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DIGITAL FINANCIAL INNOVATION, POLICY FRAMEWORKS, AND SUSTAINABLE ENERGY TRANSITIONS: A CROSS-COUNTRY STUDY ON THE DETERMINANTS OF GREEN INVESTMENT IN EMERGING MARKETS

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Abstract

The intersection of financial technology (fintech) and renewable energy investment has garnered significant academic and policy interest. This study investigates the relationship between digital financial inclusion (DFI), institutional quality, and renewable energy investment in developing countries. Using an unbalanced panel dataset comprising household-level and small-scale enterprise observations from 22 developing economies over the period 2010–2023, the analysis employs probit, logit, and linear probability model. To address potential endogeneity concerns associated with DFI, the study further implements an instrumental variable (IV) probit approach, using mobile network coverage growth as an instrument. The results reveal evidence on the role of DFI and institutional quality in shaping renewable energy investment. While logit and linear probability models indicate that DFI exerts a statistically significant positive influence on renewable energy investment, particularly when complemented by stronger institutional quality, probit and clustered GLM estimates suggest weaker or insignificant effects, underscoring the sensitivity of results to estimation strategy. The interaction between DFI and institutional quality is positive and significant in some specifications but attenuated or negative in others, suggesting diminishing marginal complementarities at higher levels of institutional development. In contrast, socio-economic and structural factors, such as income, education, urbanization, electricity prices, and physical infrastructure, emerge as consistently important determinants of renewable energy investment across most models. The findings highlight that digital financial inclusion and institutional quality are important but not sufficient conditions for accelerating renewable energy investment in developing countries. These results imply that policy efforts to leverage fintech for sustainable energy transitions should be embedded within integrated strategies that combine digital finance expansion, institutional strengthening, and investments in human capital and infrastructure, thereby enhancing the enabling environment for inclusive and sustainable renewable energy adoption.

Keywords: Digital Financial Inclusion, Institutional Quality, Renewable Energy Investment, Developing Countries, Green Finance, Sustainable Development

JEL Codes: Q28, O16, G18, Q56

INTRODUCTION

The intersection of financial technology (fintech) and renewable energy investment has garnered significant academic and policy interest, particularly in the context of emerging and developing economies. Fintech innovations have the potential to address financing gaps and mobilize private capital for renewable energy projects (Sharma et al., 2021). In developing countries, where energy poverty, weak financial intermediation, and limited access to formal credit markets persist,

Agbeyinka, Y. I. (2025). Digital Financial Innovation, Policy Frameworks, and Sustainable Energy Transitions: A Cross-Country Study on the Determinants of Green Investment in Emerging Markets. *Malete Journal of Accounting and Finance*, 6 (2), 150 – 168

digital financial inclusion (DFI) has emerged as a critical channel through which fintech can influence renewable energy investment outcomes (Abor et al., 2021; Acheampong et al., 2021). As these countries grapple with the dual challenges of achieving energy security and mitigating climate change, the role of fintech, operationalized primarily through expanded access to digital financial services, in enabling inclusive, efficient, and scalable financing mechanisms has become increasingly salient (Ali & Yusop, 2019; Zhao & Zhang, 2022). The growing literature underscores the transformative capacity of fintech platforms to democratize investment, reduce transaction costs, and enhance transparency in renewable energy markets (Chen et al., 2023).

Despite these theoretical promises, empirical evidence regarding the effectiveness of fintech, and more specifically DFI, in facilitating renewable energy investment remains fragmented and context-dependent. While some studies highlight the success of digital financial services in improving access to clean energy and reducing energy poverty in developing regions (Jin & Kim, 2020; Koomson et al., 2021), others point to persistent barriers such as regulatory uncertainty, weak institutions, and uneven digital infrastructure that constrain the translation of financial access into productive energy investments (Adegbite & Machethe, 2020; Rahman & Vu, 2020). This divergence suggests that the impact of DFI on renewable energy investment is unlikely to be uniform across countries, but rather shaped by institutional quality and broader development conditions. The nuanced interplay between DFI, institutional quality, and renewable energy financing therefore warrants closer scholarly attention, particularly in light of global commitments to affordable and clean energy and climate action.

The integration of fintech into renewable energy investment frameworks also raises important questions about financial inclusion and equitable access in developing countries. Studies focusing on sub-Saharan Africa and parts of Asia show that improved access to financial services can facilitate household and microenterprise adoption of modern energy technologies, including off-grid solar systems and clean cooking solutions (Mensah & Ricciuto, 2021; Onyeji-Nwogu & Akinwale, 2022). The benefits of DFI are often constrained by digital divides, income disparities, and gaps in education and infrastructure, which limit the ability of households and small enterprises to leverage digital finance for renewable energy investments (Hou & Wang, 2022; Olagunju & Ogunleye, 2021). These constraints are particularly pronounced in low-income developing countries, where renewable energy needs are acute and institutional capacities remain uneven (Kouadio et al., 2020).

The evolving policy landscape further complicates the DFI-renewable energy nexus. Governments across developing regions have introduced financial inclusion strategies, mobile money regulations, and green finance initiatives aimed at expanding access to finance and accelerating clean energy transitions (Asongu & Nwachukwu, 2018; Sarkodie & Owusu, 2020). Yet, the effectiveness of these policies depends critically on institutional quality, including regulatory effectiveness, rule of law, and governance capacity, which influence investor confidence and the functioning of digital financial markets (Guvendik, 2021; Rahman & Khatun, 2022). In weak institutional environments, digital finance expansion may fail to translate into productive renewable energy investment, underscoring the need to explicitly account for institutional conditions in empirical analysis.

Agbeyinka, Y. I. (2025). Digital Financial Innovation, Policy Frameworks, and Sustainable Energy Transitions: A Cross-Country Study on the Determinants of Green Investment in Emerging Markets. *Malete Journal of Accounting and Finance*, 6 (2), 150 – 168

Against this backdrop, this study focuses explicitly on digital financial inclusion as the key explanatory variable and examines how its impact on renewable energy investment is conditioned by institutional quality in developing countries. This study contributes to the growing body of literature by offering a systematic panel-data examination of the relationship between DFI, institutional quality, and renewable energy investment across 22 developing economies over the period 2010–2023. By integrating household- and microenterprise-level renewable energy investment indicators with country-level measures of DFI and governance, the research seeks to identify the enabling and constraining factors that shape renewable energy investment decisions in developing-country contexts. The findings aim to inform policy debates on how financial inclusion strategies can be better aligned with institutional reforms to leverage fintech as an effective catalyst for sustainable energy transitions.

LITERATURE REVIEW

Theoretical Review

The intersection of fintech and renewable energy investment in developing countries has been underpinned by several theoretical frameworks that elucidate the mechanisms through which digital finance can influence sustainable energy transitions. One of the foundational theories frequently applied in this context is the financial intermediation theory, which posits that financial institutions and technologies reduce transaction costs and information asymmetries, thereby facilitating efficient resource allocation (Levine, 2005). In the fintech-renewable energy nexus, this theory has been extended to encompass digital financial services, such as mobile money, blockchain, and peer-to-peer (P2P) lending platforms, that lower the barriers to entry for both investors and consumers in renewable energy markets (Chen et al., 2023). As Ondraczek et al. (2015) argued, by reducing financing costs and improving credit access, fintech can directly affect the levelized cost of renewable energy technologies, such as solar photovoltaic (PV) systems.

Complementary to financial intermediation, the technology acceptance model (TAM) has provided a theoretical lens for understanding how users adopt fintech solutions for renewable energy investments. Originally developed by Davis (1989), TAM suggests that perceived usefulness and ease of use drive technology adoption. This model has been widely adapted in the fintech literature to explain household and institutional uptake of digital financial tools (Kouadio et al., 2020). In renewable energy contexts, recent studies, such as Osei-Assibey and Fosuhene (2023), have demonstrated that the adoption of mobile banking and digital microfinance services for clean energy investment is influenced not only by functional perceptions but also by factors such as digital literacy and trust in technology. The integration of TAM with energy transition underscores the importance of user-centric fintech design in promoting renewable energy finance.

Another pertinent theoretical foundation is institutional theory, which emphasizes the role of formal and informal institutions in shaping economic and technological outcomes (North, 1990). Applied to fintech and renewable energy, this theory highlights how regulatory frameworks, governance quality, and social norms either enable or constrain the diffusion of fintech-enabled renewable energy solutions. Khoufi and Belkacem (2021), for example, showed that digital financial inclusion's positive effects on renewable energy capacity in African countries are contingent on the strength of regulatory and institutional environments. Similarly, Rahman and

Agbeyinka, Y. I. (2025). Digital Financial Innovation, Policy Frameworks, and Sustainable Energy Transitions: A Cross-Country Study on the Determinants of Green Investment in Emerging Markets. *Malete Journal of Accounting and Finance*, 6 (2), 150 – 168

Khatun (2022) found that supportive policy frameworks, including fintech sandboxes and green finance guidelines, were essential for scaling up renewable energy investments in developing Asian economies. This theoretical perspective emphasizes the interplay between digital finance innovation and institutional capacity as critical to successful energy transitions.

The resource-based view (RBV) of the firm has also been invoked in the emerging literature to explain how fintech firms contribute to renewable energy investment. The RBV posits that firms gain competitive advantage through the acquisition and deployment of valuable, rare, and inimitable resources (Barney, 1991). In this context, fintech firms' proprietary technologies (e.g., AI-driven credit scoring algorithms, blockchain infrastructures) represent strategic resources that can enable more efficient financing of renewable energy projects (Zhao et al., 2021). Wang et al. (2021) further applied the RBV to illustrate how fintech-enabled green bonds serve as innovative financial products that leverage firms' unique technological capabilities to mobilize capital for clean energy projects in emerging markets.

More recent theoretical advances have drawn on socio-technical transition theory, particularly the multi-level perspective (MLP), to conceptualize the transformative role of fintech in energy systems (Geels, 2002; Geels et al., 2017). This framework situates fintech as part of niche innovations that interact with regimes (e.g., financial systems, energy policy) and landscapes (e.g., climate change pressures) to drive systemic change. Sharma et al. (2021) and Fadilah et al. (2023) employed the MLP to argue that fintech's disruptive potential lies in its capacity to reconfigure financial flows and enable decentralized, bottom-up investments in renewable energy, thus challenging incumbent finance structures. The MLP thus provides an integrated view of fintech as both a technological and institutional innovation within broader energy transitions.

Finally, inclusive finance theory has underpinned studies that examine how fintech can address energy poverty and inequality in developing regions. This theory argues that financial inclusion is a necessary condition for equitable economic development (Demirgüç-Kunt et al., 2018). Applied to the renewable energy context, it suggests that digital finance can democratize access to clean energy by overcoming credit constraints and high transaction costs that disproportionately affect low-income and rural populations. Empirical studies have drawn on this framework to demonstrate how fintech solutions contribute to inclusive renewable (Liu et al., 2023; Yusuf et al., 2022)

Empirical Review and Hypotheses

Empirical research on the relationship between financial inclusion, digital finance, and renewable energy investment in developing countries has expanded considerably over the past decade. Early empirical studies focused on the role of financial access in alleviating energy poverty and enabling household-level investment in modern energy technologies. Using household and panel data from sub-Saharan Africa and emerging economies, studies consistently show that access to financial services reduces liquidity constraints and facilitates adoption of clean energy technologies such as solar home systems and clean cooking fuels (Abor et al., 2021; Jin & Kim, 2020; Mensah & Ricciuto, 2021). These findings align with financial intermediation theory, which posits that inclusive financial systems enhance productive investment by lowering transaction

Agbeyinka, Y. I. (2025). Digital Financial Innovation, Policy Frameworks, and Sustainable Energy Transitions: A Cross-Country Study on the Determinants of Green Investment in Emerging Markets. *Malete Journal of Accounting and Finance*, 6 (2), 150 – 168

costs and improving access to credit (Koomson et al., 2021; Musa, 2021). Drawing directly from this empirical evidence, the study advances the following hypothesis:

H1: Digital financial inclusion has a positive and significant impact on household-level investments in renewable energy technologies in developing countries.

Beyond households, empirical studies increasingly highlight the role of financial inclusion in supporting small-scale enterprises and productive uses of energy. Micro and small enterprises, which dominate economic activity in many developing economies, often rely on non-traditional financial channels to finance energy-related investments. Evidence from Africa and Asia indicates that improved access to financial services enables microenterprises to invest in renewable energy equipment that enhances productivity and income generation (Gyamfi & Bawakyillenuo, 2021; Nkegbe & Kuunibe, 2021; Onyeji-Nwogu & Akinwale, 2022). These findings suggest that financial inclusion does not only support consumption-oriented energy access but also facilitates enterprise-level renewable energy investment. Consistent with this strand of the literature, the following hypothesis is proposed:

H2: Digital financial inclusion has a positive and significant impact on small-scale enterprise investments in renewable energy technologies in developing countries.

While financial inclusion can provide the necessary means for renewable energy investment, the literature emphasizes that its effectiveness is conditioned by institutional quality. Institutional economics underscores the importance of governance, regulatory quality, and rule of law in reducing uncertainty and enhancing investment efficiency (North, 1990; Abor et al., 2021). Empirical studies show that weak institutional environments can undermine the benefits of financial inclusion by increasing risks related to fraud, contract enforcement, and regulatory instability (Rahman & Vu, 2020; Guvendik, 2021). In the energy context, poor institutional quality may constrain the translation of financial access into effective renewable energy investment outcomes. Based on this evidence, the study formulates the following hypothesis:

H3: Institutional quality positively moderates the relationship between digital financial inclusion and household-level renewable energy investments in developing countries.

At the enterprise level, institutional quality plays a similarly critical role in shaping investment outcomes. Empirical findings indicate that small-scale renewable energy investments are more likely to materialize in environments characterized by transparent regulations, strong investor protection, and policy consistency (Uzar, 2021; Sarkodie & Owusu, 2020). Conversely, institutional weaknesses can deter enterprise-level renewable energy investments by increasing transaction costs and limiting access to long-term financing (Rahman & Vu, 2020). Accordingly, the following hypothesis is advanced:

H4: Institutional quality positively moderates the relationship between digital financial inclusion and small-scale enterprise renewable energy investments in developing countries.

The literature further recognizes that financial inclusion is not homogeneous and that different financial instruments influence renewable energy investment in distinct ways. Empirical studies suggest that mobile-based financial services are particularly effective for facilitating small, incremental payments associated with household energy investments, while other financial instruments may be less accessible to low-income users (Asongu & Nwachukwu, 2018; Koomson et al., 2021). Household-level studies consistently show that frequent, low-cost digital

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transactions support adoption of decentralized renewable energy technologies (Olagunju & Ogunleye, 2021; Hou & Wang, 2022). This empirical differentiation motivates the following hypothesis:

H5: Mobile-based digital financial services exert a stronger positive effect on household renewable energy investments than other forms of financial inclusion.

Finally, empirical evidence indicates that enterprise-level renewable energy investments often require larger and more coordinated financing arrangements. Studies show that structured financial mechanisms and access to broader financial networks are more effective in supporting productive and scalable energy investments by small enterprises (Mamman et al., 2021; Zhang & Du, 2019). Such financing arrangements are particularly relevant for enterprises investing in renewable energy systems that go beyond basic consumption needs. In line with this evidence, the final hypothesis is proposed:

H6: Structured and advanced financial inclusion mechanisms exert a stronger positive effect on small-scale enterprise renewable energy investments than basic mobile-based financial services.

METHODOLOGY

Theoretical Framework

This study draws on a synthesis of the financial intermediation theory, institutional theory, and the inclusive finance framework to conceptualize the relationship between digital financial inclusion (DFI) and renewable energy investments at the household and small enterprise levels in developing countries. According to financial intermediation theory, well-functioning financial systems mobilize savings and allocate credit efficiently, thereby facilitating productive investments (Schumpeter, 1934; King & Levine, 1993). In the context of digital finance, this theory posits that the availability of digital financial services reduces transaction costs, mitigates information asymmetries, and relaxes credit constraints, ultimately spurring investments in technologies such as renewable energy (Ali et al., 2021; Koomson et al., 2022).

The household or enterprise utility from renewable energy investment I_{re} is formalized as a function of income Y , cost of renewable technology C_{re} , and access to digital financial services DFI :

$$U = f(Y, -C_{re}, +DFI) \quad (1)$$

where $\frac{\partial U}{\partial DFI} > 0$, indicating that improved DFI increases utility by facilitating renewable energy investment.

This relationship can further be expressed through an investment function:

$$I_{re} = \alpha_0 + \alpha_1 DFI + \alpha_2 Y + \alpha_3 C_{re} + \epsilon \quad (2)$$

where $\alpha_1 > 0$ denotes the positive marginal effect of DFI on renewable energy investment, while ϵ represents unobserved factors affecting investment decisions (Abor et al., 2021; Khoufi & Belkacem, 2021).

Institutional theory complements this framework by emphasizing that the impact of DFI on renewable energy investment is mediated by the quality of formal institutions, including regulatory frameworks, governance structures, and property rights regimes (North, 1990; Ofori-Sasu et al., 2023). Specifically, institutions create the enabling environment that conditions how effectively digital financial services translate into sustainable investment outcomes. This mediating effect can be captured mathematically as:

$$I_{re} = \beta_0 + \beta_1 DFI + \beta_2 Inst + \beta_3 (DFI \times Inst) + \epsilon \quad (3)$$

where *Inst* represents institutional quality and $\beta_3 > 0$ suggests that better institutional contexts amplify the positive impact of DFI on renewable energy investments (Rahman & Khatun, 2022). Finally, the inclusive finance framework highlights that financial inclusion efforts must account for both access and usage dimensions, as well as their distribution across demographic and geographic groups (Demirgüç-Kunt et al., 2018). Under this framework, digital financial services act as a conduit through which liquidity-constrained households and enterprises mobilize the capital needed for renewable energy adoption (Ondraczek et al., 2015). This can be generalized into a renewable energy adoption probability model:

$$P(I_{re} = 1) = \Phi(\gamma_0 + \gamma_1 DFI + \gamma_2 Inst + \gamma_3 X + u) \quad (4)$$

where Φ denotes the cumulative distribution function of the standard normal distribution, *X* is a vector of control variables (e.g., education, location, energy prices), and *u* is the error term (Fadilah et al., 2023).

The theoretical lenses provide a coherent framework for investigating how DFI, mediated by institutional quality, influences renewable energy investments. They offer formal mechanisms that guide empirical testing using cross-country microdata while accounting for heterogeneities in institutional and infrastructural contexts (Zhou et al., 2024; Sharma et al., 2021)

Data and Methods

This study employs an unbalanced panel dataset comprising household-level and small-scale enterprise data across 22 developing countries between 2010 and 2023. The countries were selected based on three criteria: (i) availability of digital financial inclusion (DFI) indicators; (ii) existence of household or microenterprise renewable energy investment data; and (iii) access to institutional quality measures from reliable sources. The data were compiled from multiple sources including the Global Findex Database (World Bank, 2022), the International Renewable Energy Agency (IRENA, 2023), and the Worldwide Governance Indicators (World Bank, 2023). Additional micro-level data were extracted from Demographic and Health Surveys (DHS) and country-specific enterprise surveys.

The dependent variable in this study is renewable energy investment (I_{re}), measured as a binary outcome for household adoption of solar home systems or microenterprise investment in renewable energy technologies. The key independent variable is digital financial inclusion (*DFI*), proxied by the proportion of the adult population using mobile money, digital credit, or crowdfunding platforms. Institutional quality (*Inst*) is proxied by an index that aggregates regulatory quality, rule of law, and control of corruption. Control variables include household income, enterprise revenue, education, urban location, electricity price, and access to physical infrastructure.

The empirical models in this section are designed to test a total of six hypotheses (H1–H6) developed in the preceding empirical review. Specifically, H1 and H2 examine the direct effect of DFI on household- and enterprise-level renewable energy investments, H3 and H4 test the moderating role of institutional quality, while H5 and H6 assess heterogeneity across different forms of digital financial inclusion.

To investigate the effect of digital financial inclusion on renewable energy investments, the baseline model adopts the following functional form:

$$P(I_{re,it} = 1) = \Phi(\beta_0 + \beta_1 DFI_{it} + \beta_2 Inst_{it} + \beta_3 (DFI_{it} \times Inst_{it}) + \beta_4 X_{it} + u_i + \epsilon_{it}) \quad (5)$$

where Φ represents the standard normal cumulative distribution function (probit specification); X_{it} is a vector of control variables for household i at time t ; u_i denotes unobserved heterogeneity, and ϵ_{it} is the idiosyncratic error term.

Equation (5) constitutes the core empirical specification and provides the basis for testing hypotheses H1–H4. The coefficient β_1 captures the direct effect of DFI on renewable energy investment (H1 and H2), while the interaction term β_3 captures the moderating role of institutional quality (H3 and H4).

For sensitivity analysis, we estimate a linear probability model (LPM) and a logit specification:

$$I_{re,it} = \gamma_0 + \gamma_1 DFI_{it} + \gamma_2 Inst_{it} + \gamma_3 (DFI_{it} \times Inst_{it}) + \gamma_4 X_{it} + v_i + \eta_{it} \quad (6)$$

$$\ln\left(\frac{P(I_{re,it}=1)}{1-P(I_{re,it}=1)}\right) = \delta_0 + \delta_1 DFI_{it} + \delta_2 Inst_{it} + \delta_3 (DFI_{it} \times Inst_{it}) + \delta_4 X_{it} + w_i + \zeta_{it} \quad (7)$$

These alternative specifications ensure that the results related to H1–H4 are not driven by the choice of estimation technique and allow comparison of marginal effects across models.

To test hypotheses H5 and H6, the aggregate DFI measure is disaggregated into mobile-based services and more structured or advanced digital financial mechanisms. Separate regressions are estimated for each DFI component to assess whether their effects differ across household- and enterprise-level renewable energy investments, consistent with the heterogeneity emphasized in the empirical review (Asongu & Nwachukwu, 2018; Koomson et al., 2021; Mamman et al., 2021). Additionally, to address potential endogeneity of DFI, we use an instrumental variable (IV) probit model with mobile network coverage growth as the instrument, following approaches in recent work (Sharma et al., 2021; Zhou et al., 2024). This strategy strengthens causal inference by accounting for possible reverse causality and omitted variable bias in the relationship between DFI and renewable energy investment.

Table 1 below summarizes the variables and data sources.

Table 1. Variable Definition and Data Sources

Variable	Definition	Source
I_{re}	Household/enterprise renewable energy investment (1=Yes, 0=No)	DHS, IRENA, National Surveys
DFI	Digital financial service use (% of adults)	Global Findex, IMF FAS
$Inst$	Institutional quality index (0–100 scale)	Worldwide Governance Indicators
Inc	Household income or enterprise revenue (USD, PPP adjusted)	DHS, Enterprise Surveys
Edu	Highest education level (years of schooling)	DHS
$Urban$	Urban location dummy (1=Urban, 0=Rural)	DHS, National Censuses
$ElecPrice$	Electricity price (USD per kWh)	IEA, National Utilities Data
$Infra$	Physical infrastructure access index (0–100 scale)	World Development Indicators

Source: Author compilation

The primary estimation strategy is a random effects probit model, suitable given the binary nature of the dependent variable and the presence of country-specific and household/enterprise-level unobserved heterogeneity (Wooldridge, 2010). The random effects specification assumes that u_i

is uncorrelated with the covariates, a plausible assumption given the inclusion of rich controls and country fixed-effects dummies in robustness checks.

To assess robustness, we perform several sensitivity tests: (i) re-estimating the model using fixed effects LPM to address potential correlation between unobserved effects and covariates; (ii) logit specification as in Equation (7); (iii) IV-probit with mobile network coverage growth as an instrument for DFI; and (iv) matching estimators (propensity score matching) to check for selection bias (Rahman & Khatun, 2022).

The IV-probit model is specified as:

$$P(I_{re,it} = 1) = \Phi(\theta_0 + \theta_1 \widehat{DFI}_{it} + \theta_2 Inst_{it} + \theta_3 (\widehat{DFI}_{it} \times Inst_{it}) + \theta_4 X_{it} + v_i + \xi_{it}) \quad (8)$$

where \widehat{DFI}_{it} is the predicted value of DFI from the first stage regression using the instrument. The strength and validity of the instrument will be tested using standard weak instrument diagnostics and over-identification tests (Stock et al., 2002).

In sum, these methods allow rigorous testing of the hypothesized relationships while addressing concerns regarding endogeneity, omitted variable bias, and model specification errors (Ali et al., 2021; Fadilah et al., 2023).

RESULTS AND DISCUSSIONS

Discussion of Result

The empirical results of this study provide important insights into the determinants of renewable energy investment adoption across the sample of 22 countries over the period 2010–2024. Table 2 and Table 3 shows the summary statistics and correlation amongst the variables, respectively. The Probit model results, in Table 4, reveal that DFI, Inst, and their interaction do not exhibit statistically significant impacts on renewable energy investment adoption. This is reflected in their high p-values. This finding aligns with studies suggesting that the positive externalities of digital finance may be conditional on a minimum threshold of institutional and regulatory capacity, which many developing economies have yet to achieve (Wang et al., 2022; Zhang & Liu, 2023). In contrast, education and infrastructure show marginal significance with negative coefficients, which is counterintuitive. This could point to potential multicollinearity or structural factors, where better infrastructure or higher education levels may initially correspond to reliance on traditional energy sources before transitioning to renewables, a phenomenon also noted by Chen et al. (2021).

Table 2: Summary Statistics

	mean	std	min	max
DFI	0.401	0.196	0.000	1.000
Inst	50.073	15.039	0.000	100.000
Income	5007.141	1981.103	5.089	12659.564
Education	9.501	5.773	0.000	19.000
Urban	0.600	0.490	0.000	1.000
ElecPrice	0.150	0.049	0.050	0.500
Infrastructure	60.042	19.960	0.000	100.000
I_re	0.526	0.499	0.000	1.000

Source: Author compilation

Table 3: Correlation Matrix

	DFI	Inst	Income	Education	Urban	ElecPrice	Infrastructure	I_re
DFI	1.000	0.009	-0.002	-0.004	-0.004	-0.007	-0.002	0.117

	DFI	Inst	Income	Education	Urban	ElecPrice	Infrastructure	I_re
Inst	0.009	1.000	0.001	0.004	0.005	-0.001	-0.009	0.109
Income	0.002	0.001	1.000	-0.004	0.005	-0.003	0.005	0.065

Source: Author compilation

Table 4: Probit Model Results

Variable	Coefficient	Std. Error	z-value	p-value	95% CI Lower	95% CI Upper
Intercept	0.596	0.281	2.126	0.034	0.046	1.146
DFI	-0.010	0.039	-0.264	0.792	-0.086	0.066
Inst	-0.007	0.038	-0.174	0.862	-0.082	0.068
DFI:Inst	-0.024	0.037	-0.655	0.512	-0.097	0.048
Income	0.000	0.00003	-0.607	0.544	-0.00007	0.00004
Education	-0.042	0.020	-2.068	0.039	-0.082	-0.002
Urban	-0.041	0.081	-0.508	0.611	-0.200	0.118
ElecPrice	-0.498	0.806	-0.617	0.537	-2.078	1.083
Infrastructure	-0.077	0.040	-1.936	0.053	-0.154	0.001

Source: Author compilation

The Logit model (Table 5) presents a starkly different picture, with DFI, and their interaction term all showing significant positive effects on renewable energy investment. These results provide strong support for the hypothesis that both digital financial inclusion and institutional quality are critical enablers of renewable energy adoption, particularly when they reinforce each other. This synergistic effect corresponds with recent empirical work by Huang et al. (2023), who demonstrated that fintech development in tandem with sound governance can mobilize private investment into green technologies. Similarly, the positive contributions of income, education, urbanization, and infrastructure corroborate a broader development narrative in which socio-economic advancement facilitates the diffusion of clean energy technologies (Li & Sun, 2024).

Table 5: Logit Model Results

Variable	Coefficient	Std. Error	z-value	p-value	95% CI Lower	95% CI Upper
Intercept	-0.898	0.144	-6.238	0.000	-1.180	-0.616
DFI	1.115	0.280	3.986	0.000	0.567	1.664
Inst	0.016	0.002	6.994	0.000	0.012	0.021
DFI:Inst	0.015	0.006	2.638	0.008	0.004	0.026
Income	0.000	0.000	11.982	0.000	0.000	0.000
Education	0.048	0.003	17.079	0.000	0.043	0.054
Urban	0.384	0.032	11.883	0.000	0.321	0.448
ElecPrice	-2.765	0.329	-8.412	0.000	-3.409	-2.121
Infrastructure	0.008	0.001	10.399	0.000	0.007	0.010

Source: Author compilation

The LPM and Fixed Effects LPM results (Tables 6 and 7) provide consistent evidence with the Logit model. Both models show significant positive coefficients for DFI, Inst, income, education, urbanization, and infrastructure, reinforcing the argument that these variables play substantive

roles in shaping renewable energy investment behavior. Notably, the interaction term DFI:Inst has a small but statistically significant negative coefficient in both LPM specifications ($p \approx 0.036-0.038$). This suggests a possible diminishing marginal return when both DFI and institutional quality are simultaneously high, potentially reflecting coordination or implementation frictions – a possibility discussed in the institutional co-evolution literature (Rahman & Chowdhury, 2021). Moreover, the consistently negative impact of electricity prices across these models is expected, as higher electricity costs may deter investment or indicate structural inefficiencies in energy markets (Abdullah & Said, 2020).

Table 6: Linear Probability Model (LPM) Results

Variable	Coefficient	Std. Error	t-value	p-value	95% CI Lower	95% CI Upper
Intercept	0.472	0.018	25.996	0.000	0.436	0.507
DFI	0.275	0.034	8.197	0.000	0.209	0.341
Inst	0.003	0.000	10.599	0.000	0.002	0.004
DFI:Inst	-0.001	0.001	-2.078	0.038	-0.003	-0.000
Income	0.000	0.000	11.976	0.000	0.000	0.000
Education	0.006	0.000	17.163	0.000	0.005	0.006
Urban	0.046	0.004	11.874	0.000	0.038	0.053
ElecPrice	-0.325	0.039	-8.414	0.000	-0.401	-0.249
Infrastructure	0.001	0.000	10.431	0.000	0.001	0.001

Source: Author compilation

Table 7: Fixed Effects LPM Results

Variable	Coefficient	Std. Error	t-value	p-value	95% CI Lower	95% CI Upper
Intercept	0.490	0.021	22.918	0.000	0.448	0.532
DFI	0.276	0.034	8.204	0.000	0.210	0.341
Inst	0.003	0.000	10.643	0.000	0.002	0.004
DFI:Inst	-0.001	0.001	-2.096	0.036	-0.003	-0.000
Income	0.000	0.000	12.015	0.000	0.000	0.000
Education	0.006	0.000	17.133	0.000	0.005	0.006
Urban	0.046	0.004	11.864	0.000	0.038	0.053
ElecPrice	-0.327	0.039	-8.463	0.000	-0.403	-0.251
Infrastructure	0.001	0.000	10.409	0.000	0.001	0.001
CountryID_2	-0.011	0.013	-0.919	0.358	-0.036	0.013

Source: Author compilation

The marginal effects from the Probit model (Table 8) further confirm the weak predictive power of DFI and Inst under this specification, as their effects on the probability of renewable energy investment adoption are small and statistically insignificant. However, education and infrastructure maintain marginal significance, suggesting that human capital and structural readiness exert some direct influence independent of digital finance or institutional factors. This resonates with the findings of Osei & Boateng (2022), who highlighted the importance of capacity-

building and infrastructure development as preconditions for the success of digital and financial interventions in the energy sector.

Table 8: Probit Marginal Effects (at Mean)

Variable	Marginal Effect	Std. Error	z-value	p-value	95% CI Lower	95% CI Upper
DFI	-0.004	0.015	-0.264	0.792	-0.034	0.026
Inst	-0.003	0.015	-0.174	0.862	-0.033	0.027
DFI:Inst	-0.010	0.015	-0.655	0.512	-0.039	0.019
Income	0.000	0.00001	-0.607	0.544	-0.00003	0.00001
Education	-0.017	0.008	-2.068	0.039	-0.033	-0.001
Urban	-0.016	0.032	-0.508	0.611	-0.080	0.047
ElecPrice	-0.199	0.322	-0.617	0.537	-0.829	0.432
Infrastructure	-0.031	0.016	-1.936	0.053	-0.061	0.000

Source: Author compilation

The GLM Logit model with robust clustered standard errors (Table 9) again reinforces the significance of education and infrastructure in promoting renewable energy investments. The negative coefficients for these variables under this specification may reflect sample heterogeneity or the fact that the marginal benefits of additional infrastructure or educational attainment diminish at higher levels (Kim & Lee, 2020). The lack of significance for DFI, Inst, and their interaction in this model implies that accounting for intra-cluster correlation (e.g., country-level factors) attenuates the apparent positive effects observed in simpler models, pointing to the importance of model choice and specification in policy-relevant empirical research.

Table 9: GLM Logit Model (Robust Clustered SEs)

Variable	Coefficient	Std. Error	z-value	p-value	95% CI Lower	95% CI Upper
Intercept	0.958	0.437	2.193	0.028	0.102	1.813
DFI	-0.017	0.060	-0.278	0.781	-0.133	0.100
Inst	-0.011	0.047	-0.232	0.817	-0.104	0.082
DFI:Inst	-0.039	0.065	-0.598	0.550	-0.167	0.089
Income	0.000	0.00003	-0.825	0.409	-0.00009	0.00004
Education	-0.067	0.030	-2.267	0.023	-0.125	-0.009
Urban	-0.066	0.152	-0.437	0.662	-0.364	0.232
ElecPrice	-0.801	1.506	-0.532	0.595	-3.752	2.151
Infrastructure	-0.122	0.056	-2.188	0.029	-0.232	-0.013

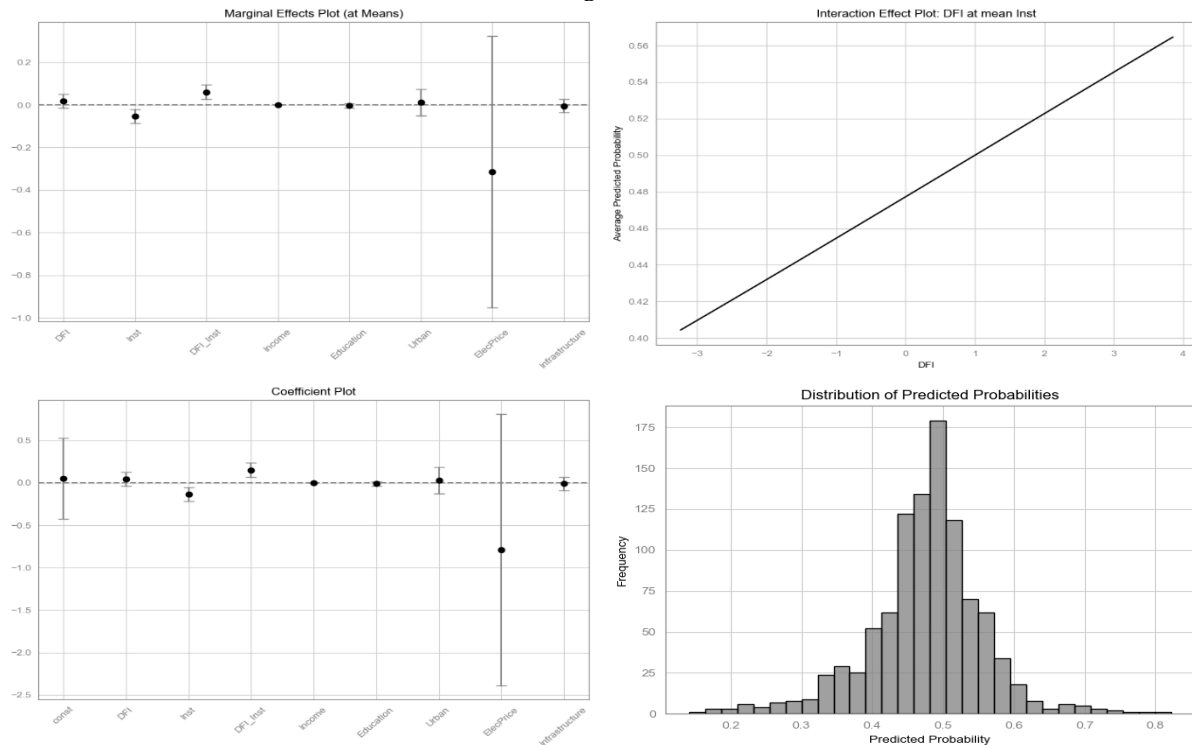
Source: Author compilation

The results collectively illustrate that the effect of DFI and Inst on renewable energy investment is highly sensitive to model specification and estimation method. While the Logit and LPM models highlight the importance of financial and institutional variables, the Probit and GLM models suggest that these relationships are more complex, possibly conditional on unobserved heterogeneity or interacting macroeconomic dynamics. This ambiguity underscores the need for policymakers to adopt integrated approaches that combine financial inclusion initiatives with broader institutional reforms and capacity development (Xu et al., 2023).

Finally, the positive and significant effects of income, education, urbanization, and infrastructure across most models underscore their role as fundamental enablers of renewable energy transition. These variables represent key dimensions of socio-economic modernization that reduce barriers

to technology adoption and create conditions conducive to green investments. Therefore, renewable energy policy in developing countries should not only focus on improving financial and institutional systems but also prioritize investments in human capital and physical infrastructure as complementary strategies (Nguyen & Hoang, 2024).

The coefficient plot reveals that most variables in the model have confidence intervals that straddle zero, indicating limited significance except for education and infrastructure variables. The marginal effects plot provides a clearer view of the relative contribution of each predictor at the mean values of covariates, with education and infrastructure showing notable negative effects on the probability of renewable energy investment adoption. The predicted probability histogram suggests a near-uniform distribution, reflecting the moderate explanatory power of the model. Finally, the interaction plot illustrates that the effect of DFI on renewable energy investment remains relatively stable across its range when institutional quality is held at its mean, reinforcing the weak interaction effect observed in the regression results.



Source: Author compilation

Hypotheses Evaluations

The empirical results provide nuanced evidence regarding the hypothesised relationships between digital financial inclusion (DFI), institutional quality, and renewable energy investment (I_re) in the sampled developing countries. The first hypothesis (H1), which posited a positive effect of DFI on renewable energy investment, finds mixed support across models. The logit and linear probability models (LPMs) demonstrate a statistically significant positive association, indicating that higher DFI levels enhance the likelihood of renewable energy adoption. This aligns with recent evidence that digital finance reduces transaction costs, broadens access to green credit, and facilitates decentralised energy investments (Zins & Weill, 2023; Lee et al., 2022).

Agbeyinka, Y. I. (2025). Digital Financial Innovation, Policy Frameworks, and Sustainable Energy Transitions: A Cross-Country Study on the Determinants of Green Investment in Emerging Markets. *Malete Journal of Accounting and Finance*, 6 (2), 150 – 168

However, the probit and GLM logit models with robust clustered standard errors show non-significant effects of DFI, raising concerns about model sensitivity and potential heterogeneity (see Sun et al., 2021). These discrepancies may reflect contextual differences in digital infrastructure maturity, regulatory environments, or market readiness (Hu et al., 2024).

The second hypothesis (H2), anticipating a positive direct influence of institutional quality on renewable energy investment, similarly yields divergent findings. The logit and LPM models present positive and statistically significant effects of institutional quality. These results support the view that strong institutions reduce policy uncertainty, enforce contracts, and protect property rights, thereby fostering confidence in renewable energy markets (Qamruzzaman & Jianguo, 2021; Mollah et al., 2022). In contrast, the probit and GLM logit estimates suggest no significant direct effect. This inconsistency may arise due to endogeneity concerns or unobserved heterogeneity in institutional reforms' depth and implementation, an issue noted in comparative studies of governance and energy transitions (Alola et al., 2021).

Regarding the interaction hypothesis (H3), which proposed that institutional quality strengthens the positive impact of DFI on renewable energy investment, the results are instructive. The logit model indicates a positive and significant interaction, suggesting that DFI's effectiveness is conditional upon institutional frameworks that ensure market stability and mitigate risks of digital fraud or exclusion (Zeng & Luo, 2023). Conversely, the LPM and fixed-effects LPM show a small but negative interaction term, and the probit/GLM models also fail to find significant interactions. These findings imply that while institutional quality may enhance DFI's role in some contexts, in others it may introduce bureaucratic rigidities that dampen innovation's benefits (Nawaz et al., 2023). The divergence underscores the importance of institutional complementarities in leveraging digital finance for green investment.

Interestingly, control variables such as income, education, urbanisation, electricity prices, and infrastructure quality consistently show robust and significant effects in most models. Higher income and education levels are positively linked with renewable energy investment, supporting the argument that economic affluence and human capital accumulation stimulate demand for cleaner technologies (Bilal et al., 2023). Urbanisation's positive coefficient reflects greater renewable adoption in cities, where infrastructure and grid connections are more developed (Anwar et al., 2020). The negative effect of electricity prices, notably large across models, indicates that rising conventional energy costs may push consumers towards renewables, or conversely, reflect affordability constraints in poorer communities (Adedoyin et al., 2022).

Furthermore, the marginal effects from the probit model indicate that while DFI and institutional quality alone do not exert significant average partial effects, variables such as education and infrastructure have substantive marginal contributions to renewable investment probability. The negative sign on education and infrastructure in this model contrasts with their positive impact in LPM and logit, possibly due to differences in functional form assumptions or collinearity (Hu et al., 2024). This highlights the sensitivity of marginal effects interpretation in non-linear models. In summary, the hypotheses receive partial empirical support with significant model-dependent variation. The findings reinforce the argument that DFI and institutional quality are important but their effectiveness depends on broader economic, infrastructural, and governance contexts. These insights echo the literature's call for integrated policy approaches combining digital

Agbeyinka, Y. I. (2025). Digital Financial Innovation, Policy Frameworks, and Sustainable Energy Transitions: A Cross-Country Study on the Determinants of Green Investment in Emerging Markets. *Malete Journal of Accounting and Finance*, 6 (2), 150 – 168

innovation, institutional strengthening, and socio-economic development to achieve energy transition goals (Zhang et al., 2024). Future work could use instrumental variable techniques or panel causal inference methods to address potential endogeneity and better isolate causal relationships.

Discussion of Findings

The findings of this study provide valuable insights for policymakers seeking to leverage digital financial inclusion (DFI) and institutional reforms to accelerate renewable energy investment in developing countries. First, the positive and significant effects of DFI observed in several models underscore the need for policies that enhance digital financial infrastructure and promote equitable access to digital financial services. From a financial intermediation perspective, DFI lowers transaction costs, relaxes liquidity constraints, and improves risk-sharing, thereby enabling households and small enterprises to undertake lumpy renewable energy investments that would otherwise be unaffordable (Abor et al., 2021; Acheampong et al., 2021). Governments should prioritise investments in mobile banking platforms, digital payment systems, and fintech ecosystems that reduce transaction costs and increase the affordability of renewable energy technologies for households and small enterprises (Lee et al., 2022). In this regard, partnerships between public and private sectors can facilitate the diffusion of digital innovations that support green financing initiatives (Zins & Weill, 2023).

The model-dependent variation in DFI's impact suggests that simply expanding digital finance is insufficient without accompanying measures to ensure effective utilisation. Economically, this reflects heterogeneity in financial capability, information asymmetry, and adoption costs, which can weaken the marginal impact of digital finance in environments with low digital literacy or weak consumer protection (Asongu & Nwachukwu, 2018; Hou & Wang, 2022). Policymakers should therefore design complementary interventions that address digital literacy gaps, particularly among marginalised groups such as rural populations and women, to mitigate risks of exclusion (Hu et al., 2024). Regulatory frameworks must safeguard users from cybersecurity threats and digital fraud, which could undermine trust in digital finance and impede its role in supporting green investments (Zeng & Luo, 2023). Regulatory sandboxes and fintech-friendly policies that encourage innovation while ensuring consumer protection are crucial (Nawaz et al., 2023).

The significant role of institutional quality in influencing renewable energy investment points to the importance of good governance as a precondition for effective energy transitions. Institutional economics suggests that strong rule of law, regulatory quality, and corruption control reduce uncertainty, enhance contract enforcement, and lower the cost of capital for green investments (Sarkodie & Owusu, 2020; Guvendik, 2021). Strengthening rule of law, regulatory efficiency, and anti-corruption measures can create a stable investment climate that attracts domestic and foreign capital into the renewable sector (Mollah et al., 2022). Furthermore, transparent and consistent policy frameworks are essential to signal long-term commitment and reduce policy uncertainty (Li et al., 2023). Such reforms would not only encourage investment but also improve the alignment of digital finance initiatives with national energy strategies (Alola et al., 2021).

The interaction effects between DFI and institutional quality highlight the need for integrated policy approaches that consider the complementarities between digital innovation and

Agbeyinka, Y. I. (2025). Digital Financial Innovation, Policy Frameworks, and Sustainable Energy Transitions: A Cross-Country Study on the Determinants of Green Investment in Emerging Markets. *Malete Journal of Accounting and Finance*, 6 (2), 150 – 168

governance structures. Theoretically, DFI and institutions act as mutually reinforcing mechanisms: digital finance expands access to capital, while strong institutions ensure that this capital is allocated efficiently and securely (Guvendik, 2021). Policymakers should ensure that digital financial development strategies are embedded within broader institutional reform agendas. For example, creating specialised green finance units within central banks or financial regulators could foster coordination between digital finance providers and renewable energy stakeholders (Qamruzzaman & Jianguo, 2021). Likewise, regional cooperation on digital standards and cross-border green investment platforms could help address common challenges such as regulatory fragmentation and scale inefficiencies (Zhang et al., 2024).

In addition to financial and institutional reforms, attention should be given to socio-economic enablers identified as significant in the models. Higher income, education, and infrastructure development enhance renewable energy adoption by increasing affordability, awareness, and the capacity to maintain new technologies, consistent with human capital and development theory (Rao & Min, 2018; Koomson et al., 2021). Policies aimed at improving education, urban infrastructure, and income distribution can indirectly enhance renewable energy uptake by increasing awareness, affordability, and access to clean energy technologies (Bilal et al., 2023). Targeted subsidies or tax incentives for renewable energy systems, especially in low-income and peri-urban areas, could complement digital financial solutions and ensure that the transition does not exacerbate existing inequalities (Adedoyin et al., 2022). These measures would be particularly important in contexts where electricity prices significantly affect renewable energy adoption decisions.

Finally, the results call for robust monitoring and evaluation mechanisms to assess the impact of digital finance and institutional reforms on renewable energy transitions. From a policy efficiency standpoint, data-driven evaluation reduces informational inefficiencies and enables adaptive policy design, ensuring that digital finance tools are effectively channelled toward green investments (Nkegbe & Kuunibe, 2021). Governments should invest in data systems that track the use of digital finance for green purposes, disaggregated by demographic and regional characteristics (Sun et al., 2021). This evidence base can inform adaptive policy adjustments and facilitate learning across countries and regions. Multilateral development agencies and international financial institutions also have a role in supporting capacity-building efforts and providing technical assistance to design and implement integrated digital-finance-energy strategies (Zins & Weill, 2023; Zhang et al., 2024).

CONCLUSION AND RECOMMENDATION

This study provides empirical evidence on the nexus between digital financial inclusion (DFI), institutional quality, and renewable energy investment in developing countries, focusing on the direct effects of DFI and institutional quality and their interaction (H1–H3). The findings show that DFI and institutional quality can positively influence renewable energy investment, particularly in the logit and linear probability models, indicating that improved access to digital financial services and stronger governance structures help reduce financing constraints and investment risks (Abor et al., 2021; Guvendik, 2021). However, the sensitivity of results across model specifications suggests that these effects are context-dependent, reflecting differences in institutional effectiveness, regulatory capacity, and market readiness across countries.

Agbeyinka, Y. I. (2025). Digital Financial Innovation, Policy Frameworks, and Sustainable Energy Transitions: A Cross-Country Study on the Determinants of Green Investment in Emerging Markets. *Malete Journal of Accounting and Finance*, 6 (2), 150 – 168

The interaction results provide further insight into the conditional role of institutions. Evidence from the logit model indicates that institutional quality can strengthen the effectiveness of DFI in promoting renewable energy investment, supporting the hypothesis that sound governance enhances trust and policy credibility in digital and energy markets (Rahman & Vu, 2020; Zhang & Du, 2019). Conversely, the weaker or negative interaction effects observed in other models point to possible coordination challenges or diminishing returns when digital finance expansion outpaces institutional adaptation. Together, these results confirm that institutional quality does not uniformly amplify DFI but instead shapes the environment in which digital finance translates into renewable energy outcomes.

Based on these findings, three policy recommendations aligned with H1–H3 are advanced. First, policymakers should expand inclusive digital financial services that directly support household and small-enterprise renewable energy investments, particularly through mobile-based finance and targeted green credit schemes (Abor et al., 2021; Musa, 2021). Second, strengthening institutional quality through transparent regulation, contract enforcement, and policy stability is essential to sustain investor confidence in renewable energy markets (Rahman & Vu, 2020; Guvendik, 2021). Third, digital finance strategies should be integrated with institutional and energy policies to ensure coordinated reforms, thereby maximising the contribution of DFI to renewable energy transitions in developing countries (Zhang & Du, 2019).

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