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How Does Fintech Affect Green Total Factor Energy Efficiency? Evidence from 240 Cities in China

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Abstract

Improving the green total factor energy efficiency (GTFEE) is an important way to adhere to sustainable development. This paper evaluates the impact of fintech on GTFEE based on an SBM-Malmquist-Luenberger model with annual data from 2011 to 2021 of 240 cities in China. The findings reveal that fintech can significantly promote GTFEE and the conclusion remains robust after conducting the endogeneity test and substituting the independent and dependent variables. Specifically, the mechanism analysis indicates that fintech can improve GTFEE by alleviating financing constraints and promoting technological innovation. What's more, fintech significantly enhances GTFEE in eastern China, non-resource-based cities, service cities, and larger-sized urban centers. This study provides valuable policy implications for promoting the energy efficiency.

Keywords*:* fintech; green total factor energy efficiency; financing constraints; technological innovation

JEL: P28; Q56; R11

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1. Introduction

Amidst the converging historical processes of an intensifying global climate crisis and accelerating sustainable development, enhancing energy utilization efficiency has become paramount for the international community in jointly tackling climate change challenges and achieving a green, low-carbon transition. The *Renewable Energy Statistics 2025* released by the International Renewable Energy Agency (IRENA) indicates that the global renewable energy installed capacity achieved a compound annual growth rate (CAGR) of 15.1% from 2017 to 2024. In 2024, global renewable capacity additions reached 585 gigawatts (GW), accounting for 92.5% of the total expansion in power generation capacity. Countries worldwide are exploring low-carbon development pathways through means such as technological innovation, policy incentives, and market regulation (Shangguan et al., 2025) [1]. **Within this process, fintech is increasingly emerging as a crucial force driving the energy transition (Wu et al., 2025) [2].** Smart algorithms significantly enhance renewable energy utilization rates by optimizing energy resource allocation; for instance, machine learning-driven grid load forecasting systems can effectively mitigate the intermittency issues associated with wind and solar power generation (Benti et al., 2023) [3]. Blockchain technology constructs transparent carbon asset trading systems, substantially reducing the costs of green certification and cross-border settlement (Su et al., 2024) [4]. Meanwhile, big data-empowered ESG investment analytics tools systematically transform capital allocation efficiency within the low-carbon sector (Liu et al., 2024) [5]. **It is evident that fintech holds significant importance for**

improving GTFEE, providing the foundational framework for the transition of human civilization from an industrial-metabolic model to a digital-ecological paradigm.

China's rapid economic growth has incurred severe environmental costs. Characterized by excessive resource input, high energy consumption, and substantial pollution, this unsustainable development model poses critical challenges (Zhou et al., 2022) [6]. To address this, China's "dual-carbon" targets not only demonstrate its international commitment but also aim to mitigate domestic resource and environmental constraints (Dong et al., 2024) [7]. Against this backdrop, GTFEE, as a comprehensive metric balancing economic growth and environmental quality, has become a key standard for evaluating urban sustainable development levels (Tian and Mu, 2024) [8]. **However, China currently faces challenges of resource depletion and energy price volatility (Chen et al., 2023)** [9], **creating an urgent need to improve energy efficiency.** Substantial capital within the financial sector can provide considerable support for sustainable development, promoting energy efficiency gains, and numerous fintech companies are also beginning to demonstrate interest in undertaking environmental and social responsibilities (Li et al., 2025) [10]. **The unique institutional environment and market structure in China provide a distinctive sample for studying the interaction between fintech and GTFEE.** As the world's largest carbon emitter and the largest digital payment application market, China simultaneously faces the rigid constraints of the dual-carbon goals and the requirement for tasks of financial system reform. This dual pressure has given rise to solutions with Chinese characteristics. On one hand, the green finance functional modules of the central bank digital currency (CBDC) have begun pilot implementation in provinces like Zhejiang and Guangdong, enabling intelligent linkage between carbon credits and currency flows. On the other hand, regulatory sandbox-based fintech innovation pilots for green finance, such as Ant Group's "Carbon Account" and Tencent's "Green Supply Chain Finance Platform", are reconstructing the incentive structure for traditional energy efficiency improvement by incorporating personal carbon footprints and corporate ESG ratings into credit decision systems. **This government-guided and market-driven model (Guo et al., 2024) [11] is shaping a distinctive Chinese Pathway for enhancing GTFEE supported by fintech.**

The contributions of this study are as follows: Firstly, existing literature offers limited in-depth exploration of the link between fintech and energy efficiency, particularly GTFEE. GTFEE, given its emphasis on environmental friendliness and sustainability, has become a key comprehensive indicator for assessing urban sustainable development. This paper innovatively focuses on the relationship between fintech and GTFEE, systematically investigating the enabling role and intrinsic mechanisms of fintech on GTFEE. This significantly broadens the boundaries of existing research. On one hand, it introduces fintech, an emerging driver, into the research framework for enhancing green energy efficiency. On the other hand, it delves into the specific pathways through which fintech influences GTFEE, addressing a gap in the current literature regarding mechanism exploration. Concurrently, this study enriches relevant empirical data and its analytical depth by constructing a more comprehensive indicator system. **Secondly, this paper not only verifies the direct impact of fintech on GTFEE but also, through rigorous econometric methods, deeply reveals its mechanisms of action.** It innovatively proposes and empirically tests the dual mediating effects of financing constraint alleviation and green technology innovation. This mechanism analysis provides direct justification for policymakers to directionally optimize financial tools, strengthen green technology incentive mechanisms, and dynamically calibrate policy support intensity. **Finally, moving beyond aggregate-level analysis, this study conducts detailed heterogeneity analysis from multi-dimensional perspectives.** Specifically, it explores the differential characteristics of fintech's impact on GTFEE across four key dimensions: regional distribution, economic development stage, and urban scale. The analysis reveals significant heterogeneity results, **providing a solid empirical foundation for governments to formulate more targeted and differentiated regional green fintech development strategies and energy efficiency enhancement policies based on local conditions.**

The remainder of this paper is structured as follows: Section 2 presents the literature review. Section 3 develops the research hypotheses. Section 4 introduces the research design, explaining

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variable selection, data sources, and model specification. Section 5 reports the empirical results, including baseline regression findings, results for the mediating effects, and outcomes of the heterogeneity analyses. Section 6 conducts robustness checks. Section 7 concludes the study and provides policy recommendations.

2. Literature Review

The nexus between fintech and energy has garnered significant scholarly attention. Some scholars have conducted research on the relationships between fintech and the energy market, energy transition and energy efficiency. Su and He (2024) noticed that the fintech market and the clean energy market have a significant mutual influence [12]. Additionally, Bouteska and Harasheh (2024) also discovered that the relationship between financial innovation and the energy market has significantly strengthened in the long term. Furthermore, some scholars have also focused on the role of fintech in promoting the energy transition [13]. Li et al.,(2023) conducted research on the impact of fintech in industrial enterprises on the energy transition and found that fintech promotes energy transition by reducing the amount of carbon consumption [14]. Moreover, Aziz et al.,(2024) confirmed fintech promotes green growth through the path of energy transition in China [15]. This catalytic role extends globally, with evidence highlighting fintech's significant contribution to low-carbon energy transitions across BRICS nations (Dai et al., 2025; Zeng et al., 2024) [16,17]. Notably, beyond these macro-level systemic shifts, fintech directly enhances micro-level energy utilization efficiency. Specifically, Teng and Shen (2023) empirically established that fintech development substantially improves energy efficiency in OECD economies [18], providing critical evidence for fintech 's direct impact on this core performance metric.

The impact of fintech on energy efficiency manifests through a multi-dimensional pathway, ultimately culminating in its significant role in advancing GTFEE. Initial research broadly establishes fintech's contribution to environmental sustainability and emissions reduction, providing the foundational context for its energy-related effects. Studies by Bonsu et al. (2025) [19] and Li and Zhang (2025) [20] demonstrate fintech's positive influence on the environmental sustainability of manufacturing and the sustainability of urban green innovation., respectively, while Li et al. (2024) [21] empirically confirm that the development of fintech and the improvement of energy efficiency can both reduce carbon emissions. Research on energy efficiency presents more nuanced findings, fintech boosts mineral resource green utilization efficiency (Yang and Razzaq, 2024) [22] by facilitating green technology innovation and optimizing energy consumption structures. Additionally, fintech enhances traditional total factor energy efficiency through improved capital allocation mediated by industrial structure optimization (Zhang et al., 2022) [23]. Synergy with green finance further amplifies energy efficiency gains by operating through mediating channels such as green and digital technological innovation. The effects of this synergy are moderated by climate policy uncertainty and environmental regulations (Shi and Yang, 2024) [24]. As a holistic metric, GTFEE systematically accounts for environmental externalities, thereby uncovering the catalytic role of financial technology in sustainable transitions. Wu et al. (2024) [25] directly establish digital finance’s significant impact on GTFEE. They identify the optimization of production factor allocation as the core mechanism, which specifically involves alleviating distortions in capital, labor, and energy markets and enhancing marginal output-price matching. The synergistic development of fintech and green finance substantially augments this effect, significantly influencing GTFEE across spatial and temporal dimensions (Zhang and Sun, 2025) [26]. Furthermore, complementary government digital transformation affects GTFEE improvements by optimizing regulatory mechanisms (Bie et al., 2024) [27]. Conversely, fintech may exert a negative impact on energy efficiency.; Hou et al. (2024) [28] demonstrate fintech's adverse impact in industrial-dominated Asian economies, where it stimulated expansion in high-energy-consuming sectors, increasing energy-intensive production and degrading efficiency.

Overall, existing research on the relationship between fintech and energy efficiency remains relatively scarce, and studies specifically examining the impact of fintech on GTFEE are notably absent. GTFEE serves as a metric for evaluating the economic benefits relative to the environmental impact within an economy's production activities. It primarily measures the ratio of green economic value created per unit of energy consumption in economic activities. Compared to traditional energy efficiency measures, GTFEE incorporates considerations for green energy inputs and undesirable outputs (such as pollution), placing greater emphasis on environmental friendliness and sustainable development. Given the escalating global emphasis on sustainable development and carbon neutrality, enhancing GTFEE is pivotal for achieving a green economic transition. In addition, most literature investigating fintech's influence on energy efficiency has failed to conduct a joint analysis incorporating the mediating roles of financing constraints and technological innovation alongside the moderating effect of the digital economy. Understanding these complex mechanisms is crucial, as it holds significant potential for formulating targeted policy recommendations to maximize fintech's positive contribution to sustainable energy utilization. Furthermore, there is a distinct lack of research focused specifically on this relationship at the city level, despite cities being critical hubs for energy consumption, financial activities, and technological innovation, and the primary sites where fintech interventions are most actively implemented. Moreover, the impact varies significantly across regions at different economic development stages, by whether a city is resource-based, and by urban scale. In light of these research gaps, this paper positions GTFEE as its core research subject and conducts an empirical analysis of the aforementioned issues, placing particular emphasis on city-level data to yield more nuanced and actionable insights.

3. Research Hypotheses

Fintech is reshaping the traditional landscape of the financial industry, providing new avenues for investment, trading, and wealth management. Digital finance innovations have emerged as an effective facilitator for enhancing GTFEE. Fintech substantially enhances information processing efficiency and transparency within financial markets (Feng et al., 2025) [29], while greatly expanding the coverage and accessibility of financial services (Ahl et al., 2019) [30]. This enhanced capacity for information integration and transmission directly optimizes the efficiency of cross-temporal and spatial allocation of financial resources, thereby reducing the comprehensive costs associated with searching, matching, and executing financial transactions (Li et al., 2023) [31]. Concurrently, fintech-driven innovative business models (e.g., digital payments, smart contracts) effectively promote diversified interactions among market participants, directing capital flows towards a broader spectrum of green economic activities. Collectively, these mechanisms influence the comprehensive energy utilization efficiency of economies operating under economic and environmental constraints, empowering the improvement of GTFEE. Based on this, we propose Hypothesis H1:

H1: Fintech can promote GTFEE.

Fintech reduces information asymmetry between enterprises and financial institutions through three key mechanisms, including innovating financial service models, expanding diversified financing channels (including both new products from traditional institutions and services from emerging platforms), and optimizing financial resource allocation. This enables financial institutions to assess corporate operational status, financial health, and green transformation potential more comprehensively and accurately, consequently strengthening trust and willingness to provide financing. The direct result is a significant alleviation of the financing constraints faced by enterprises, lowering financing thresholds and costs (Khan and Ahmad, 2025) [32]. Key actions in corporate green transformation processes, such as adopting stricter environmental management standards, implementing energy efficiency retrofits, obtaining environmental certifications, and meeting compliance requirements, all necessitate stable and continuous capital investment as a fundamental guarantee (Huang and Sun, 2019) [33]. The fintech-driven mitigation of financing constraints provides crucial funding support precisely for these non-technological, foundational green transformation inputs, thereby aiding in enhancing energy efficiency. Based on the above reasoning, we propose Hypothesis H2:

H2: Fintech can promote GTFEE by alleviating financing constraints.

The core capability of fintech lies in utilizing advanced technological tools such as big data analytics and artificial intelligence (Liao et al., 2024) [34] to enable precise identification, risk assessment, and efficient screening of green projects. This technology-enabled mechanism is manifested in the intelligent matching of innovation factors. For instance, blockchain technology ensures the tamper-proof nature of green patent information, while real-time energy efficiency data collected by Internet of Things（IoT）devices provides empirical evidence for selecting technological pathways. Machine learning-based climate risk prediction models optimize the technical parameter configurations of green infrastructure, such as wind power layouts. These synergistic technological effects significantly enhance the innovation production possibility frontier of energy systems, constituting the core transmission pathway through which fintech influences GTFEE. This directly accelerates the research and development (R&D), application, commercialization, and large-scale diffusion of green low-carbon technologies (Wan et al., 2025) [35], such as renewable energy technologies, carbon capture and storage (CCS), and advanced energy-saving processes, driving a fundamental transformation of the energy system towards decarbonization and higher efficiency. Based on the above reasoning, we propose Hypothesis H3:

H3: Fintech can promote GTFEE by optimizing technological innovation.

Based on the research hypotheses outlined above, we establish an empirical model to explore the impact mechanism of fintech on GTFEE, specifically investigating the mediating roles of financing constraints and technological innovation within this relationship.

4. Research Design

4.1. Slack-Based Measure (SBM) Model

Traditional Data Envelopment Analysis (DEA) models commonly employ radial measurement approaches, whose primary deficiency lies in the insufficient consideration of the systemic impact of undesirable outputs (e.g., industrial pollution emissions) on efficiency evaluation. To overcome this technical limitation, this study introduces the non-radial, non-angular SBM model proposed by Tone (2001) [36]. This study assumes the existence of n Decision Making Units (DMUs). Each DMU consumes m types of production factors (inputs) and obtains s types of outcomes (outputs). The corresponding input matrix is denoted as $X = (x_{ij}) \in R^{m\times n}$ and the output matrix as $Y = (y_{ij}) \in R^{s\times n}$. The model is formulated as follows:

$$\min \varrho = \frac{1-\frac{1}{m}\sum_{i=1}^{m} s_i^-/x_{i0}}{1+\frac{1}{s}\sum_{i=1}^{x} s_i^+/y_{i0}} \quad (1)$$

$$\text{s.t.} \quad x_0 = X\lambda + s^-, y_0 = Y\lambda - s^+$$

$$\lambda \geq 0, s^- \geq 0, s^+ \geq 0$$

where $X\lambda$ and $Y\lambda$ represent the input and output quantities on the production frontier, respectively; s^+ and s^- denote the input excess and output shortfall slacks. The SBM model can effectively incorporate undesirable outputs and measure efficiency more accurately.

4.2. Malmquist —Luenberger (ML) Index

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It is an efficiency evaluation index based on the DEA methodology. This index measures technical efficiency changes between two time points or organizations while accounting for both technological progress and technical efficiency components. The index can be decomposed into a technological progress index and a technical efficiency change index, thereby providing a detailed explanation of efficiency dynamics.

The directional distance functions for two adjacent periods are defined as follows:

$$\vec{D}_0^{t+1}(x^t,\ y^t,\ b^t; \mathrm{g}) = \sup\{\beta: (y^t, b^t) + \beta \mathrm{g} \in p^{t+1}(x^t)\} \tag{2}$$

where x^t represents the input vector at period t; y^t denotes the desirable output vector at period t; b^t indicates the undesirable output vector at period t; g is the directional vector (g=(g$_y$,−g$_b$)) specifying the expansion of desirable outputs and contraction of undesirable outputs; β is a scalar representing the maximum feasible proportional expansion/contraction; $p^{t+1}(x^t)$ describes the production possibility set at period *t*+1for given inputs x^t.

Second, the ML index between period *t* and *t+1* is formally specified as follows:

$$ML_t^{t+1} = \left[\frac{(1+\vec{D}_0^{t+1}(x^t, y^t, b^t; y^t, -b^t))}{(1+\vec{D}_0^{t+1}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})} \times \frac{(1+\vec{D}_0^{t}(x^t, y^t, b^t; y^t, -b^t))}{(1+\vec{D}_0^{t}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}\right]^{1/2} \tag{3}$$

We then decompose the ML index into two constituent components the technical efficiency change index $MLEFFCH_t^{t+1}$ and the technological change index $MLTECH_t^{t+1}$ to conduct source decomposition analysis of GTFEE. The multiplicative decomposition is formally expressed as:

$$\mathrm{ML} + MLEFFCH_t^{t+1} \times MLTECH_t^{t+1} \tag{4}$$

$$MLEFFCH_t^{t+1} = \frac{1+\vec{D}_0^{t}(x^t, y^t, b^t; y^t, -b^t)}{1+\vec{D}_0^{t}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})} \tag{5}$$

$$MLEFFCH_t^{t+1} = \frac{1+\vec{D}_0^{t}(x^t, y^t, b^t; y^t, -b^t)}{1+\vec{D}_0^{t}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})} \tag{6}$$

In the above expression, $MLEFFCH_t^{t+1}$measures the shift in the technical efficiency production possibility frontier between periods t and t+1. $MLEFFCH_t^{t+1} = 1$ signifies no contribution from technical efficiency; $MLEFFCH_t^{t+1} > 1$ denotes increasing technical efficiency with positive contribution;$MLEFFCH_t^{t+1} < 1$ reflects declining technical efficiency that hinders GTFEE growth. Meanwhile, $MLTECH_t^{t+1}$ aptures technological change or innovation intensity across the same periods: $MLTECH_t^{t+1} > 1$ 时 indicates technological progress enhancing GTFEE; $MLTECH_t^{t+1} < 1$ implies technological regression impeding GTFEE growth; $MLTECH_t^{t+1} = 1$ suggests stagnant technology with neutral impact (Wang et al., 2020) [37].

4.3. Data Sources

This study employs prefecture-level panel data from 2011 to 2021. During data preprocessing, observations with missing values were systematically screened and excluded. Core indicators were constructed as follows: Regional fintech development was quantified using Baidu News' advanced search function to capture annual exposure of fintech-related keywords(Xuan et al., 2025) [38]. GTFEE was dynamically measured using the SBM-ML index model. Data for control variables were integrated from multiple sources, including China City Statistical Yearbooks, local statistical bulletins, provincial economic databases, and listed companies' annual reports, ensuring comprehensive coverage. To mitigate potential distortion from extreme outliers, all variables were winsorized at the 1st and 99th percentiles.

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4.4. Variables Selection

4.4.1. Dependent Variable

Following Li and Chen (2021) [39], this study measures GTFEE using the SBM-ML index method. Inputs include labor, capital, and energy consumption. Desirable output is regional GDP, while undesirable outputs comprise industrial SO_2 emissions, industrial soot/dust emissions, and industrial wastewater discharge.

4.4.2. Independent Variable

Fintech represents an innovative business model integrating modern technologies (e.g., information technology, artificial intelligence, blockchain) with financial services to enhance accessibility, efficiency, and transparency. Adopting Chen et al. (2024) [40] 's approach, we quantified fintech development through Python-based web scraping of 48 keywords (e.g., EB storage, NFC payment, cognitive computing, deep learning, big data, blockchain, data mining, business intelligence, smart financial contracts) from Baidu News. Total keyword occurrences were aggregated for each of China's 300+ prefecture-level cities and log-transformed.

4.4.3. Control Variables

To enhance research precision, control variables are incorporated to mitigate confounding effects:

(1) Industrial structure (IS): As industrial composition significantly influences GTFEE due to sectoral variations in energy intensity and environmental impact, industrial-dominated structures typically exhibit lower energy utilization efficiency and higher pollution, thereby constraining GTFEE. Following Wu et al. (2024) [25], IS is measured as the ratio of secondary industry output value to real GDP.

(2) Urbanization rate (UR): Reflecting rural-to-urban population migration, UR exerts a dual effect on GTFEE. On the one hand, stricter environmental regulations and the transition to sustainable consumption, facilitated by policy leadership and increased public awareness, may improve GTFEE. On the other hand, prioritizing rapid urban expansion over development quality could hinder such efficiency improvements. This variable is measured by the proportion of permanent urban residents to total population

(3) Environmental regulation intensity (ERS): Representing corporate pollution abatement costs, increased ERS elevates operational expenses, incentivizing adoption of advanced green technologies and low-pollution industrial restructuring, ultimately improving GTFEE. We measure ERS as the ratio of annual industrial waste gas/water treatment investment to industrial output value in listed companies' regions.

(4) Foreign direct investment (FDI): Reflecting global market integration, FDI facilitates technology spillovers through clean technology transfers, management expertise, or green patents (e.g., renewable energy technologies), potentially enhancing host-country energy efficiency. This study quantifies FDI as the ratio of actually utilized FDI to local GDP.

(5) Capital investment (INV): Recognizing that high-efficiency equipment (e.g., smart grids, carbon capture systems) requires substantial capital expenditure, and that R&D in energy-saving/clean energy technologies (e.g., photovoltaics, hydrogen) necessitates sustained funding, which may independently boost GTFEE beyond fintech effects. We operationalize this variable as the ratio of local general budgetary expenditure to GDP.

(6) Energy consumption structure (SEC): Directly affecting carbon emissions and pollution, traditional coal-fired power plants exhibit lower energy conversion efficiency (30%-40%) compared to natural gas (50%-60%) or renewables (zero fuel loss). Higher coal dependency increases energy input requirements per economic output, thereby reducing GTFEE. Following standard practice in

energy economics, we quantify SEC as the proportion of coal consumption to total energy consumption.

Major variables and their operationalization are systematically presented in Table 1.

Table 1. Variables' description.

Type	Variables	Explanation	Measurement
Explained variable	GTFEE	Green total factor energy efficiency	SBM—ML method calculation
Explanatory variable	fintech	fintech	Fintech-related keywords were extracted from Baidu News; the total search result counts for all keywords corresponding to each prefecture-level city or municipality directly under the central government were aggregated and log-transformed.
Control variable	IS	Industrial structure	Value-added of secondary industry / real GDP
	UR	Urbanization rate	Permanent urban population / total population
	ERS	Environmental regulation strength	Annual expenditure on waste gas/water pollution control in listed companies' regions / annual industrial output value
	FDI	Foreign direct investment	Annual utilized FDI amount / regional GDP
	INV	Capital investment intensity	General budgetary expenditure of local government / regional GDP
	SEC	Energy consumption structure	Coal consumption / total energy consumption

4.5. Indicator Construction

To systematically investigate the causal relationship between financial technology development and green productivity enhancement, we specify the following econometric model:

$$GTFEE_{i,t} = \alpha_0 + \alpha_1 fintech_{i,t} + \sum_{j=2}^{7} \alpha_j \, Controls_{i,t} + \theta_t + \gamma_i + \varepsilon_{i,t} \quad (7)$$

where i and t denote time and region respectively. Green total factor energy efficiency (*GTFEE)* is the dependent variable of interest, and fintech ($fintech$) is the core explanatory variable. $Controls$ denotes the vector set of control variables, including Industrial structure (*IS*), Urbanization Rate (*UR*), Environmental regulation strength (*ERS*), Foreign direct investment (*FDI*), Capital investment intensity (*INV*), and Energy consumption structure (*SEC*). α is the parameter to be estimated for each variable, and θ_t and γ_i are the individual effect and residual term that do not vary over time, respectively. $\varepsilon_{i,t}$ is the random disturbance term.

5. Empirical Analysis

5.1. Descriptive Statistics

Table 2 reports the descriptive statistics of key variables. The mean value of GTFEE is 0.655 with a standard deviation of 0.162, while fintech development shows a mean of 3.800 and standard deviation of 1.115. These results indicate moderate variation across sample observations for core variables. Control variables exhibit distributions consistent with existing literature and fall within plausible empirical ranges.

Table 2. Descriptive statistics.

VarName	Obs	Mean	SD	Min	P25	Median	P75	Max
GTFEE	12174	0.655	0.162	0.424	0.538	0.611	0.719	1.049
fintech	12174	3.800	1.115	2.079	2.944	3.689	4.615	6.698
IS	12174	0.462	0.069	0.273	0.413	0.470	0.519	0.571
UR	12174	0.698	0.143	0.488	0.595	0.687	0.762	1.000
ERS	12174	0.002	0.001	0.000	0.001	0.002	0.003	0.005
FDI	12174	0.004	0.002	0.001	0.002	0.004	0.005	0.010
INV	12174	0.131	0.032	0.083	0.106	0.127	0.148	0.197
SEC	12174	0.794	0.088	0.612	0.722	0.803	0.858	0.936

5.2. Baseline Regression

Table 3 presents the baseline regression results for Model (7). Column (1) reports the univariate regression results, demonstrating that the coefficient of fintech on GTFEE is 0.055, which is statistically significant at the 5% level. This provides preliminary evidence that fintech exerts a positive effect on GTFEE.

Column (2) displays the regression results after incorporating control variables. The estimated coefficient of fintech remains positive (0.035) and statistically significant at the 1% level, further confirming that fintech significantly enhances GTFEE. Notably, the urbanization rate exhibits a negative coefficient significant at the 10% level, suggesting a modest inhibitory effect on GTFEE. In contrast, capital investment shows a significantly positive coefficient at the 5% level, indicating its robust contribution to improving energy efficiency. Most strikingly, environmental regulation intensity demonstrates a strongly positive coefficient significant at the 1% level, highlighting the crucial role of stringent environmental policies in promoting GTFEE.

These empirical findings collectively validate Hypothesis 1, confirming the positive relationship between fintech development and green total-factor energy efficiency enhancement.

Table 3. Baseline regression.

	(1)	**(2)**
	GTFEE	GTFEE
fintech	0.055**	0.035***
	(2.45)	(4.55)
IS		0.339
		(1.32)
UR		-0.283*
		(-1.72)
ERS		13.561***
		(3.05)
FDI		-3.778
		(-0.82)
INV		2.864**
		(2.21)
SEC		-0.039

		(-0.40)
_cons	0.210**	-0.030
	(2.44)	(-0.10)
Firm fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
N	12172	12172
R^2	0.839	0.891
AR^2	0.837	0.890

Note: *t* statistics in parentheses.* *p*<0.1, ** *p*<0.05, *** *p*<0.01.

5.3. Mechanism Analysis

5.3.1. Mediating Effect of Financing Constraints

Financing constraints (FC) are measured using the absolute value of the SA index (Li and Wu, 2025) [41]. Table 4 presents the mediating role of financing constraints in the relationship between fintech and GTFEE. Column (1) displays the estimated coefficient is -0.010 and statistically significant at the 10% level, supporting Hypothesis 2. This suggests that fintech enhances GTFEE by alleviating financing constraints.

Table 4. Mediating Effect.

	(1)	**(2)**
	FS	TI
fintech	-0.010*	0.006***
	(-1.85)	(6.28)
IS	-0.045	0.193***
	(-0.49)	(10.35)
UR	0.057	-0.042***
	(0.79)	(-3.59)
ERS	-2.395	1.108***
	(-1.25)	(2.81)
FDI	3.375*	1.648***
	(1.96)	(4.35)
INV	0.123	-0.181***
	(0.99)	(-6.12)
SEC	0.010	0.049***
	(0.17)	(4.08)
_cons	3.740***	4.369***
	(35.70)	(316.31)
Firm fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
N	12172	12172
R^2	0.153	0.978
AR^2	0.139	0.978

Mechanistically, fintech mitigates corporate financing constraints, particularly for green transition enterprises, through three key channels: (1) reducing information asymmetry in capital markets, (2) expanding financing channels beyond traditional banking systems, and (3) lowering transaction costs in financial intermediation. The resultant improvement in financing accessibility provides critical capital support for firms to undertake green technology innovation, upgrade production equipment, and optimize environmental management systems. These operational

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enhancements collectively improve firms' capability to transform energy inputs and pollution emissions into economic outputs, thereby elevating GTFEE through the financing constraint channel.

5.3.2. Mediating Effect of Technological Innovation

Following Klein (2025) [42], we measure technological innovation (TI) using the natural logarithm of invention patent applications. The regression results in Table 4 Column (2) demonstrate a significantly positive coefficient (0.006) at the 1% level, confirming Hypothesis 3 that fintech promotes GTFEE through fostering technological innovation.

The underlying mechanisms operate through multiple pathways. First, fintech adoption directly stimulates corporate R&D investment by improving capital allocation efficiency. Second, blockchain-based intellectual property protection and AI-driven innovation analytics help optimize resource allocation for green technology development. Third, fintech platforms facilitate risk assessment and management for innovation projects, while policy-oriented fintech solutions (e.g., green credit scoring) strengthen institutional support. These synergistic effects enhance firms' capacity to develop and implement energy-saving technologies, clean production processes, and circular economy solutions all critical drivers for improving GTFEE through the technological innovation channel.

5.4. Heterogeneity Analysis

5.4.1. Regional Heterogeneity Analysis

To examine whether the impact of fintech on GTFEE varies geographically, we partition the sample into China’s eastern, central, and western regions. Columns (1)-(3) in Table 5 present the heterogeneous effects of it respectively. The Chow test statistic of 245.965 confirms statistically significant spatial heterogeneity in the marginal contributions of fintech to GTFEE across regions, ultimately forming differentiated energy efficiency optimization pathways.

(1) Eastern region

The regression results in Column (1) show a coefficient of 0.035, significant at the 1% level, indicating fintech significantly enhances GTFEE in eastern China. This can be attributed to several structural advantages. First, as China's most economically developed region, the eastern area features mature industrial structures dominated by advanced manufacturing and modern services. Second, its well-developed financial ecosystem and higher fintech adoption enable more effective use of big data and blockchain technologies to lower financing barriers for green projects. Third, the concentration of high-tech enterprises and green technology R&D centers strengthens the synergistic effects between fintech and green industries (Wang et al., 2024) [43].

(2) Central region

Column (2) reports a coefficient of 0.012 (significant at 10% level), suggesting a positive but weaker fintech-GTFEE relationship. This moderated effect reflects the region's transitional development stage, where national policies like the "Guidelines on Promoting High-quality Development in Central China" have established institutional support for manufacturing upgrading and ecological protection. While central fiscal transfers and special funds for technological innovation provide foundational support, the financial ecosystem remains less mature than in eastern regions (Appiah-Otoo et al., 2023) [44].

(3) Western region

The insignificant coefficient (0.027) in Column (3) reveals limited fintech impact despite Western Development Strategy implementation. Three constraints explain this. (i) resource-dependent industrial structures with limited high-value sectors, (ii) inadequate targeted policy support for fintech-enabled green transitions, and (iii) technological and institutional bottlenecks in policy execution. These structural factors constrain fintech's potential to improve energy efficiency (Yang et al., 2023) [45].

The comparative analysis demonstrates a clear regional gradient. Fintech's GTFEE enhancing effect is strongest in the east (0.035**), followed by the center (0.012), while statistically insignificant in the west, reflecting regional disparities in financial development, industrial structure, and policy effectiveness.

Table 5. Heterogeneity Test I : Regional heterogeneity analysis.

	(1) Eastern	(2) Central	(3) Western
	GTFEE	GTFEE	GTFEE
fintech	0.035***	0.012*	0.027
	(3.21)	(1.83)	(1.40)
IS	0.501	0.042	-0.064
	(1.49)	(0.33)	(-0.18)
UR	-0.522**	0.247***	0.220
	(-2.62)	(3.68)	(0.35)
ERS	14.829**	1.676	11.568
	(2.24)	(0.22)	(1.31)
FDI	-10.689	-2.594	6.410
	(-1.48)	(-0.42)	(1.57)
INV	3.403***	0.304	-0.923
	(2.72)	(1.20)	(-1.10)
SEC	-0.065	-0.044	1.211***
	(-0.50)	(-0.56)	(4.94)
_cons	0.035***	0.012*	0.027
	(3.21)	(1.83)	(1.40)
Firm fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
Chow Test		245.965	
P-Value		0	
N	8826	3144	202
R^2	0.900	0.889	0.989
AR^2	0.899	0.886	0.988

5.4.2. Stages of Economic Development Heterogeneity Analysis

The heterogeneity in economic development stages significantly moderates the intensity and direction of the impact of fintech on GTFEE (Juknies et al., 2017) [46]. Based on the median ratio of tertiary industry added value to secondary industry added value, this study divided the sample into service cities and industrial cities for grouped regression analysis(Zhang and Sun, 2025) [26]. The results, as shown in Table 6, indicate that fintech development exerts a significant positive effect on the GTFEE of both city types. A Chow test statistic of 840.043 confirms a significant difference between the groups. The regression coefficients demonstrate that the enhancing effect is more pronounced in service cities (evidenced by significantly higher coefficient estimates). Industrialization-stage economies rely on energy-intensive manufacturing where production-centric operations, technological inertia, and high retrofit costs constrain efficiency gains. Conversely, servitization-stage service-sector dominance enables greater technological adaptability. Green finance facilitates funding for eco-equipment and operational upgrades (e.g., tourism sector improvements as demonstrated by Zeng et al., 2024 [47]), while fintech leverages big-data analytics for precision energy management. This dual-action synergy, financial enablement and technological optimization, capitalizes on service-sector characteristics to maximize GTFEE improvements where services prevail. (Zhang and Sun, 2025) [26].

Table 6. Heterogeneity Test II : Economic development heterogeneity analysis.

	(1)	(2)

	Service cities		Industrial cities
	GTFEE		GTFEE
fintech	0.036***		0.015***
	(15.79)		(5.47)
IS	0.552***		-0.298**
	(7.83)		(-2.57)
UR	-0.226***		0.005
	(-6.89)		(0.27)
ERS	11.108***		6.414**
	(5.50)		(2.59)
FDI	-7.924***		6.637***
	(-8.27)		(3.62)
INV	2.735***		0.031
	(7.95)		(0.22)
SEC	0.085***		-0.081*
	(3.14)		(-1.75)
_cons	-0.216**		0.488***
	(-2.46)		(6.09)
Firm fixed effect	Yes		Yes
Year fixed effect	Yes		Yes
Chow Test		840.043	
P-Value		0	
N	8345		2198
R^2	0.873		0.929
AR^2	0.870		0.925

5.4.3. Resource Endowment Heterogeneity Analysis

Resource endowment constitutes a critical factor influencing GTFEE. Following the classification framework established in the National Plan for Sustainable Development of Resource-Based Cities (2013-2020) (Zhang and Sun, 2025) [26], we divide our sample into resource-based and non-resource-based cities to examine potential heterogeneity. The grouped regression results presented in Table 7 indicate that the development of fintech exerts a significant positive effect on GTFEE only in non-resource cities. A Chow test statistic of 171.141 further confirms the significant difference between the groups. Clearly, the regression coefficient in Column (2) is significantly positive at the 1% level for non-resource cities， the divergent outcomes stem from industrial heterogeneity. Resource-based cities exhibit concentrated industrial structures focused on extraction and primary processing (Zhang and Zhao, 2024) [48], characterized by high capital intensity, limited technological sophistication, and entrenched resource dependency. This uniformity constrains energy efficiency improvements while reducing firms' incentives and capacity to leverage fintech for innovation, thereby limiting GTFEE gains.

Conversely, non-resource cities' diversified industrial bases, spanning manufacturing, services, and high-technology sectors, possess greater innovative capacity and technology/financial absorption capabilities. High-tech industries particularly harness fintech for energy optimization and green finance for R&D funding, driving significant GTFEE enhancement through this synergy. He et al. (2023) [49] corroborate this pattern, showing stronger pollution-carbon reduction synergies from green finance in non-resource cities (Zhang and Sun, 2025) [26].

Table 7. Heterogeneity Test III:Resource endowment heterogeneity analysis.

	(1) Resource-based	(2) Non-resource-based
	GTFEE	GTFEE

fintech	-0.002		0.039***
	(-0.32)		(14.03)
IS	0.116**		0.357***
	(2.21)		(5.17)
UR	0.017		-0.301***
	(0.85)		(-6.74)
ERS	3.108		16.503***
	(1.06)		(10.62)
FDI	-0.394		-4.283***
	(-0.31)		(-5.20)
INV	-0.092		3.180***
	(-1.43)		(10.66)
SEC	0.010		-0.005
	(0.34)		(-0.20)
_cons	0.254***		-0.081
	(6.35)		(-1.11)
Firm fixed effect	Yes		Yes
Year fixed effect	Yes		Yes
Chow Test		255.625	
P-Value		0	
N	1660		10420
R^2	0.897		0.895
AR^2	0.892		0.893

5.4.4. Urban Scale Heterogeneity Analysis

City size heterogeneity manifests in distinct patterns of energy consumption, technological advancement, and digitalization strategy implementation. Owing to their intricate economic structures and elevated population densities, large cities tend to adopt more advanced technologies and pursue comprehensive digital transformations, enhancing energy efficiency and addressing environmental pressures. Conversely, small and medium-sized cities often encounter significant barriers in the energy efficiency process, constrained by geographic isolation, capital limitations, and talent deficits. Regression analyses stratified by city tier reveal significant heterogeneity in the relationship between fintech and GTFEE (Bie et al., 2024) [27]. The results, as shown in Table 8, reveals pronounced heterogeneity in how fintech development affects GTFEE across cities of different sizes, with distinct patterns emerging based on urban scale characteristics. Large cities (Tiers 1-4 classified as Tiers 1-4 following the China City Statistical Yearbook 2019) demonstrate significant positive coefficients, indicating fintech effectively enhances their energy efficiency. This aligns with their inherent advantages, including mature digital infrastructure, robust policy frameworks, and agglomeration economies that facilitate technology diffusion and implementation. The Chow test statistic (2131.628) confirms these inter-tier differences are statistically significant.

Conversely, Tier 5 cities show an insignificant relationship reflecting the challenges smaller urban centers face in translating fintech advancements into energy efficiency gains. Their geographic isolation, capital constraints, and talent shortages create implementation barriers that outweigh potential benefits. These findings underscore the critical moderating role of city size on the fintech and GTFEE relationship, suggesting that policy interventions must be tailored to urban development levels, leveraging existing advantages in larger cities while addressing structural limitations in smaller ones.

Table 8. Heterogeneity Test IV: Urban scale heterogeneity analysis.

	(1)	**(2)**	**(3)**	**(4)**	**(5)**

	Tier 1 cities	Tier 2 cities	Tier 3 cities	Tier 4 cities	Tier 5 cities
	GTFEE	GTFEE	GTFEE	GTFEE	GTFEE
fintech	0.013***	0.013***	0.013***	0.012***	-0.017
	(6.11)	(4.31)	(4.04)	(3.86)	(-1.26)
IS	0.884***	-0.265***	-0.080	0.121***	0.796
	(11.03)	(-4.37)	(-0.97)	(2.97)	(1.50)
UR	-0.111***	0.169***	-0.001	-0.020	-0.730
	(-3.54)	(4.00)	(-0.03)	(-0.94)	(-0.90)
ERS	8.746***	19.229***	-0.891	-2.109	21.543
	(3.55)	(16.44)	(-0.35)	(-1.56)	(1.30)
FDI	9.960***	3.911***	5.697***	1.548*	2.174
	(8.60)	(5.50)	(4.51)	(1.89)	(0.54)
INV	4.318***	-0.940***	-0.405***	-0.307	0.719
	(40.45)	(-8.84)	(-4.48)	(-1.63)	(0.79)
SEC	0.189***	-0.275***	-0.200***	0.005	0.494
	(5.58)	(-9.25)	(-6.95)	(0.13)	(1.60)
_cons	-0.553***	0.628***	0.545***	0.281***	-0.203
	(-11.15)	(15.72)	(13.56)	(4.45)	(-0.48)
Firm fixed effect	Yes	Yes	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes	Yes	Yes
Chow Test			2131.628		
P-Value			0		
N	4380	4200	2149	1193	176
R^2	0.968	0.790	0.771	0.901	0.834
AR^2	0.967	0.788	0.764	0.895	0.793

6. Robustness Tests

6.1. Endogeneity Tests

To mitigate potential endogeneity concerns in the baseline regression, such as omitted variable bias and reverse causality, this study employs an instrumental variable (IV) approach for additional robustness verification. We utilize the average fintech development level of other cities (afintech) as the instrumental variable for local fintech. This selection satisfies the necessary conditions for a valid instrument based on two key rationales: (1) While local GTFEE is influenced by local fintech conditions, it remains theoretically uncorrelated with the average fintech level of other cities; (2) Given the spatial spillover effects characteristic of fintech diffusion, where technological

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advancements typically propagate from high-adoption to low-adoption regions, the instrument demonstrates both relevance and exogeneity.

The constructed instrument afintech represents annually computed average fintech values across peer cities. IV regression results presented in Table 9 confirm the instrument's validity. The Cragg-Donald Wald F-statistic (16.38) substantially exceeds the 10% critical value threshold, effectively rejecting the weak instrument hypothesis. Most importantly, the IV estimates maintain statistical significance and directional consistency with our baseline findings, thereby robustly confirming the study's primary hypothesis even after accounting for endogeneity concerns.

Table 9. Robustness Test I: Endogeneity Regression Results.

	(1)	**(2)**
	fintech	GTFEE
afintech	-215.122***	
	(-146.620)	
IS	-0.676***	0.371***
	(-8.108)	(12.357)
UR	-0.008	-0.032
	(-0.128)	(-1.519)
ERS	-20.238***	11.572***
	(-6.948)	(11.027)
FDI	-13.490***	-2.734***
	(-6.886)	(-3.890)
INV	1.861***	2.789***
	(13.656)	(56.217)
SEC	-0.096**	-0.122***
	(-1.987)	(-7.071)
fintech		0.018***
		(7.242)
_cons	418.728***	-0.072**
	(147.660)	(-2.571)
Firm fixed effect	Yes	Yes
Year fixed effect	Yes	Yes
N	12174	12174
R^2	0.968	0.012
Cragg-Donald Wald F	20806.763	

6.2. Explained Variable Replacement

To assess the robustness of the baseline regression results, this study substitutes the dependent variable in Equation (7). Specifically, we modify the measurement of GTFEE. Unlike the SBM approach, we employ the super-efficiency Charnes-Cooper-Rhodes (CCR) model to calculate GTFEE. This model evaluates energy utilization efficiency within the traditional DEA framework by incorporating environmental constraints (e.g., industrial SO_2 emissions, soot/dust emissions, and wastewater discharge), considering both economic output and environmental impact.

Table 10. Robustness Test II: Explained Variable Replacement.

	(1)
	lnsuperccr
fintech	0.043**
	(2.39)
IS	-0.416
	(-1.49)
UR	-0.096
	(-0.64)
ERS	15.401**
	(2.38)
FDI	2.569
	(0.44)
INV	0.146
	(0.33)
SEC	-0.414**
	(-2.14)
_cons	-0.091
	(-0.34)
Firm fixed effect	Yes
Year fixed effect	Yes
N	12172
R^2	0.897
AR^2	0.895

6.3. Explanatory Variable Replacement

Existing scholars predominantly measure financial technology (fintech) using either data mining techniques or the Digital Financial Inclusion Index developed by Peking University's Financial Research Center (Shang and Liu, 2024) [50]. While the preceding analysis employed the data mining approach, this section adopts the alternative measurement system. As demonstrated in Table 11, the regression results indicate that the Digital Financial Inclusion Index, coverage breadth of digital finance, and usage depth of digital finance all show statistically significant positive coefficients at the 1% level. These findings confirm that the fintech's positive effect on GTFEE remains robust after substituting the explanatory variables.

Table 11. Robustness Test III: Explanatory Variable Replacement.

	(1)	**(2)**	**(3)**
	GTFEE	GTFEE	GTFEE
index _aggregate	0.001***		
	(2.72)		
IS	0.335	0.316	0.353
	(1.14)	(1.08)	(1.24)
UR	-0.342*	-0.387**	-0.268*
	(-1.96)	(-2.18)	(-1.80)
ERS	12.865***	12.859***	13.801***
	(3.06)	(2.92)	(3.17)
FDI	0.006	0.004	0.008
	(0.37)	(0.27)	(0.57)
INV	0.375*	0.358*	0.381*
	(1.86)	(1.85)	(1.92)
SEC	-0.031	-0.031	-0.030
	(-0.29)	(-0.29)	(-0.27)
coverage _breadth		0.002***	
		(3.39)	
usage _depth			0.001***
			(2.97)
_cons	-2.425	-2.348	-2.515
	(-1.48)	(-1.46)	(-1.54)
Firm fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
N	12172	12172	12172
R^2	0.881	0.883	0.882

AR^2	0.879	0.881	0.880

7. Conclusions and Policy Implications

7.1. Conclusions

This study integrates fintech and GTFEE within a unified framework. By identifying fintech-related keywords and utilizing the Baidu News Advanced Search page to quantify fintech, employing the SBM-ML index model incorporating undesirable outputs to measure Chinese urban GTFEE from 2011 to 2021, and constructing a two-way fixed effects model to empirically examine the impact of fintech on urban GTFEE, we conclude that fintech can significantly enhance GTFEE. Furthermore, fintech exerts a negative impact on financing constraints, thereby enhancing GTFEE through the alleviation of these constraints. Additionally, fintech positively influences technological innovation, consequently improving GTFEE specifically through mechanisms such as heightened investment efficiency and optimized resource allocation. Heterogeneity analysis reveals that the magnitude of fintech's impact on GTFEE exhibits regional heterogeneity. Fintech development in Eastern China demonstrates a significant driving effect on GTFEE, while the effect is comparatively weaker in Central China; conversely, fintech development in Western China exhibits no statistically significant association with GTFEE improvement. Significant resource-based heterogeneity exists fintech exerts a significantly positive impact on GTFEE exclusively in non-resource-based cities. Economic development stage heterogeneity is observed. The influence of fintech on GTFEE is notably greater in service cities. Furthermore, urban scale heterogeneity is evident. Fintech significantly affects GTFEE only in larger cities. The empirical results remain robust after undergoing rigorous robustness checks, including the instrumental variables approach, alternative explanatory variables, and modified dependent variable specifications.

7.2. Policy Implications

Enhancing GTFEE not only improves energy utilization effectiveness, alleviating current challenges of resource scarcity and finite non-renewable energy, but also addresses pressing environmental issues, thereby contributing significantly to energy conservation and environmental protection goals. Importantly, GTFEE can be substantially elevated through fintech pathways. The conclusions of this study provide a theoretical foundation for leveraging fintech models to improve financing constraints and promote technological innovation, consequently enhancing GTFEE. Therefore, the policy implications derived from this research are as follows:

First, governments should promote deep integration between finTech and GTFEE. Given the rapid advancement of contemporary technology, governments should align with the overarching trend of integrated development between fintech and the green, high-efficiency energy industry. This entails closely monitoring global technological frontiers while tailoring approaches to national conditions. Providing robust policy support to green energy enterprises is crucial to incentivize fintech-enabled financial assistance for this sector. Through fintech innovation, more suitable financing models and financial products for green energy projects should be developed. This will foster the continuous innovation and diversification of green, high-efficiency products and technologies, ultimately propelling GTFEE enhancement.

Second, governments should implement targeted fiscal policies to alleviate financing constraints. While maintaining financial stability, governments can mitigate financing constraints through mechanisms such as tax incentives and fiscal subsidies. Support should be directed towards fintech enterprises developing green financial instruments, including green financial bonds and green energy funds. This broadens financing channels for green energy projects, delivers more targeted financial support, enhances capital utilization efficiency, and consequently boosts GTFEE.

Third, optimizing technological innovation ecosystems requires coordinated policy frameworks. Governments may implement measures such as tax credits for R&D investments by green technology

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innovation firms and tax reductions for their innovative products. Concurrently, fostering collaboration between fintech companies, universities, and research institutions is essential to jointly conduct green technology innovation research. This accelerates the translation and application of scientific and technological achievements, improves the efficiency of green technology innovation, and thereby empowers GTFEE improvement.

Fourth，strategic spatial policies are critical to harness fintech's industrial growth potential. Policymakers should prioritize infrastructure and talent development in western regions while sustaining central area support, with funding allocated based on regional readiness metrics. Public-private partnerships and continuous evaluation are crucial for reducing regional disparities. Non-resource cities, leveraging their diverse industrial structures and robust innovation capabilities, should intensify support for the synergistic development of fintech and green finance. The government can formulate specific policies to encourage financial institutions to establish dedicated fintech and green finance units or innovation hubs, thus facilitating the innovation and dissemination of green financial products and services. Meanwhile, cities in the servitization stage should prioritize the development of green fintech services, promoting the integration and innovative application of fintech and green finance within the service sector. The government can design a service industry development plan, delineating the focus and direction for fintech and green finance, to drive the green upgrade and sustainable growth of the service industry. Lastly, the uniqueness of regional development should be taken into account. This means that policy measures formulated in big scale cities may need to differ from those in small scale cities.

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