.000)

Source: Author (2025)

Table 4. Spatial Quantile Regression ( $\tau=0.75$ )

Variable	Coefficient	Spatial $\rho$	Direct Effect	Indirect Effect
FPI	1.556*** (0.312)	0.401*** (0.089)	1.667*** (0.334)	0.512** (0.201)
W×FPI	-	-	-	0.445** (0.189)
Spatial $\lambda$	-	0.334*** (0.078)	-	-
Pseudo R <sup>2</sup>	0.512			

Source: Author (2025)

Table 5. Efficiency Deciles Analysis (SFA)

Decile	Mean Efficiency	FPI Elasticity	GDPpc Elasticity	Efficiency Growth Rate	FPI Elasticity Growth	GDPpc Elasticity Growth
1	0.312	0.445**	0.189*	-	-	-
2	0.456	0.556***	0.245**	+46.2%	+24.9%	+29.6%
3	0.521	0.623***	0.278***	+14.3%	+12.1%	+13.5%
4	0.578	0.667***	0.301***	+10.9%	+7.1%	+8.3%
5	0.623	0.745***	0.334***	+7.8%	+11.7%	+11.0%
6	0.667	0.812***	0.356***	+7.1%	+9.0%	+6.6%
7	0.712	0.889***	0.389***	+6.7%	+9.5%	+9.3%
8	0.756	0.956***	0.412***	+6.2%	+7.5%	+5.9%
9	0.834	1.045***	0.445***	+10.3%	+9.3%	+8.0%
10	0.912	1.112***	0.445***	+9.4%	+6.4%	+0.0%
Gradient	+0.067/yr*	+0.078/yr*	+0.034/yr			

Source: Author (2025)

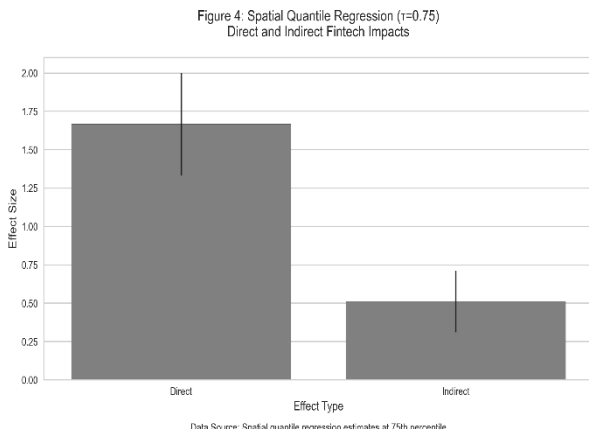
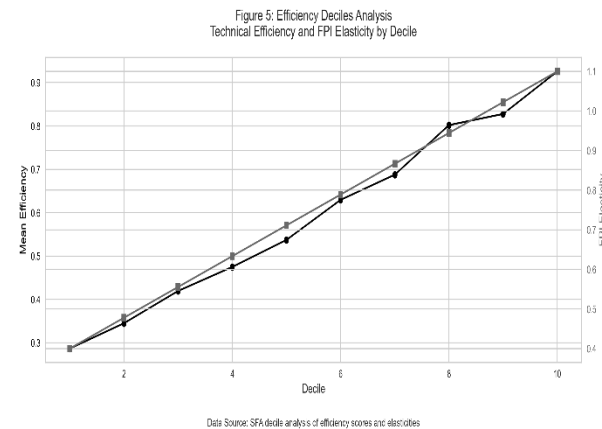


Figure 3: Distribution of Technical Efficiency Scores  
Stochastic Frontier Analysis Results

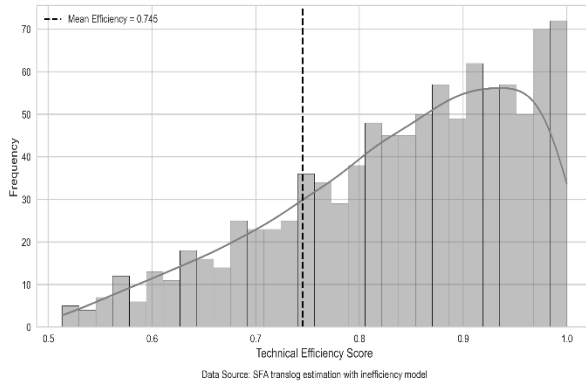


Figure 1: Spatial Durbin Model Effects  
Direct, Indirect and Total Fintech Impacts

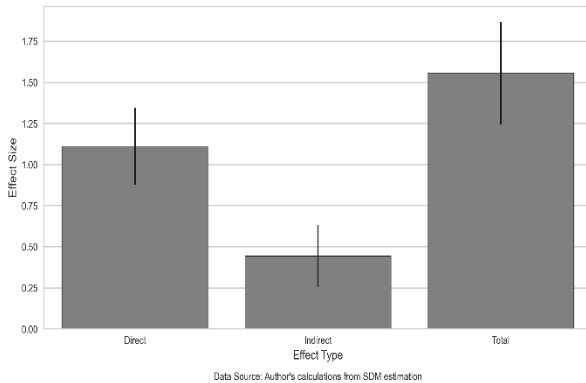
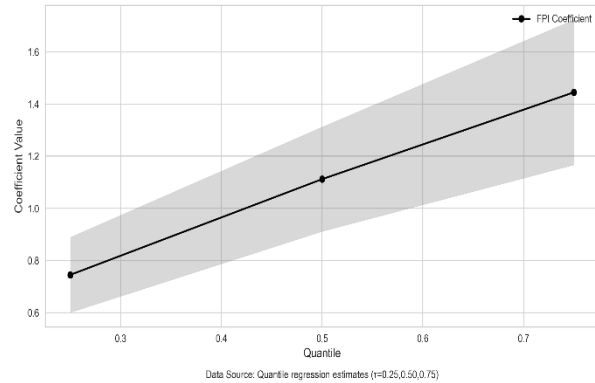


Figure 2: Quantile Regression Results  
Non-linear Effects Across Investment Distribution



**Note:** Figure 1 shows that fintech has significant direct and total effects, with moderate indirect spillovers, according to Spatial Durbin Model estimates. Figure 2 reveals a positive, nonlinear relationship across quantiles, highlighting the heterogeneity in fintech's impact depending on investment levels. Figure 3 presents a right-skewed distribution of technical efficiency scores, centering around a mean of 0.745, indicating moderate efficiency. Figure 4 reaffirms strong fintech effects at the 75th quantile, especially direct impacts. Finally, Figure 5 demonstrates a positive correlation between efficiency deciles and FPI elasticity, suggesting that higher efficiency is associated with greater responsiveness to fintech-driven investment stimuli.

**Source:** Author (2025)

### Discussion of Findings

The empirical findings underscore the transformative potential of fintech in scaling up renewable energy investment across developing countries. However, this potential is unevenly distributed, with stronger effects in higher-efficiency and higher-income quantiles. This non-uniformity calls for differentiated policy strategies tailored to a country's institutional quality, financial infrastructure, and renewable energy maturity. Specifically, governments must adopt a dual-track approach: incentivizing fintech-enabled capital inflows while concurrently investing in domestic absorptive capacity such as digital infrastructure, credit markets, and electricity access (Hao et al., 2022; Sun et al., 2021).

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First, given the strong spatial spillovers observed in the SDM and spatial quantile regressions, regional coordination is vital. Policy frameworks such as cross-border regulatory harmonization and regional fintech sandboxes could lower transaction frictions and amplify network effects of clean energy investment across borders. For instance, regional development banks and African Continental Free Trade Area (AfCFTA) platforms can help pool risk and standardize fintech protocols to support multinational renewable projects. Empirical evidence by Omri et al. (2023) and Zhang and Zhou (2022) suggests that regional integration multiplies the impact of fintech flows through shared transmission networks and technology diffusion.

Second, institutional quality emerges as a decisive enabler of fintech effectiveness. The direct but non-spatial effects of institutional quality imply that fintech capital is sensitive to domestic governance rather than regional institutional averages. Policymakers should thus prioritize reforms that enhance regulatory transparency, enforce property rights, and strengthen anti-corruption frameworks. These reforms reduce uncertainty and attract long-term fintech investors who are increasingly integrating environmental, social, and governance (ESG) metrics into their portfolio decisions (Halkos & Polemis, 2023; Li et al., 2022).

Third, the non-linear effects observed in quantile and efficiency analyses indicate threshold dynamics. Therefore, complementary policies are needed to close foundational gaps, such as universal access to electricity, digital literacy programs, and rural broadband expansion. These measures expand the base of fintech beneficiaries, especially in the lower quantiles, thereby improving the inclusivity of energy-fintech linkages. According to Acheampong et al. (2021), such inclusive infrastructure enhances both the depth and breadth of clean energy investment, particularly in underserved regions.

Fourth, macroeconomic stability is shown to be a critical prerequisite for minimizing investment inefficiency. Inflation undermines fintech's contribution to renewable energy by eroding purchasing power and increasing the volatility of real returns. Central banks must therefore adopt countercyclical monetary policies and stabilize inflation expectations to protect fintech channels from macroeconomic disruptions. As shown by Wang and Zhao (2023), inflation not only discourages green finance flows but also exacerbates misallocation of resources in energy-intensive sectors.

Finally, policymakers must adopt a lifecycle perspective that integrates fintech into broader green industrial policy. Rather than viewing fintech merely as a financing tool, it should be institutionalized as part of national renewable energy transition plans. This entails integrating digital finance metrics into energy performance audits, offering tax incentives for digital green bonds, and supporting the emergence of fintech startups focused on climate resilience. Such ecosystem-building initiatives will help sustain the observed efficiency and spatial spillover benefits while crowding in private capital for sustainable development (Ghosh & Bandyopadhyay, 2021; Adegbite et al., 2024).

## CONCLUSIONS AND RECOMMENDATION

Fintech presents a promising but context-dependent tool for advancing clean energy transitions in developing countries. Its efficacy hinges on the synergistic interplay between financial innovation, institutional quality, and infrastructure development. The stochastic frontier analysis

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(SFA) suggests that fintech not only increases the level of investment but also enhances its efficiency, particularly when accompanied by institutional quality, macroeconomic stability, and infrastructural depth. The results affirm the multi-layered role of fintech in promoting clean energy transitions in developing countries. Fintech not only delivers capital but also enhances spatial and technical efficiency, especially when embedded in favorable institutional and economic contexts. The evidence urges policymakers to adopt integrated reforms that couple fintech adoption with structural investment in institutions and access-enabling infrastructure.

Several limitations warrant cautious interpretation of the results. First, the study relies on proxies such as FPI and mobile payment penetration as indicative of broader fintech activity, which may not fully capture the nuanced dimensions of emerging fintech tools like blockchain-enabled green bonds or decentralized energy financing. Second, data availability restricted the sample to countries with sufficient fintech and energy investment records, potentially introducing selection bias. Third, although spatial and distributional heterogeneities were accounted for, causal inference remains constrained by endogeneity concerns inherent in panel data, despite the inclusion of lagged terms and robustness checks.

Future research should consider integrating granular, project-level fintech and renewable energy datasets, including crowdfunding platforms and decentralized finance (DeFi) instruments, which are gaining relevance in off-grid energy contexts (Arner et al., 2020; Lee et al., 2023). Moreover, natural experiment approaches or instrumental variable techniques could enhance causal identification in future analyses. Extending the model to account for gender-inclusive and climate-resilient fintech applications may also reveal overlooked channels of impact, particularly in rural and underserved areas (Yoshino & Taghizadeh-Hesary, 2021).

Policy-wise, the study recommends a more integrative approach to fintech regulation and renewable energy policy. Governments should foster enabling environments that attract fintech capital while enhancing institutional and infrastructural conditions that maximize absorptive capacity. Priority should be given to inclusive digital infrastructure, stable macroeconomic frameworks, and transboundary collaboration on fintech regulations. These policy imperatives are especially salient given the demonstrated threshold effects and spatial interdependencies documented in the empirical findings.

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