Green Finance, Digital Economic Infrastructure and India's Renewable Energy Transition: Evidence from Multivariate Quantile-On-Quantile and KRLS approaches

Sunil Kumar, Urvashi Shrivastava, Sushma Singh

https://doi.org/10.1590/SciELOPreprints.15917

Submitted on: 2026-04-22
Posted on: 2026-06-30 (version 1)
(YYYY-MM-DD)

Green Finance, Digital Economic Infrastructure and India's Renewable Energy Transition: Evidence from Multivariate Quantile-On-Quantile and KRLS approaches

Sunil Kumar[a], Urvashi Shrivastava, Sushma Singh[c]

[a]**Corresponding author:** Department of Management
Affiliation : Bhilai Institute of Technology, Durg
Address : Chhattisgarh, 490010, India
Email : s.kushwaha@bitdurg.ac.in
Phone : +91 8889756215
ORCID : https://orcid.org/0000-0002-8395-3899

[b]**author** **:** Department of Management
Affiliation : Bhilai Institute of Technology, Durg
Address : Chhattisgarh, 490010, India
ORCID : https://orcid.org/0000-0001-5540-6049

[c]**author** **:** Department of Management
Affiliation : Bhilai Institute of Technology, Durg
Address : Chhattisgarh, 490010, India
ORCID : https://orcid.org/0009-0003-5392-2869

Authors Contributions:

Urvashi Shrivastava: Writing-review & editing, Writing-original draft, Validation, Supervision. **Sushma Singh:** Writing-review & editing, Writing-original draft, Resources, Conceptualization. **Sunil Kumar:** Writing-review & editing, Visualization, Methodology, Formal analysis. Validation, Software, Data curation.

Abstract

India's transition toward renewable energy is critical for achieving its net-zero emissions target by 2070 and ensuring sustainable economic growth. This study investigates the dynamic, nonlinear and complementary effects of green finance and digital economic infrastructure on India's renewable energy transition over the period 2005-2026. Composite indices are constructed using Principal Component Analysis to capture distributional heterogeneity and nonlinear interdependencies. The study employs a multivariate quantile-on-quantile regression approach, complemented by Kernel Regularized Least Squares and Granger causality analysis for robustness. The findings reveal pronounced nonlinear and stage-dependent relationships. Green finance exhibits weak and negative effects at lower quantiles but becomes significantly positive at higher quantiles, indicating that financial depth and sustained investment are essential for accelerating renewable energy adoption. Digital economic infrastructure demonstrates adverse effect initially, due to increased energy demand associated with digital expansion and contributes positively at medium-to-high quantiles by enhancing efficiency, smart grid integration and energy management. The multivariate results highlight strong complementarity between green finance and digital infrastructure with the improvements in renewable energy transition which occurs when both systems are well developed. Kernel-based estimates indicate that 1% increase in green finance and digital infrastructure, improves renewable energy transition by 0.132% and 0.521% respectively. Granger causality results confirm unidirectional causality from green finance to renewable energy transition and bidirectional causality between digital infrastructure and renewable energy transition. The study underscores the importance of integrated financial and digital policy frameworks to accelerate India's clean energy transition and provides actionable insights for policymakers, regulators and financial institutions.

Keywords: Green finance; Digital economy; Renewable energy transition; India; Quantile-on-quantile regression; Digital payments; Sustainable energy.

1. Introduction

Addressing climate change represents one of the most critical global challenges, requiring immediate structural reforms in energy consumption and production (Erdoğdu, Dayi, Yanik, Yildiz, & Ganji, 2025; Prabhakar, 2025). Developing economies such as India are facing dual challenge of sustaining rapid economic growth and shifting toward low-carbon emission energy systems (Gbadeyan, Muthivhi, Linganiso, & Deenadayalu, 2024). As the world's third-largest energy consumption and emitter of carbon dioxide after US and China and one of the fastest-growing major economies, India plays a critical role in global climate mitigation efforts (Kumari, Shashwat, Verma, & Giri, 2025). India has committed to achieving net-zero emissions by 2070 and increasing its non-fossil fuel energy capacity to 500 GW by 2030, reflects a strategic shift towards renewable energy for sustainable development (Bisht & Sharma, 2025).

India's energy transition is driven by rising energy demand due to economic expansion, urbanization and industrialization (Johri, et al., 2025). The electricity consumption between 2005 to 2026 has increased substantially which reflects the growing demand from manufacturing sector, transportation and infrastructure sectors. Despite significant progress in renewable energy deployment, fossil fuels continue to dominate India's energy requirements and accounts a substantial share of total electricity generation (Kumar, C, & Majid, 2020). The structural dependence emphasizes the importance of renewable energy adoption to reduce carbon emissions, enhance energy security and promote sustainability (Elkhatat & Al-Muhtaseb, 2024; Wang, Wang, Wei, & Li, 2018).

Renewable energy transition (RET) refers to the systematic shift of energy consumption from fossil fuel to renewable and low-carbon energy sources (Kabeyi & Olanrewaju, 2022). This transition requires substantial capital investment in renewable energy infrastructure, technological innovation and strong policy framework. Achieving India's energy goals of zero carbon emission, necessitates mobilizing large-scale financial resources and leveraging technological advancements and system integration (Kishore, Kumar, & Ippili, 2025). The green finance and digital economic infrastructure in this perspective have emerged as critical enablers (Murty & Singh, 2026).

Green finance is the financing framework designed to support sustainable investments with special focus on environment for renewable energy projects, energy efficient process and climate mitigation technologies (Fu, Lu, & Pirabi, 2023). The financial instruments such as green bonds, renewable energy investment funds and climate finance are part of green finance which facilitate capital mobilization for sustainable infrastructure (Erdoğdu, Dayi, Özbek, Ganji, & Benek, 2025). Since 2015 the India has emerged as one of the leading green bond markets with substantial growth in green bond issuance among emerging economies (Saha & Maji, 2025). These financial instruments enable both public and private sector participation in funding renewable energy projects and thereby accelerating the energy transition.

Digital economic infrastructure is another critical driver for energy transition (Bergman & Foxon, 2023). India has experienced rapid digital shifts through initiatives such as Digital India, Unified Payments Interface (UPI), FASTag for electronic toll collection, broadband expansion and widespread adoption of digital payment systems like Paytm, PhonePe etc. These digital technologies improve energy efficiency, enable smart-grid management, facilitate renewable energy integration and reduce transaction costs associated with energy markets. Digital infrastructure also supports real-time energy monitoring, decentralized energy systems and improved energy distribution efficiency (Idries, Krogstie, & Rajasekharan, 2022).

However, there are numerous challenges associated with adoption of digitalization for energy transition. The expansion of digital infrastructure increases electricity demand due to energy-intensive data centers and telecommunications networks services (Idries, Krogstie, & Rajasekharan, 2022). Thus, digitalization may initially increase energy consumption before contributing to long-term efficiency improvements and favourable outcomes. Understanding the nonlinear and stage-dependent effects of digital infrastructure on renewable energy transition is therefore critical. Similarly, green finance may exhibit heterogeneous effects depending on financial market maturity, regulatory support and institutional capacity (Erdoğdu, Dayi, Özbek, Ganji, & Benek, 2025). At initial stages of adoption, the green finance may be insufficient to offset fossil fuel dominance but moving forward at advanced stages the increased financial depth can significantly accelerate renewable energy deployment.

There are limited evidences in growing literatures on green finance and digitalization for examining their combined impact on India's renewable energy transition. Existing studies often focus on developed economies and employ linear econometric models that fails to capture nonlinear and heterogeneous effects across different stages of transition (Berg, Borensztein, Sahay, & Zettelmeyer, 2024). There is need for country-specific empirical analysis for emerging economies like India's due to their unique economic structure, financial system and digital transformation trajectory. This study addresses these gaps by developing a comprehensive empirical framework. The nonlinear and distributional effects of green finance and digital economic infrastructure on India's renewable energy transition is examined. In specific, this study seeks to answer the following research questions:

i. Do green finance initiatives significantly endorse India's renewable energy transition?
ii. How does digital economic infrastructure will influence renewable energy transition?

iii. Do green finance and digital infrastructure have interrelated and complementary effects?

iv. Are these relationships nonlinear and heterogeneous across different stages of transition within context of existing environment?

These questions are addressed through econometric techniques, including Principal Component Analysis (PCA), multivariate quantile-on-quantile regression (QQR), Kernel Regularized Least Squares (KRLS) and Granger causality analysis (GCA) (Adebayo & Özkan, 2024). These methods will consolidate the comprehensive examination of nonlinear, heterogeneous and causal relationships among the variables under study. This study contributes to the literature in several important ways. First, it provides the comprehensive empirical analyses examining the combined effects of green finance (GF) and digital economic (DE) infrastructure on India's renewable energy transition (RET). Second, it employs India-specific digital indicators like UPI transactions, FASTag adoption and digital payment infrastructure. This will provide more accurate representation of digital economic development. Third, it employs a multivariate quantile-based framework that captures nonlinear and heterogeneous effects often overlooked in conventional regression models. Finally, the study provides policy-relevant insights for accelerating India's transition toward sustainable energy systems.

2. Literature Review

2.1. Green Finance and Renewable Energy Transition

Green finance has emerged as a critical tool for supporting sustainable economic development and renewable energy deployment (Wen, He, Jing, & Haroon, 2025). The green finance considers financial instruments and policies specifically designed as special purpose vehicle (SPV) to promote sustainable investments considering environment while mitigating climate risks. Green bonds, energy investment funds and climate focused finance mechanisms enable governments and private sector entities to mobilize capital for renewable energy projects (Kumar, Taneja, & Ozen, 2025). Positive relationship between green finance and renewable energy development has been demonstrated in previous studies (Fu, Lu, & Pirabi, 2023). Green bonds provide long-term financing for renewable energy infrastructure thereby reducing financing constraints (Erdoğdu, Dayi, Özbek, Ganji, & Benek, 2025). Renewable energy projects are capital intensive and requires significant upfront investment thereby the green finance mechanisms reduce financing constraints and improve investment feasibility (Saha &

Maji, 2025). Such Financing mechanism increases capital allocation efficiency which enables investments in sustainable technologies.

The effectiveness of green finance depends on strong regulatory framework, matured financial market and institutional quality (Udo, et al., 2025). The impact of green finance may be weak in emerging economies due to limited financial market depth and regulatory constraints. At initial stage green finance markets may lack sufficient capital to support large-scale renewable energy deployment in compared to further stages (Alahmadi, 2024). The green finance market has expanded significantly in India over the past decade through regulatory thrust with increasing green bond issuance and renewable energy investment. Government initiatives such as the "*National Solar Mission*" with focused climate finance policies have facilitated renewable energy investment. However, there are limited empirical evidence examining the nonlinear effects of green finance on India's energy transition.

2.2. Digital economic infrastructure and renewable energy transition

Digital economic infrastructure has dual role to play in energy transition. At one end the digital technologies improve energy efficiency by enabling real-time monitoring, smart grid management and energy optimization (Kabeyi & Olanrewaju, 2022). While the other role is that the digital payment systems improve financial inclusions, thus enabling investment in renewable energy technologies. India's digital transformation has been driven by widespread adoption of digital payment systems like UPI and FASTag (Kishore, Kumar, & Ippili, 2025). These technologies improve economic efficiency by reducing transaction costs and facilitate technological innovation. However, digital infrastructure expansion increases electricity demand due to data centers, networks and digital services (Murty & Singh, 2026). Therefore, digitalization may initially increase energy consumption before improving efficiency. Empirical studies have demonstrated nonlinear relationships between digitalization and energy consumption (Bergman & Foxon, 2023).

2.3. Literature gap

Despite extensive research on renewable energy transition (RET), there exist significant research gaps in understanding the combined effect of digital economic infrastructure (DE) and green finance (GF) on renewable energy transition (RET) in India. Most of the existing studies has been on global context or multi-country panel data thus, offering limited country-specific insights. Despite India's distinctive institutional structure and rapidly growing green finance market with unique digital ecosystem driven by large-scale digital financial inclusion. While prior evidence suggests that digitalization and green finance individually promote renewable energy development but their combined and nonlinear connections remain inadequately examined. Moreover, existing research largely employs linear econometric models that may overlook heterogeneous and stage-dependent effects in short run and long run. There is limited study on use of advanced nonlinear approaches such as Multivariate Quantile-on-Quantile Regression (QQR) to analyze the DE - GF - RET relationship in India. These gaps are addressed in this study to capture dynamic interdependencies by constructing composite indices using PCA and employing nonlinear econometric techniques.

2.4. Theoretical Framework

An integrated theoretical framework has been adopted in this study through, Innovation Diffusion Theory (IDT), Institutional Theory, Environmental Kuznets Curve (EKC) and the Finance Growth grounded in Sustainable Development Theory. These theories explain the role of green finance (GF) and digital economic infrastructure (DE) that will influence India's renewable energy transition (RET) (Khezri, Karimi, & Naysary, 2026). Institutional Theory highlights the importance of regulatory frameworks, financial systems and policy support in facilitating renewable energy investment. The EKC hypothesis suggests that as India's income and technological capacity increases, the environmental degradation declines through adoption of cleaner energy which is supported by green finance (Leal & Marques, 2022). The Finance Growth Relationship emphasizes the importance of financial development in mobilizing capital and reducing investment barriers for renewable energy projects. Innovation Diffusion Theory explains the infrastructure efficiency, financial inclusion and renewable energy integration through digital technologies such as UPI, FASTag etc. These theories capture the nonlinear, interdependent and complementary roles of financial development and digitalization in accelerating India's sustainable energy transition.

3. Data and Methodology

3.1 Data sources and research design

This study examines the dynamic relationship between green finance (GF), digital economic infrastructure (DE) and renewable energy transition (RET) over the period between 2005 to 2026 in India's context. These multidimensional indicators representing renewable energy transition (RET), green finance (GF) and digital economic infrastructure (DE) are integrated empirically. The duration has been selected to capture all the major structural transformations in India's financial system, renewable energy deployment and digital infrastructure expansion (Cornelli, Frost, Gambacorta, Sinha, & Townsend, 2024). These transformations include the Digital India initiative with expansion of renewable energy capacity and widespread adoption of digital payment systems such as Unified Payments Interface (UPI) and FASTag.

Table 1: Data Indicators descriptions.

Index	Primary indicators	Unit / Measurement	Source of Data
Renewable Energy Transition (RET)	Renewable energy consumption	% of total energy consumption	World Bank (WDI)
	Renewable electricity generation	GWh	International Energy Agency (IEA)
	Renewable energy investment	USD	MNRE, Bloomberg NEF
	Carbon emissions	Metric tons per capita	World Bank (WDI)
	Carbon intensity	CO_2 emissions per GDP	World Bank (WDI)
	Energy intensity	Energy use per GDP	World Bank (WDI)
Green Finance (GF)	Green bond issuance	USD	Climate Bonds Initiative, SEBI
	Renewable energy financing	USD	RBI, Bloomberg NEF
	Climate finance flows	USD	RBI, OECD Climate Finance
	Green energy investment	USD	MNRE, IEA
Digital Economic Infrastructure (DE)	Internet users	% of population	World Bank (WDI), ITU
	Mobile cellular subscriptions	Per 100 people	World Bank (WDI), ITU
	Fixed broadband subscriptions	Per 100 people	World Bank (WDI), ITU
	Digital payment transactions	Volume (millions)	Reserve Bank of India (RBI)
	Unified Payments Interface (UPI) transactions	Volume (millions)	National Payments Corporation of India (NPCI)
	FASTag electronic toll transactions	Volume (millions)	NPCI, NHAI
	ICT goods exports	% of total goods exports	World Bank (WDI)
	ICT goods imports	% of total goods imports	World Bank (WDI)

Notes: Using Principal Component Analysis (PCA) RET, GF and DE are constructed as composite indices. Monetary variables: expressed at constant prices to adjust inflation. Logarithmic transformation used to reduce heteroskedasticity. Data collected annually over the period 2005 to 2026 from sources including WDI, IEA, MNRE, RBI, NPCI, SEBI and Bloomberg.

The study utilizes annual data obtained from multiple sources to ensure data reliability and consistency. Renewable energy transition (RET) indicators are obtained from the World Bank, World Development Indicators (WDI), International Energy Agency (IEA) and India's

Ministry of New and Renewable Energy (MNRE). Green finance indicators include green bond issuance and renewable energy investment flows are sourced from the Climate Bonds Initiative, Reserve Bank of India (RBI), Bloomberg New Energy Finance (BNEF) and SEBI databases. Digital economic infrastructure (DE) indicators include internet penetration, mobile subscriptions, broadband connectivity, UPI transactions, FASTag adoption and digital payment volumes which are obtained from the Reserve Bank of India, National Payments Corporation of India (NPCI), International Telecommunication Union (ITU) and World Bank databases.

3.2. Measurement of variables

The India's renewable energy transition (RET) is measured through the composite index which is constructed using Principal Component Analysis (PCA) which integrates carbon intensity, carbon emissions, energy intensity, renewable energy consumption and renewable energy investment. The structural progress toward low-carbon energy systems is captured through this multidimensional approach. On the basis of internet penetration, mobile subscriptions, broadband access, UPI transactions, FASTag usage and digital payment volumes the digital economy (DE) index is developed using PCA. The digital economy (DE) index reflects technological readiness and financial digitalization. Similarly, the index for green finance (GF) is proxied through green bond issuance, renewable energy financing and climate finance flows

3.3. Empirical methodology

The study employs advanced econometric techniques to examine the determinants of India's renewable energy transition (RET). The stationarity properties of the time series data are assessed using Augmented Dickey - Fuller (ADF), Phillips - Perron (PP), Elliott – Rothenberg - Stock (ERS), Perron - Vogelsang (PV) and Canova–Hansen tests to evaluate the stochastic behavior and integration order of the variables. The Brock – Dechert - Scheinkman (BDS) test is applied to examine nonlinearity and detect complex dependence structures within the data. For baseline estimation, both Bivariate and Multivariate Quantile-on-Quantile Regression (QQR) models are employed to capture nonlinear, heterogeneous and quantile-dependent interactions between green finance, digital economic infrastructure and renewable energy transition. Robustness is further validated using Kernel Regularized Least Squares (KRLS) and QQ comparison plots to ensure the stability and reliability of the estimates. Finally, the Granger causality (GC) test is conducted to identify the direction of causal relationships among the variables in the Indian context.

3.3.1. Quantile-on-Quantile Regression (QQR) approaches

Traditional quantile regression (QR) examines how explanatory variables influence different quantiles of a dependent variable's conditional distribution. However, QR does not account for how the distribution of explanatory variables themselves affects the dependent variable's distribution. The Bivariate Quantile-on-Quantile Regression (QQR) approach addresses this limitation by analyzing how the τ-th quantile of an explanatory variable affects the θ-th quantile of the dependent variable. Nevertheless, this approach becomes restrictive when multiple explanatory variables interact simultaneously. The Multivariate Quantile-on-Quantile Regression (QQR) framework extends by incorporating multiple explanatory variables, which enables the estimation of combined and nonlinear effects across the distribution (Uche, Das, Cifuentes-Faura, & Osabohien, 2025). This framework will examine the combined effects of green finance (GF) and digital economic infrastructure (DE) on India's renewable energy transition (RET) across different transition stages.

The functional form of the Multivariate QQR model is expressed as:

$$Z_t = \alpha_0(\theta, \psi_1, \psi_2, \dots, \psi_m) + \alpha_1(\theta, \psi_1)(W_{1t} - W_{1\psi_1}) + \alpha_2(\theta, \psi_2)(W_{2t} - W_{2\psi_2}) + \cdots + \alpha_m(\theta, \psi_m)(W_{mt} - W_{m\psi_m}) + \delta_\theta Z_{t-1} + \eta_t^\theta$$

where:

- Z_t represents the dependent variable: (RET)
- $W_{1t}, W_{2t}, \dots, W_{mt}$ represent independent variables: Green Finance Index (GF) and Digital Economic Infrastructure Index (DE)
- θ denotes the quantiles of the dependent variable distribution
- $\psi_1, \psi_2, \dots, \psi_m$ represent the quantiles of the explanatory variables
- $\alpha_m(\theta, \psi_m)$represents the quantile slope coefficients which captures nonlinear and distribution effects if any
- $\delta_\theta$represents the dynamic adjustment parameter for lagged dependent variable
- η_t^θ represents the error term.

3.3.2. Robustness estimations

This study employs Kernel Regularized Least Squares (KRLS) as nonparametric machine learning technique and Quantile-on-Quantile Regression (QQR) plots to ensure the robustness and reliability of the benchmark results. KRLS is particularly suitable for small sample sizes and effectively captures complex, nonlinear relationships without imposing restrictive functional form assumptions. While the Multivariate QQR approach identifies heterogeneous and distribution-specific effects of green finance (GF) and digital economic infrastructure (DE) on renewable energy transition (RET), particularly at lower and upper quantiles, KRLS complements this analysis by estimating the average marginal effects across the entire sample. This enables an evaluation of the overall economic significance of GF and DE in influencing India's renewable energy transition.

The average marginal effect of an explanatory variable Won the dependent variable $Z$is expressed as:

$$\mathbb{E}\left(\frac{\partial Z}{\partial W_i}\right) = \frac{1}{\lambda^2 M}\sum_{j=1}^{M} \omega_j \ \exp\left(\frac{\| W_i - W_j \|^2}{\lambda^2}\right)(W_i - W_j)$$

where: $\mathbb{E}\left(\frac{\partial Z}{\partial W_j}\right)$represents the expected marginal effect of explanatory variable Won the renewable energy transition index Z, Mrepresents the total number of observations, λdenotes the kernel bandwidth parameter controlling smoothness, $\omega_i$represents kernel weights and $\| W_i - W_j \|$denotes the Euclidean distance between observations.

Furthermore, the robustness of the Multivariate QQR estimates is evaluated by averaging quantile-specific slope coefficients across all quantiles of the explanatory variables. This produces standard quantile regression estimates for comparison, expressed as:

$$\bar{\alpha}(\theta) = \frac{1}{R}\sum_{r=1}^{R} \alpha(\theta, \psi_r) \qquad (3)$$

where:

$\bar{\alpha}(\theta)$: represents the averaged slope coefficient at quantile θ, R: represents the total number of explanatory variable quantiles and $\alpha(\theta, \psi_r)$: represents the Multivariate QQR slope coefficient.

The averaged QQR estimates, QQ plots and KRLS results provides comprehensive robustness validation. The QQR explores the stage dependent and nonlinear effects of green finance (GE) and digital economic infrastructure (DE) on India's renewable energy transition (RET). The KRLS confirms the statistically significant effects and financial feasibility on an average. This integrated approach further strengthens the reliability of the empirical findings and confirms the complementary roles of green finance (GF) and digital infrastructure (DE) in accelerating India's renewable energy transition (RET).

3.3.3. The granger causality test

The Granger causality (GC) test is employed to examine the directional relationships among the explanatory variables, green finance (GF) and digital economic infrastructure (DE) on the dependent variable, renewable energy transition (RET). This approach evaluates the statistical significance of past values of variable GF or DE, containing information that helps to predict future changes on RET. In the Indian context, this is important to understand whether the expansion of green bond markets, renewable energy financing and digital infrastructure and digital payment systems contributes in accelerating renewable energy transition. The GC test identifies both the existence and direction of causality (unidirectional or bidirectional), thereby providing critical insights into the dynamic and temporal interactions among dependent and explanatory variables.

4. Empirical results and discussion

4.1. Preliminary outcomes

The descriptive statistics summarized in Table 2 represents the statistics of India's renewable energy transition (RET), green finance (GF) and digital economic infrastructure (DE). The RET index has mean of 0.842 (range: 0.412 to 1.486, SD: 0.287) with positive skewness of 0.563, indicating stronger improvements in recent years with longer right tail. GF has a mean of 0.761 (range: 0.214–1.592, SD: 0.354), with positive skewness (0.742) and slightly leptokurtic distribution (kurtosis: 3.412), reflecting accelerated growth in green bond issuance and renewable energy financing. DE shows a mean of 1.114 (range: 0.305–2.385, SD: 0.521) with positive skewness (0.835), indicating rapid expansion in digital infrastructure driven by UPI, FASTag and digital payments. Jarque–Bera statistics confirm non-normality in GF and DE and marginal non-normality in RET. Centered VIF values indicate no multicollinearity. These results justify the application of nonlinear and quantile-based econometric methods.

Table 2:Descriptive statistics.

	RET	GF	DE
Mean	0.842	0.761	1.114
Median	0.791	0.704	1.042
Maximum	1.486	1.592	2.385
Minimum	0.412	0.214	0.305
Std. Dev.	0.287	0.354	0.521
Skewness	0.563	0.742	0.835
Kurtosis	2.918	3.412	2.756
Jarque–Bera	5.284	8.917	10.462

Probability	0.071	0.012	0.005
Centered VIF	—	1.28	1.34

4.2. Unit root test

To assess stationarity, five complementary unit root tests (i) Augmented Dickey - Fuller (ADF), (ii) Phillips - Perron (PP), (iii) Elliott-Rothenberg-Stock (ERS), (iv) Perron - Vogelsang (PV) and (v) Canova-Hansen are applied, as reported in Table 3, using India's annual data from 2005 to 2026. The results indicate that the Renewable Energy Transition (RET), Green Finance (GF) and Digital Economic Infrastructure (DE) indices are non-stationary at levels but become stationary after first differencing, with statistical significance at the 1% level. This confirms that all variables follow an integrated order of one, I(1), process, thereby avoiding spurious regression and supporting the use of quantile-based econometric techniques.

Table 3: Unit root tests results.

Tests	RET		GF		DE	
	Level	Δ	Level	Δ	Level	Δ
ADF	−2.147	−7.184*	−1.928	−7.962*	−1.563	−7.438*
PP	−2.284	−7.362*	−1.741	−8.114*	−1.704	−7.615*
ERS	−1.203	−9.287*	−1.388	−9.874*	−1.116	−9.042*
PV	−3.426	−15.973*	−3.912	−11.548*	−4.317	−10.283*
Break Date	2020	2021	2016	2017	2019	2020
Canova - Hansen	1.438		2.017		1.862	

*Note: * and ** indicate statistical significance at the 1% and 5% levels, respectively. Canova - Hansen critical values: K = 11, 1%: 3.270, 5%: 2.750.*

Structural break analysis identifies key transition periods in India is summarised in figure-1. In year 2015-16, corresponds to the rapid expansion of green bond markets and renewable energy investments; in year 2016-17, reflects the major digital transformation with introduction of Unified Payments Interface (UPI) and Digital India initiatives; while in year 2019-20, associates with nationwide FASTag execution and accelerated capacity expansion of renewable energy. Further there was significant regime shifts in India's renewable energy transition over the extended period between 2020 to 2026 in line with earlier breakpoints. The break around 2020-2021 reflects the impact of the COVID-19 pandemic which disrupted energy demand, followed by a rapid recovery driven by green investments and accelerated digital adoption. The subsequent phase between 2022-26) represents consolidation and expansion supported by strengthened green finance mechanisms, increased renewable energy capacity and further integration of digital technologies like smart grids and AI-based energy management. The Perron-Vogelsang test (PV) effectively captures these structural shifts. The Canova-Hansen statistics confirm the absence of seasonal instability. Thus, validation of dynamic regime changes and support the application of nonlinear and quantile-based econometric techniques.

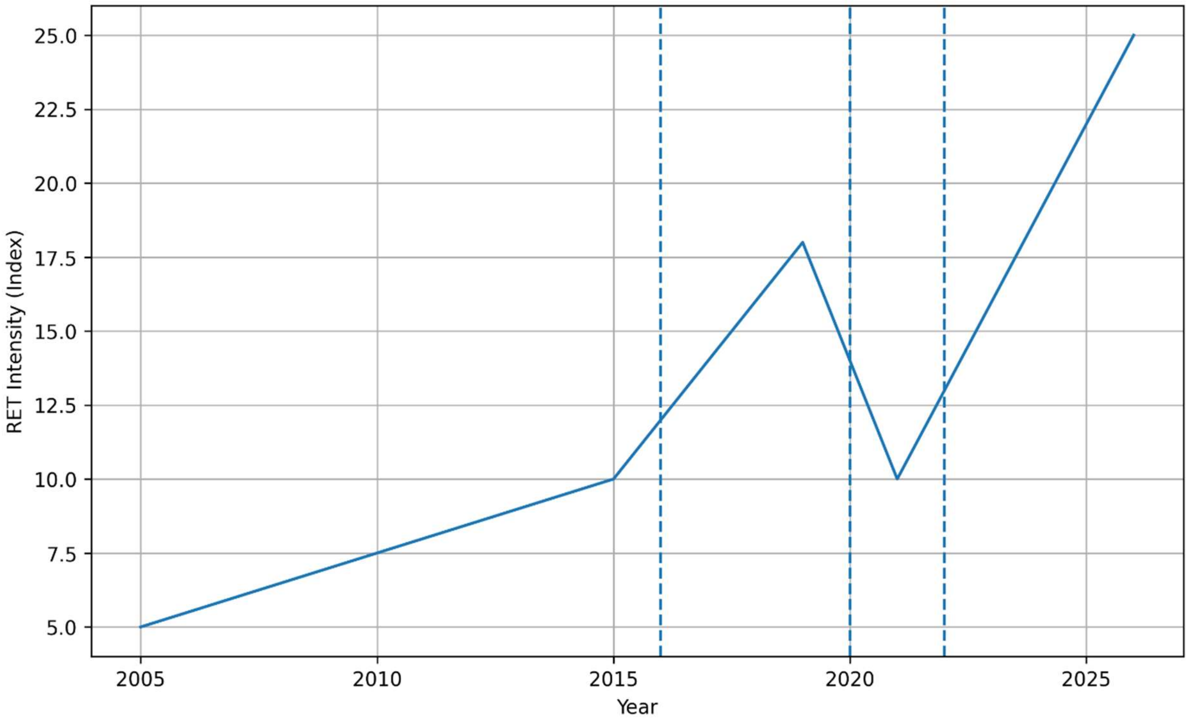

Figure 1: Lifecycle of India's Renewable Energy Transition (2005–2026)

4.3. Test for nonlinearity

The Brock-Dechert-Scheinkman (BDS) test is conducted before applying nonlinear estimation techniques in order to evaluate the independence and linearity assumptions of the data. Table 4 presents the BDS test results for the Renewable Energy Transition (RET), Green Finance (GF) and Digital Economic Infrastructure (DE) indices across the dimensions (m = 2 to 6) for over the period 2005 to 2026. The z-statistics is significant at 1% level across all embedding dimensions and variables. This leads to rejection of the null hypothesis of independent and identical distribution of residuals. These results confirm the presence of nonlinear dependence and complex distributional dynamics among RET, GF and DE. Thus, linear econometric models may be insufficient to capture the fundamental relationships. Therefore, the Multivariate Quantile-on-Quantile Regression (QQR) framework is justified to effectively capture nonlinear, asymmetric and heterogeneous interactions between variables under study.

Table 4: BDS test for nonlinearity.

Variables	m = 2	m = 3	m = 4	m = 5	m = 6

	z-stat	p-value	z-stat	p-value	z-stat	p-value	z-stat	p-value	z-stat	p-value
RET	18.437	0.000	19.652	0.000	21.183	0.000	23.417	0.000	26.104	0.000
GF	15.926	0.000	16.884	0.000	18.273	0.000	20.491	0.000	23.258	0.000
DE	21.743	0.000	22.981	0.000	24.615	0.000	27.104	0.000	30.492	0.000

Note: m represents embedding dimensions. The null hypothesis assumes independent and identically distributed (i.i.d.) residuals. Residuals are rejected at 1% significance in all cases.

4.4 Benchmark estimation-quantile-on-quantile regression(QQR)

The primary objective of this study is to examine the impact of green finance (GF) and digital economic infrastructure (DE) on India's renewable energy transition (RET). Using Bivariate and Multivariate Quantile-on-Quantile Regression (QQR) approaches, the analysis captures how these relationships vary across different quantiles of the variables. Specifically, the slope function $\alpha_1(\theta, \tau)$measures how the θ-th quantile of GF and DE influences the τ-th quantile of RET. Figures 1 and 2 present the Bivariate-QQR estimates for the models $RET = \hat{f}(GF)$and $RET = \hat{f}(DE)$, where the axes represent the quantiles of the explanatory variables and RET. Figures 3 display the Multivariate-QQR results for the models $RET = \hat{f}(GF, DE)$and $RET = \hat{f}(DE, GF)$. These three-dimensional surfaces illustrate the combined effects of GF and DE on RET; the color scale indicates the magnitude and direction of the QQR coefficients where blue represents negative scale and yellow-red indicates the positive. This reflects the direct and conditional strength of their combined influence on India's renewable energy transition (RET).

Bivariate Quantile-on-Quantile Regression

Figures 2 and 3 shows the nonlinear impact of green finance (GF) and digital economic infrastructure (DE) on renewable energy transition (RET). The Figure 2 illustrates the weak and negative effect of GF on RET at lower quantiles of 0.05 to 0.45 which suggest that there is limited financial intensity and insufficient investment capacity in initial stages of transition. At median quantiles of 0.50 to 0.60, indicates transitional inefficiencies and policy constraints and impact remains modest. At higher quantiles of 0.65 to 0.95, the impact of GF is strongly positive which suggest that sustained financial development significantly enhances renewable energy deployment and infrastructure expansion.

Figure 3 shows dual effect of DE on RET, as at lower quantiles of 0.05 to 0.45 the DE negatively affects RET, particularly at higher levels of digitalization due to increased energy demand. At the median quantiles of 0.50 to 0.65 the relationship stabilizes with transition towards efficiency gains. At higher quantiles of 0.70 to 0.95, the DE exhibits a positive effect on RET which suggest that the DE has significant role in improving energy efficiency thus enabling smart grid integration and facilitate renewable energy adoption. These findings underline strong nonlinear and stage-dependent dynamics.

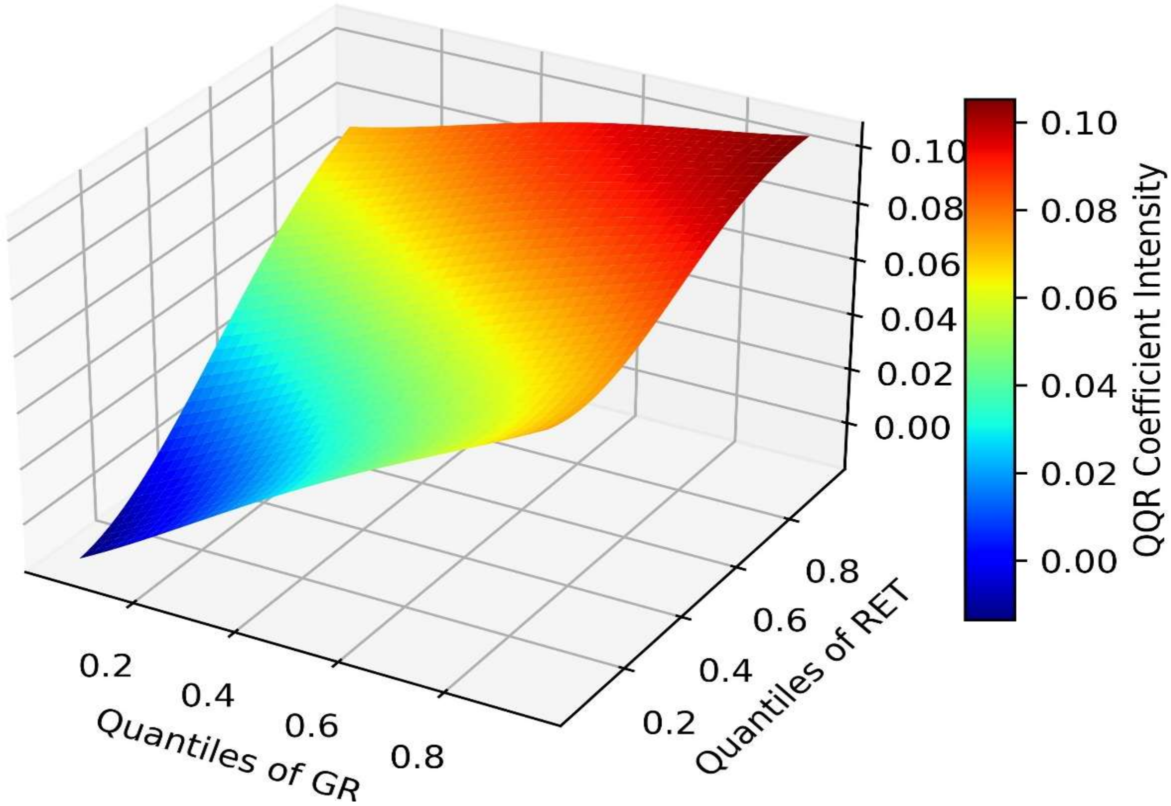

Figure 2: The Bivariate-QQR results showing influence of GF of RET

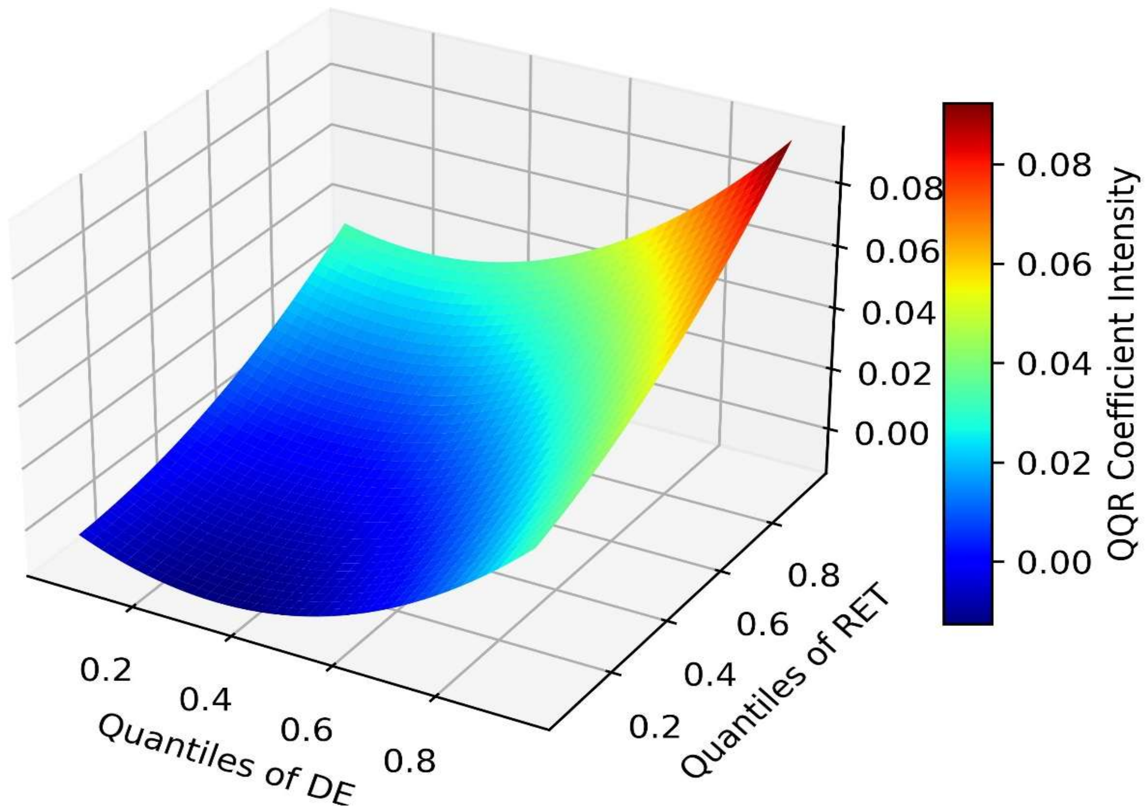

Figure 3:The Bivariate-QQR results showing influence of DE of RET

Figures 2 indicate that green finance (GF) has significant impact at higher quantiles, supporting the expansion of green bonds with targeted financial incentives in order to accelerate renewable energy transition (RET). In contrast to GF, the digital economic infrastructure (DE) initially constrains RET due to increased energy demand. But as digital systems mature the impact of DE becomes positive and integrates with energy infrastructure. These findings support the importance of digitalization with clean energy strategies. Coordinated investment in both GF and DE is therefore critical for achieving Sustainable Development Goal-7 (SDG-7).

Multivariate-QQR

The multivariate QQR estimates for India is presented in Figure 4, which captures the joint effects of green finance (GF) and digital economic infrastructure (DE) on renewable energy transition (RET) under conditional environment. When GF is analyzed under conditional on DE, the slope surface exhibits nonlinearity. At lower quantiles of GF and DE at around 0.30, RET improvements remain limited which reflects the constrained financial depth and underdeveloped digital infrastructure in initial stages. At medium quantiles of 0.40 to 0.70, there is a clear synergistic effect of GF and DE jointly in enhancing RET. The enhanced performance of RET is due to improved capital allocation, digital integration and energy efficiency. However, at higher GF quantiles of more than 0.70, RET gains tend to plateau when

DE remains low which suggests that the financial expansion alone is insufficient without adequate digital support.

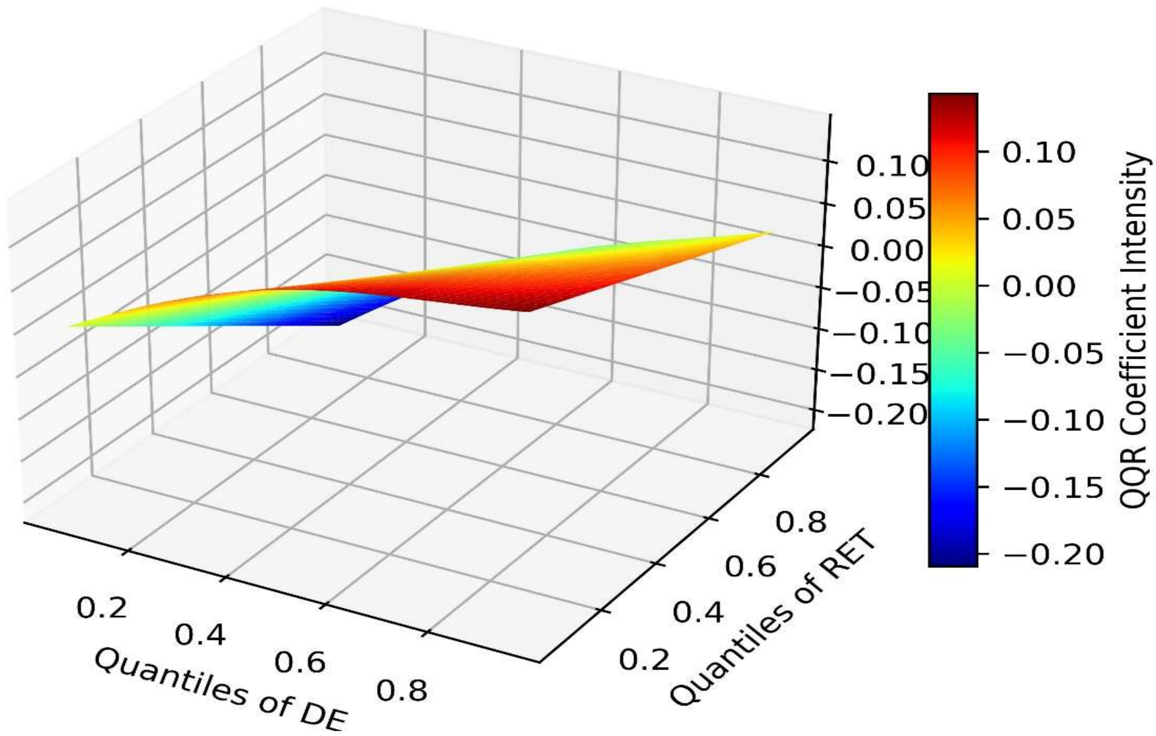

Figure 4: Estimates of Multivariate QQR evaluating the impact of GE on RET, considering the role of GF

When DE is examined under conditional environment on GF, the surface shows a negative and weak effect at lower quantiles at around 0.30. This suggest that there are transitional energy costs which is associated with digital expansion in India. At medium quantiles of 0.40 to 0.70, the effect stabilizes but remains dependent on financial support. At higher quantiles of 0.70 to 0.95, DE significantly promotes RET. This indicates that at maturity-stage both financial depth and digital readiness jointly accelerate renewable energy adoption.

Robustness Analysis

The reliability of the benchmark estimates is ensured by robustness tests, which are conducted using QQ plots and KRLS approaches. Figs. 5 and 6 compares the quantile slope estimates with τ-averaged QQR coefficients for the models RET = f(GF, DE) and RET = f(DE, GF) respectively. The close proximity of the QR estimates and the averaged QQR coefficients confirms that the QQR results are robust and are not driven by model-specific assumptions. The upward trend across quantiles further indicates that the effects of GF and DE strengthen as India progresses toward higher stages of renewable energy transition.

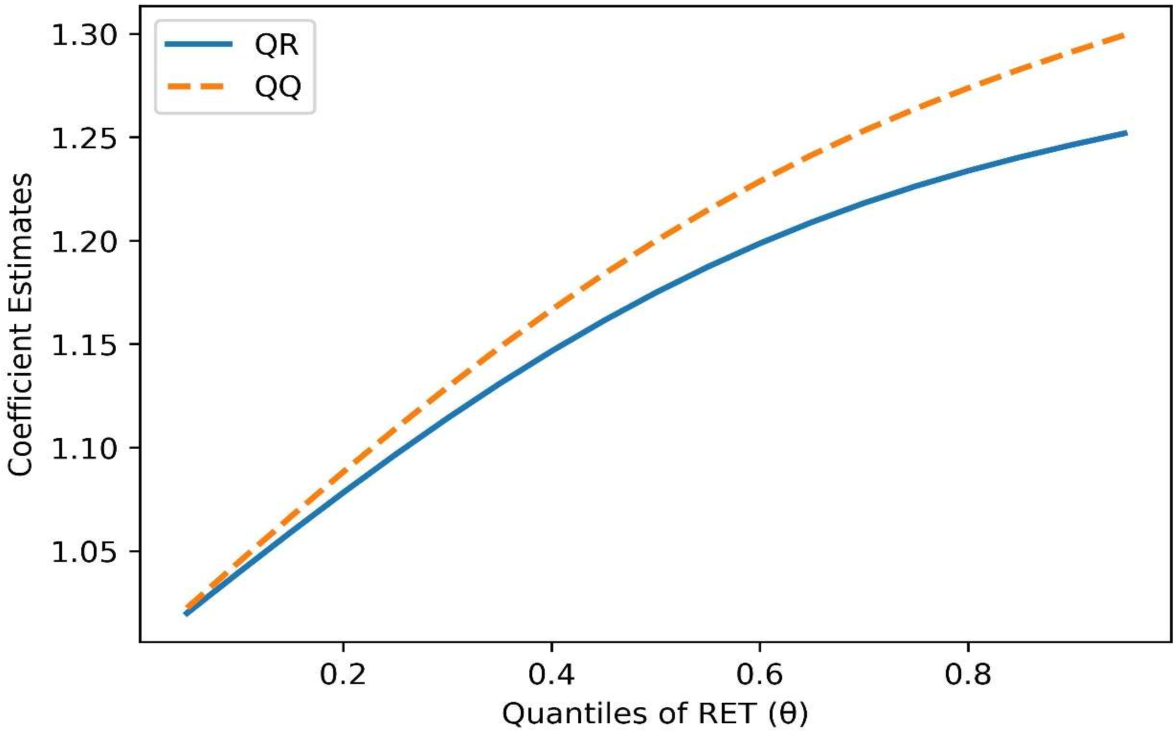

Figure 5: Robustness check outcome of the Model RET=ˆf(GF, DE): Comparison of QR and averaged QQR estimates

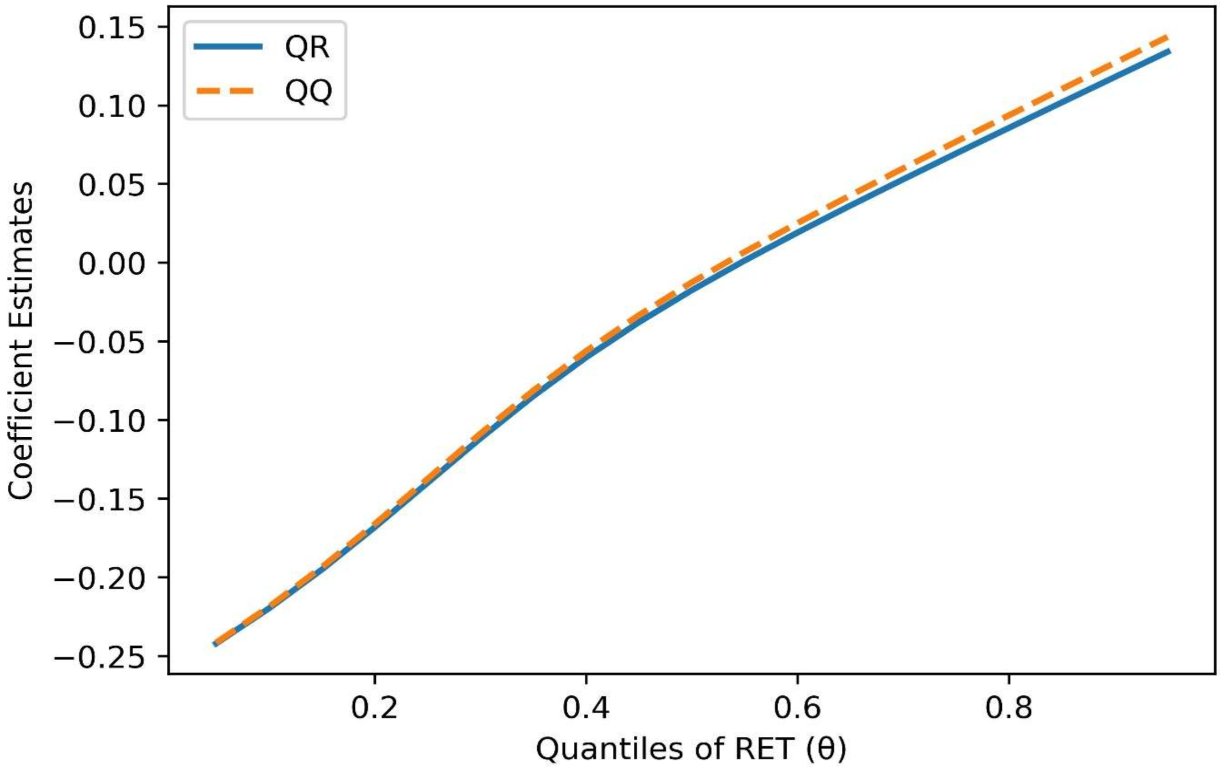

Figure 6: Robustness check outcome for the Model RET=ˆf(DE, GF): Comparison of QR and averaged QQ estimates

To further reinforce the empirical findings the KRLS approach is applied, summarised in Table 5. The results show that with 1% increase in green finance (GF) parameters there is an average

0.132% increase in RET. This highlights the role of growing green bonds with renewable financing and climate investment, supporting India's clean energy infrastructure. In contrast, with 1% increase in digital economic infrastructure (DE) there is larger average gain of 0.521% on RET. This reflects the significant contribution of digital systems in enhancing efficiency and facilitating renewable integration. The wider interquartile range for DE indicates greater variability which indicates that the impact of digitalization differs across regions and different development stages in India. These findings confirm that while green finance provides the required capital support, the digital infrastructure plays a more dynamic and transformative role in accelerating India's renewable energy transition.

Table 5: KRLS average marginal effects.

RET	Avg.	SE	t-value	p-value	P25%	P50%	P75%
GF	0.132***	0.028	4.714	0.000	0.018	0.094	0.287
DE	0.521***	0.071	7.338	0.000	−0.164	0.041	0.168
R^2	0.948	Lambda	0.047	Sigma	2	Looloss	0.982

Note: *The statistical significance at the 5% and 1% levels are * and *** respectively. P25%, P50% and P75% represent the 25th, 50th and 75th percentile marginal effects.*

Granger causality analysis

The Granger causality (GC) test is employed to examine the directional relationships of green finance (GF), digital economic infrastructure (DE) and renewable energy transition (RET). This approach enables the dynamic linkages and potential feedback mechanisms within the empirical framework.

Table 6: The Granger Causality test.

Null Hypothesis	F-Statistic
GF does not Granger Cause RET	21.483***
RET does not Granger Cause GF	0.936
DE does not Granger Cause RET	15.762***
RET does not Granger Cause DE	6.418**
DE does not Granger Cause GF	3.127*
GF does not Granger Cause DE	1.284

Note: **, ** and *** indicate statistical significance at the 10%, 5% and 1% levels, respectively.*

The GC results are reported in Table 6, suggesting unidirectional causality from GF to RET at 1% Level of significance. The finding suggests that the expansion of green finance through green bonds, renewable energy financing and climate investment flows plays a decisive role in driving renewable energy transition. However, the absence of reverse causality implies that improvements in RET do not immediately translate into increased green financial flows, indicating rigidity in financial markets in terms of structural and institutional readiness. There is bidirectional causality between DE and RET, significant at the 1% and 5% levels. This works as a feedback mechanism where digital infrastructure enhances renewable energy efficiency and integration, while the expansion of renewable energy systems stimulates demand for digital technologies. No significant causality is observed between GF and DE which shows that financial and digital systems in India operate relatively independent. These findings highlight the need for integrated policy frameworks for better alignment of financial development and digital transformation in accelerating India's renewable energy transition.

Discussion

This study provides robust evidence that green finance (GF) and digital economic infrastructure (DE) play critical and stage-dependent roles in advancing India's renewable energy transition (RET). The quantile-based results reveal significant heterogeneity, indicating that the effectiveness of financial and digital drivers varies systematically across different stages of the transition process which is consistent with findings in other emerging economies (Wei, Wu, & Anser, 2025). GF exhibits weak and negative effects at lower RET quantiles which suggest that the fragmented financial systems, limited green bond penetration and insufficient capital mobilization are inadequate to overcome the high investment costs and risks associated with early-stage renewable energy projects in India. However, as GF progresses to higher quantiles, its impact is strongly positive and indicates accelerated investment mechanism whereby sustained financial depth supports large-scale renewable deployment, infrastructure expansion and technological advancement similar observations were highlighted in the prior study's findings (Wong, Sun, Wang, & Kim, 2025). This underscores the importance of scaling up and stabilizing green financial instruments in India's evolving energy landscape.

The DE has significant nonlinear dynamics as at lower RET quantiles the digitalization exerts adverse effects which reflects that the transitional costs associated with increased electricity demand due to expanding digital infrastructure. The increased demand is driven by data centres, digital payments and communication networks. However, at median RET quantiles the DE becomes gradually positive, through efficiency-enhancing channels such as smart grids, real-time monitoring and digital energy management systems. This suggests that digitalization contributes to environmental sustainability only when supported by adequate energy infrastructure and institutional readiness which is consistent with the findings in European Union (Thanh, Ha, Dung, & Huong, 2023). Furthermore, the multivariate QQR results highlight strong complementarity between GF and DE. The explanatory variables have no substantial effect independently on RET improvements at lower levels however, their combined presence at moderate-to-high quantiles produces the strong effects. Thus, for effective renewable energy transition, there is need for financial capital and digital readiness which must co-evolve to effectively support for energy transition in India.

These findings provide strong empirical support for the theoretical framework. The observed nonlinear and heterogeneous effects are consistent with Environmental Kuznets Curve (EKC) dynamics as environmental improvements strengthen at higher levels of development. The complementarity between GF and DE aligns with Institutional Theory which emphasizes the role of financial depth, technological readiness and policy support. Moreover, the delayed yet positive impact of DE at higher quantiles supports Innovation Diffusion Theory, highlighting threshold effects and staged adoption processes in India's energy transition. Therefore, there is need for integrated financial and digital policy frameworks to accelerate India's transition toward sustainable energy systems.

Policy Implications

The findings shows that green finance (GF) and digital economic infrastructure (DE) play critical and heterogeneous roles in advancing India's renewable energy transition (RET). There is requirement of differentiated and stage-specific policy responses for effective growth in renewable energy transition. GF emerges as a key driver at advanced transition stages, through strengthening green bond markets, improving disclosure standards and enhancing monitoring and verification mechanisms. Aligning India's green taxonomy with international frameworks and expanding participation from institutional investors can further deepen financial markets and improve capital allocation efficiency.

Digital economic infrastructure shows significant positive effects primarily at medium-to-high RET levels, suggesting that digital investments yield optimal outcomes only when supported by adequate energy infrastructure and institutional capacity. Policy efforts should therefore prioritize the deployment of smart grids, digital metering, AI-enabled energy management systems and real-time monitoring technologies, particularly in energy-deficient and transition-lagging regions. Public–private partnerships can play a crucial role in scaling such digital investments.

The strong complementarity between GF and DE underscores the need for integrated policy instruments. Innovative mechanisms such as performance-linked green bonds and digital-finance-enabled energy platforms can incentivize the adoption of smart renewable technologies. Additionally, regional disparities across Indian states necessitate place-based policy approaches, ensuring that financial and digital interventions are tailored to local development levels. Finally, quantile-specific evidence supports the design of tiered subsidies, targeted financial incentives and phased digital infrastructure investments aligned with sectoral and regional stages of renewable energy transition.

Limitations and Future Research

This study is combined with exploring new direction as well as with certain limitations. First, the heterogeneous quantile effects indicate strong context dependence which limits the uniform applicability for policy recommendations. So, there is need for region and sector-specific analyses within India. Given significant interstate disparities in financial development, digital infrastructure and renewable energy capacity, the future studies should adopt panel approaches at the state level. Second, the focus on green finance (GF) and digital economic infrastructure (DE) indicators may suppress other critical drivers like regulatory quality, carbon pricing, institutional effectiveness and global energy market dynamics. Third, although the dataset extends to recent years, it may not fully capture evolving dynamics associated with post-pandemic recovery, energy price volatility and geopolitical disruptions affecting energy markets. Future research should incorporate updated data and examine structural breaks more explicitly. Disaggregation of digitalization into components such as artificial intelligence (AI), blockchain, Internet of Things (IoT) and smart grid technologies would provide more granular insights. Finally, comparative cross-country analyses and the inclusion of equity-oriented indicators such as energy access, affordability and regional inclusiveness would enhance understanding of sustainable and inclusive renewable energy transitions.

Conclusion

This study examined the impact of green finance (GF) and digital economic infrastructure (DE) in driving India's renewable energy transition (RET). The advanced econometric techniques like Bivariate and Multivariate Quantile-on-Quantile Regression (QQR) have been used. These tests are complemented by robustness checks such as Kernel Regularized Least Squares (KRLS) and quantile plots. These approaches capture nonlinear, heterogeneous and stage-dependent effects offering deeper insights than conventional linear models. The findings disclose the importance of GF which has consistent and positive role at advanced stages of the transition through mobilization of capital for renewable projects and supporting technological advancement and infrastructure development. In contrast to GF, the DE exhibits a more complex and stage-dependent effect on RET. Initially constraining RET due to increased energy demand but becomes strongly supportive at higher levels by enhancing efficiency, smart grid integration and energy management. The interaction between GF and DE generates a complementary effect, indicating that financial depth and digital readiness must evolve jointly to maximize renewable energy outcomes. These results underscore the need for coordinated, stage-specific financial and digital policies to accelerate India's renewable energy transition and achieve Sustainable Development Goal-7.

- **Ethical Approval:** Publicly available secondary data was considered.
- **Funding:** Not Applicable
- **Declaration of Competing Interest:** No competing interests.
- **Acknowledgments:** The generative artificial intelligence tools (ChatGPT by OpenAI) were used to assist with language refinement, grammatical editing.
- **Data Availability Statement:** The study is based on secondary data obtained from publicly available sources Data are collected annually for India over the period 2005–2026 from multiple authoritative sources including WDI, IEA, MNRE, RBI, NPCI, SEBI and Bloomberg New Energy Finance. The dataset was compiled and processed by the authors and is available from the corresponding author upon reasonable request for academic purposes.

Appendix

Principal Component Analysis (PCA) for Index Construction

Table A 1:RET-PCA

Component	**Eigenvalue**	**Variance Explained (%)**	**Cumulative (%)**
PC1	3.2148	53.58%	53.58%
PC2	1.8472	30.79%	84.37%
PC3	0.5926	9.88%	94.25%
PC4	0.3454	5.75%	100.00%

Indicator	**PC1 Coefficient**
Renewable Energy Investment	0.7421
Renewable Energy Consumption	0.6894
Carbon Emissions	−0.6187
Carbon Intensity	−0.7035
Energy Intensity	−0.6712

Table A 2: DE-PCA

Component	**Eigenvalue**	**Variance Explained (%)**	**Cumulative (%)**
PC1	4.1253	58.93%	58.93%
PC2	1.7641	25.20%	84.13%
PC3	0.6894	9.85%	93.98%

PC4	0.4236	6.02%	100.00%
PC5	0.0985	—	—
PC6	0.0417	—	—

Indicator	**PC1 Coefficient**
Digital Payment Transactions	0.8452
UPI Transactions	0.8237
FASTag Transactions	0.7924
Internet Users	0.7318
Fixed Broadband Subscriptions	0.7031
Mobile Cellular Subscriptions	0.6826
ICT Exports	0.4215
ICT Imports	0.3862

References

1. Adebayo, T. S., & Özkan, O. (2024). Evaluating the role of financial globalization and oil consumption on ecological quality: A new perspective from quantile-on-quantile granger causality. *Heliyon, 10*(2). doi:https://doi.org/10.1016/j.heliyon.2024.e24636
2. Alahmadi, M. (2024). Optimizing Data Quality for Sustainable Development: An Integration of Green Finance with Financial Market Regulations. *Sustainability, 16*(23), 1-17. doi:https://doi.org/10.3390/su162310418
3. Berg, A., Borensztein, E., Sahay, R., & Zettelmeyer, J. (2024). The evolution of output in transition economies: explaining the differences. *The Economics of Transition: The Fifth Nobel Symposium in Economics* (pp. 144-212). London: Palgrave Macmillan UK.
4. Bergman, N., & Foxon, T. J. (2023). Drivers and effects of digitalization on energy demand in low-carbon scenarios. *Climate Policy, 23*(3), 329-342. doi:https://doi.org/10.1080/14693062.2022.2145260
5. Bisht, A. S., & Sharma, T. (2025). Indian power sector decarbonization: Net-zero by 2050 or 2070. *Energy for Sustainable Development, 85*, 1-32. doi:https://doi.org/10.1016/j.esd.2024.101637
6. Cornelli, G., Frost, J., Gambacorta, L., Sinha, S., & Townsend, R. M. (2024). The organisation of digital payments in India–lessons from the Unified Payments Interface (UPI). *SUERF Policy Note*, 61-73.
7. Elkhatat, A., & Al-Muhtaseb, S. (2024). Climate change and energy security: a comparative analysis of the role of energy policies in advancing environmental sustainability. *Energies, 17*(13), 1-31. doi:https://doi.org/10.3390/en17133179

8. Erdoğdu, A., Dayi, F., Özbek, A., Ganji, F., & Benek, A. (2025). The role of green finance in investing in environmentally friendly technologies: Risks and returns. *Sustainability, 17*(21), 1-39. doi:https://doi.org/10.3390/su17219652
9. Erdoğdu, A., Dayi, F., Yanik, A., Yildiz, F., & Ganji, F. (2025). Innovative solutions for combating climate change: Advancing sustainable energy and consumption practices for a greener future. *Sustainability, 17*(6), 1-39. doi:https://doi.org/10.3390/su17062697
10. Fu, C., Lu, L., & Pirabi, M. (2023). Advancing green finance: a review of sustainable development. *Digital Economy and Sustainable Development, 1*(1), 1-19. doi:https://doi.org/10.1007/s44265-023-00020-3
11. Gbadeyan, O. J., Muthivhi, J., Linganiso, L. Z., & Deenadayalu, N. (2024). Decoupling economic growth from carbon emissions: a transition toward low-carbon energy systems—a critical review. *Clean Technologies, 6*(3), 1076-1113. doi:https://doi.org/10.3390/cleantechnol6030054
12. Idries, A., Krogstie, J., & Rajasekharan, J. (2022). Challenges in platforming and digitizing decentralized energy services. *Energy Informatics, 5*(1), 1-29. doi:https://doi.org/10.1186/s42162-022-00193-9
13. Johri, S., Selvakumar, P., Satyanarayana, P., Das, A., Gupta, S., & Bhattacharya, S. (2025). Urbanization and energy: The nexus of global challenges. *Geopolitical landscapes of renewable energy and urban growth* (pp. 453-478). IGI Global Scientific Publishing. doi:10.4018/979-8-3693-8814-3.ch016
14. Kabeyi, M. B., & Olanrewaju, Q. A. (2022). Sustainable energy transition for renewable and low carbon grid electricity generation and supply. *Frontiers in Energy research, 9*, 1-45. doi:https://doi.org/10.3389/fenrg.2021.743114
15. Khezri, M., Karimi, M. S., & Naysary, B. (2026). Exploring the impact of entrepreneurial indicators on CO2 emissions within the environmental Kuznets curve framework: a cross-sectional study. *Environment, development and sustainability, 28*(1), 2025-2059. doi:https://doi.org/10.1007/s10668-024-05050-1
16. Kishore, T. S., Kumar, P. U., & Ippili, V. (2025). Review of global sustainable solar energy policies: Significance and impact. *Innovation and Green Development, 4*(2), 1-15. doi:https://doi.org/10.1016/j.igd.2025.100224
17. Kumar, J., C, R., & Majid, M. A. (2020). Renewable energy for sustainable development in India: current status, future prospects, challenges, employment, and

investment opportunities. *Energy, Sustainability and Society, 10*(1). doi:https://doi.org/10.1186/s13705-019-0232-1

18. Kumar, P., Taneja, S., & Ozen, E. (2025). Exploring the influence of green bonds on sustainable development through low-carbon financing mobilization. *International Journal of Law and Management, 67*(2), 249-270. doi:https://doi.org/10.1108/IJLMA-01-2024-0030
19. Kumari, D., Shashwat, S., Verma, P. K., & Giri, A. K. (2025). Examining the nexus between carbon dioxide emissions, economic growth, fossil fuel energy use, urbanization and renewable energy towards achieving environmental sustainability in India. *International Journal of Energy Sector Management, 19*(3), 731-746. doi:https://doi.org/10.1108/IJESM-05-2024-0007
20. Leal, P. H., & Marques, A. C. (2022). The evolution of the environmental Kuznets curve hypothesis assessment: A literature review under a critical analysis perspective. *Heliyon, 8*(11), 1-18. doi:https://doi.org/10.1016/j.heliyon.2022.e11521
21. Murty, S., & Singh, V. (2026). Green finance as an institutional catalyst for sustainable technology, entrepreneurship, and economic transitions toward the SDGs. *Sustainable Technology and Entrepreneurship, 5*(2), 100133. doi:https://doi.org/10.1016/j.stae.2026.100133
22. Prabhakar, A. (2025). A sustainable and inclusive economic development: a global imperative: a global imperative. *Journal of Recycling Economy & Sustainability Policy, 4*(1), 1-16. doi:https://doi.org/10.1002/sd.70082
23. Saha, R., & Maji, S. G. (2025). Do green bonds reduce CO2 emissions? Evidence from developed and developing nations. *International Journal of Emerging Markets, 20*(7), 2913-2934. doi:https://doi.org/10.1108/IJIS-10-2020-0213
24. Thanh, T. T., Ha, L. T., Dung, H. P., & Huong, T. L. (2023). Impacts of digitalization on energy security: evidence from European countries. *Environment, development and sustainability, 25*(10), 11599-11644. doi:https://doi.org/10.1007/s10668-022-02545-7
25. Uche, E., Das, N., Cifuentes-Faura, J., & Osabohien, R. (2025). Globalization, remittances, and income inequality: a novel multivariate quantile-on-quantile regression (M-QQR) perspective for top receiving countries. *Journal of the Knowledge Economy*, 1-29. doi:https://doi.org/10.1007/s13132-025-02738-1
26. Udo, E. S., Ekwunife, F. C., Ibobo, B. I., Idamoyibo, H. R., Atakpa, O. E., & Stephen, O. U. (2025). Green finance development, governance quality, and environmental

sustainability: Evidence from Sub-Saharan Africa. *Southern African Business Review, 29*, 1-21. doi:https://doi.org/ 10.25159/1989-8125/15782

27. Wang, B., Wang, Q., Wei, Y. M., & Li, Z. P. (2018). Role of renewable energy in China's energy security and climate change mitigation: An index decomposition analysis. *Renewable and sustainable energy reviews, 90*, 187-194. doi:https://doi.org/10.1016/j.rser.2018.03.012
28. Wei, J., Wu, Y., & Anser, M. K. (2025). Unpacking the drivers of sustainable development: a quantile-based analysis of digitalization, resource efficiency, and economic diversification. *Environment, Development and Sustainability*, 1-28. doi:https://doi.org/10.1007/s10668-025-06751-x
29. Wen, B., He, Y., Jing, X., & Haroon, M. (2025). Advancing renewable energy and green finance for economic growth and ecological resilience. *Energy Strategy Reviews, 59*, 1-12. doi:https://doi.org/10.1016/j.esr.2025.101747
30. Wong, X., Sun, P., Wang, A., & Kim, J. (2025). Will digital economy, green innovation and renewable energy become catalysts for sustainable development? New insights from quantile and time perspectives. *Sustainability Accounting, Management and Policy Journal*. doi:https://doi.org/10.1108/SAMPJ-10-2024-1153