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Research on the Mechanism and Spatial Effect of Digital Finance on Energy Efficiency

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Abstract

Digital economy has become the mainstream form of global economic development in the new era. Digital finance relies on digital technology to optimize the allocation of financial resources, break traditional financial barriers, and effectively guide the flow of funds to green and low-carbon fields, which plays an important role in improving energy efficiency and promoting green transformation. Based on the realistic background of "double carbon" strategy and green energy transformation, this paper takes clarifying the impact mechanism and spatial effect of digital Finance on green all factor energy efficiency as the core goal, constructs an integrated analysis framework based on financial function theory, financial exclusion theory, endogenous growth theory and Porter hypothesis, systematically analyzes the mechanism of digital finance affecting energy efficiency from the theoretical level, and identifies three core intermediary transmission channels: technological innovation, industrial structure upgrading and regional economic development level. Systematic tests are carried out by using two-way fixed effect model, spatial Dubin model and Moran index. Theoretical analysis shows that digital finance can significantly improve the energy efficiency of regional green total factors, and the conclusion has good robustness; Digital finance can indirectly enable energy efficiency improvement through technological innovation, industrial upgrading and economic growth path; Its green enabling effect has dimension and environmental regulation heterogeneity, and shows significant positive spatial spillover characteristics. The development of local digital finance can drive the improvement of energy efficiency in neighboring areas. Based on the research conclusions, this paper puts forward optimization countermeasures from the aspects of improving digital financial infrastructure, smoothing multi-dimensional transmission paths, implementing differentiated regional policies, and building a cross regional collaborative governance mechanism, so as to provide theoretical reference and practical enlightenment for relying on digital finance to help regional energy quality and efficiency improvement and promote green and high-quality development.

Keywords

Digital finance; Mediating effects; Spatial Dubin model; "Double carbon" target.

1. Introduction

1.1. Research background

In 2023, the State Council issued a white paper on China's green development in the new era. The proportion of domestic clean energy consumption has steadily increased, and new energy tracks such as traditional energy efficient utilization technology and wind power photovoltaic have achieved breakthrough innovation, providing practical reference for China's high-quality development and global energy structure transformation. The outline of the 15th five year plan further clarifies the dual control system of carbon emissions, takes carbon peak and carbon

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neutralization as the general traction, and simultaneously promotes the coordinated landing of carbon reduction, pollution reduction, green expansion and growth. At this stage, the achievements of domestic green transformation are considerable, but the construction of new energy system still faces multiple structural constraints. Globally, geopolitical conflicts continue to disturb the international energy market, and the stability of the global energy supply chain continues to be under pressure. The structural pressure of domestic energy transformation is also prominent. Even if the proportion of non fossil energy consumption is expected to reach 20% in 2025, traditional energy consumption still accounts for 80%, the external dependence of oil and natural gas breaks through 50%, the problem of energy supply gap and high external dependence restricts the safe and stable supply of energy for a long time, and energy security and stable supply are facing a test. The inherent pattern of domestic energy consumption with coal as the core has greatly raised the landing cost of clean energy transformation. Although the clean energy industry has long-term growth potential, the shortcomings of core technology and the imperfect market-oriented mechanism continue to depress the endogenous development momentum of the industry. Therefore, improving energy efficiency, resolving the contradiction between energy supply and demand, and promoting green and low-carbon changes in energy production and consumption are the key grasps for China to achieve ecological civilization construction and high-quality economic development.

In the government work report of the State Council in 2026, it was clearly deployed to deepen five key financial tasks, such as digital finance, and comprehensively promote the reform of capital market and the improvement of quality and efficiency of the real economy of financial services. Under the environment of continuous landing of new digital infrastructure, digital finance relies on big data, cloud computing, block chain and other technologies to realize online and intelligent financial services, break through the limitations of temporal and spatial services of traditional physical financial outlets, make up for the shortcomings of traditional financial services with the unique advantages of low cost, wide coverage and high efficiency, and reshape the distribution pattern of financial resources in the whole society. At the same time, digital finance can reduce ineffective energy consumption and improve input and output efficiency through optimal allocation of resources, opening up a new path for energy efficiency improvement and green sustainable development. Based on the dual dimensions of theory and demonstration, digging deep into the impact mechanism of digital Finance on energy efficiency can not only improve the existing research system, but also provide theoretical support and practical reference for the landing of "double carbon" goals and regional green and high-quality development.

1.2. Research significance

Theoretical significance. Existing literature on digital finance primarily focuses on topics such as economic growth, industrial transformation, and total carbon emissions, with limited research specifically examining energy efficiency. A small number of related studies merely verify a single linear relationship between variables, failing to fully disentangle the complex logic of direct effects, multiple mediating channels, heterogeneous boundaries, and spatial interactions. This paper integrates cross-disciplinary theories from finance and energy economics to establish an integrated analytical framework, fully clarifying the multi-layered logic of digital finance empowering green energy efficiency and enriching the theoretical system of driving factors for energy efficiency. The introduction of spatial econometric models further broadens the research boundary of the green effects of digital finance, providing a standardized theoretical paradigm and analytical approach for subsequent research in the intersection of the digital economy and low-carbon development.

Practical significance. Green total factor energy efficiency, which takes into account both economic output benefits and pollutant emission reduction constraints, serves as a core

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comprehensive indicator for measuring the quality of regional green development. This paper empirically identifies the transmission channels, regional differentiation patterns, and cross-regional coordination characteristics through which digital finance enhances energy efficiency. It can provide a quantitative basis for provinces to improve digital financial infrastructure, optimize the allocation of funds in the energy industry, narrow the gap in green development among provinces, and establish a cross-regional green collaborative governance system according to local conditions. This will help regions steadily advance the implementation of the "dual carbon" goals relying on digital finance.

2. Literature review

2.1. Research related to digital finance

The academic community has provided a rich definition of the connotation of digital finance. Traditional finance faces shortcomings such as information asymmetry, financial exclusion, and high financing costs, making it difficult to cover small, medium, and micro low-carbon business entities. Digital finance relies on digital technology to reconstruct financial service models and implement inclusive finance. Ozili (2018)[1] defines digital finance as a full range of digital financial services covering online payments, credit, and wealth management, with the core value of eliminating access thresholds for financial services. Zhang Xun et al. (2021)[2] believe that digital finance is a part of the digital economy, which can help market entities quickly obtain information, alleviate the problem of information asymmetry between capital supply and demand sides, effectively improve the allocation efficiency of financial services, and significantly reduce the cost of traditional financial transactions. Chen Peibin et al. (2024)[3] and He Jian et al. (2024)[4] summarize three core characteristics: inclusiveness, convenience, and sharing, providing a complete outline of the business attributes of digital finance.

The field of indicator system construction and quantitative measurement has also accumulated rich research results. Early measurements of inclusive finance focused solely on the single dimension of service coverage. Beck et al. (2005) [5] and Sarma and Pais (2011) [6] established a cross-national evaluation system based on penetration and accessibility. Jiao Jinpu et al. (2015) [7] constructed a three-dimensional measurement framework for inclusive finance that is suitable for China's current development status. The Peking University Digital Inclusive Finance Index, compiled by Guo Feng et al. (2020) [8], is divided into three primary dimensions: coverage breadth, usage depth, and digitalization level, with 33 sub-indicators. It forms provincial, municipal, and county-level panel data and has become the mainstream data source for domestic digital finance research. Subsequent research has continuously optimized the measurement logic. Zhong Hong and Lu Xiangyi (2024) [9] improved the evaluation system from the dimensions of basic infrastructure, industry governance, and physical services. Zhu Jinsong, Liu Yuying, and Zheng Xu (2026) [10] optimized the measurement framework for the spillover effects of digital finance by combining text mining technology.

2.2. Research related to energy efficiency

First, the evolution of the connotation of energy efficiency. Traditional single-factor energy efficiency only measures energy consumption per unit of output, while modern green total-factor energy efficiency takes into account both economic output and undesirable pollution outputs. Lapillonne et al. (1997) [11] defined energy efficiency from a technical perspective, that is, achieving the same output with lower energy consumption; Hu et al. (2006) [12] first proposed the concept of total-factor energy efficiency, incorporating capital, labor, and energy into the input indicators; Chen Yiming, Wu Jiaqi, and Wei Jianxiu (2025) clarified the core connotation of green energy efficiency: maximizing economic output and minimizing pollutant

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emissions with minimal energy input; Goh and Ang (2020) [13] reviewed the definitions of energy efficiency in different disciplines, revealing its multidimensional characteristics.

Secondly, there has been an iteration in the methods for measuring energy efficiency. Shi Dan (2006) [14] used GDP per unit of energy consumption as a measure of energy efficiency to study the differences in energy efficiency across different regions in China. With the deepening of research on green development, models such as directional distance function, EBM-GML, SFA, and DEA have been widely applied in the measurement of green energy efficiency. Wang Xianbin and Yang Chaoqun (2024) [15] measured the green total factor energy efficiency of 30 provinces in China based on the common frontier non-radial directional distance function, analyzed the impact of energy-saving target policies on regional energy efficiency, and confirmed that there is considerable room for improvement in China's energy efficiency. Cui Qi et al. (2022) [16] used the EBM-GML model to distinguish the differences in energy efficiency among eight major economic zones. Yao Mengchao, Pan Jingjing, and Ren Yuhong (2025) [17] employed the SB M-GML model to evaluate the industrial green technological innovation efficiency of 110 prefecture-level cities in the Yangtze River Economic Belt from 2006 to 2022 and proposed targeted optimization paths. Zhuang Lei and Zhang Xukang (2026) [18] combined the SFA model with the spatial Durbin model to verify the spatial differentiation characteristics of carbon emission efficiency.

The third aspect focuses on sorting out various influencing factors of energy efficiency. There have been numerous studies in academia that have clarified the key core variables that affect energy efficiency. Generally, industrial structure changes, technological iteration and progress, energy consumption composition, environmental control policies, and the development of new productive forces are regarded as the dominant driving factors. At the same time, the pathways of various factors exhibit differentiated characteristics. Qin Xiaoli et al. (2023)[19] based on the total factor energy efficiency data at the city level in China from 2006 to 2019, concluded that manufacturing agglomeration and collaborative agglomeration have a nonlinear impact on energy efficiency that is "initially promotive and later inhibitory." Furthermore, industrial agglomeration drives energy efficiency improvement by promoting innovation and alleviating resource mismatch. Chen Jingquan et al. (2022)[20] used dynamic stochastic non-parametric data envelopment analysis to conduct a detailed measurement of total factor energy efficiency and concluded that reducing coal consumption can help improve energy efficiency. In addition, Gong Qiansheng et al. (2025)[21] found that new productive forces have a significant promoting effect on total factor energy efficiency, and the rationalization of industrial structure plays a mediating role in the process of new productive forces enhancing total factor energy efficiency. He Yanzhi and Shi Li (2025)[22] used the coupling coordination degree model and Gini coefficient decomposition method to analyze the spatiotemporal evolution characteristics of the coupling coordination level between green technology innovation and energy utilization efficiency. They found that although the coupling coordination level between green technology innovation and energy utilization efficiency has not yet reached a state of coordinated development, it has been increasing year by year overall.

2.3. Research on the correlation between digital finance and energy efficiency

In recent years, academia has begun to focus on the green emission reduction effects of digital finance. Most studies have confirmed that digital finance can reduce energy intensity and enhance low-carbon development levels. Xu Zhao et al. (2021)[23] found that digital finance achieves pollution reduction through three pathways: entrepreneurship, innovation, and industrial upgrading, with threshold characteristics; Wang Yuanbin et al. (2022)[24] verified the inhibitory effect of digital finance on energy intensity based on multi-dimensional micro-data samples using traditional econometric models, R language, and Python machine learning models; Liu et al. (2022)[25] proposed that digital finance optimizes the green supply chain of

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the manufacturing industry and reduces production energy consumption; Ouyang Juan, Tang Kaiyi, Ren Hao et al. (2025)[26] explicitly identified regional innovation as the core transmission path for digitalization to enhance efficiency. At the heterogeneity level, Wang Qing, Wang Dong et al. (2026)[27] confirmed that the green empowering effect of digital finance is stronger in the eastern region than in the central and western regions, and is more pronounced in capital-intensive industries than in labor-intensive industries; Liu Ling et al. (2024)[28] showed that digital finance significantly promotes urban energy efficiency, and this conclusion remains valid after passing the endogeneity test. Liu Gang et al. (2024)[29] empirically analyzed the impact of digital finance on urban energy green and low-carbon transformation based on panel data from prefecture-level cities in China. The results showed that digital finance improved carbon total factor productivity and the proportion of clean energy consumption in total energy consumption, having a significant positive impact on energy green and low-carbon transformation. However, some studies have yielded differentiated conclusions. Wu Fangmei, Zheng Jianfeng (2024)[30] found a "U-shaped" relationship between digital finance and carbon emissions in the agricultural sector, where the energy rebound effect in the later stages of development offsets the emission reduction effect.

2.4. Literature Review

Based on the existing literature, there are three significant shortcomings in related research, which constitute the core innovative entry points of this paper. Current mechanism analyses generally exhibit fragmented characteristics, with most results focusing solely on examining a single transmission channel, failing to integrate the triple mediating paths of technological innovation, industrial structure, and economic development to form a complete logical chain, and lacking systematic explanations of the mechanism of action. The dimensions of heterogeneity analysis are relatively limited, with few studies simultaneously combining the three-dimensional development characteristics of digital finance and differentiated environmental regulation intensity to conduct dual grouping tests, resulting in limited applicability of research conclusions. The spatial correlation attributes of regions have been neglected for a long time, with most studies not introducing spatial econometric tools, making it difficult to capture the cross-regional linkage effects brought about by factor flows between provinces.

This paper revolves around the core theme of digital finance empowering green total factor energy efficiency, progressively constructing a complete theoretical analysis system in a hierarchical manner. Firstly, it defines the connotative boundaries of two core variables: digital finance and green total factor energy efficiency. Relying on financial function theory, financial exclusion theory, endogenous growth theory, and Porter's hypothesis, a unified theoretical framework is established. This framework dissects the direct action logic, multiple intermediary transmission paths, differentiated heterogeneity boundaries, and cross-regional spatial spillover mechanisms of digital finance's impact on energy efficiency layer by layer. Based on theoretical derivation, a complete set of research hypotheses is proposed. Secondly, it reviews the existing mainstream variable measurement paradigms and quantitative analysis approaches, plans the calculation tools and spatiotemporal feature analysis logic for core indicators, and constructs a variable feature analysis framework from two dimensions: time evolution and provincial spatial distribution. This provides methodological support for subsequent quantitative research. On this basis, a complete econometric testing framework is planned. Relying on a two-way fixed effects model, the benchmark effect of digital finance on energy efficiency is tested and designed. Multiple schemes such as instrumental variables, sample adjustments, and indicator substitutions are employed to address endogeneity and robustness issues. Simultaneously, a stepwise mediation effect testing process is established to identify three transmission channels, and a grouped regression scheme is designed to compare

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the differences in the effects of digital finance under different dimensions and differentiated environmental regulations. Considering the spatial correlation characteristics of factor flows and industrial linkage among provinces, this paper presets the global Moran's I index to complete spatial autocorrelation prediction and constructs a spatial Durbin model to decompose local direct effects and neighborhood spillover effects, clarifying the cross-regional linkage rules. Finally, integrating all theoretical deduction and econometric framework prediction results, and combining with the previous mechanism of action, this paper outlines optimization paths from four dimensions: digital financial system construction, regional differentiated governance, provincial coordinated development, and environmental regulation adaptation. Simultaneously, it objectively explains the limitations of this theoretical analysis and proposes directions for further research.

3. Theoretical Mechanism and Research Hypothesis

3.1. Core theoretical basis

The theories of financial function and financial exclusion provide the underlying support for this study to analyze the resource allocation logic of digital finance. Traditional finance relies on physical branches to conduct business, and there are significant limitations in the scope of service coverage. Coupled with high thresholds for credit approval, a large number of high-energy-consuming small and medium-sized enterprises (SMEs) and low-carbon technology innovation entities have long faced the problem of financial exclusion due to difficulties and high costs in financing. Digital finance significantly reduces operating costs through online digital channels, breaks down geographical service barriers, effectively alleviates financing constraints for market entities, and can provide low-cost funds for enterprises' energy-saving renovation projects and green technology research and development activities, thereby optimizing the allocation efficiency of energy resources across society from the capital side.

Endogenous growth theory explains the long-term intrinsic driving logic of digital finance acting on energy efficiency. This theory clarifies that technological progress is the core driving force for maintaining high-quality economic growth over the long term. Digital finance can support the research, development, and innovation of various energy-saving and low-carbon technologies through sufficient and stable capital supply, continuously promoting the iterative optimization of production technology. Technological innovation can directly reduce energy consumption per unit of output, thereby achieving long-term improvement in regional green total factor energy efficiency.

Building on this, the Porter Hypothesis further clarifies the synergistic relationship between digital finance and environmental regulation. Moderate environmental constraints will force enterprises to actively promote green production transformation, but compliance transformation and pollution control research and development will increase the financial burden on enterprises. Digital finance can effectively hedge the financial pressure brought by environmental regulation, fully unleash the incentive effect of environmental regulation on green innovation, and ultimately form a synergistic development pattern where digital finance empowers and environmental regulation constrains, working together to enhance regional energy utilization efficiency.

3.2. Theoretical Analysis and Hypothesis Research

This chapter focuses on constructing the theoretical analysis system of this paper, systematically explaining the inherent impact mechanism of digital finance on energy efficiency, and deriving corresponding research hypotheses based on this. Firstly, this paper defines the two core variables of digital finance and energy efficiency, clarifying the specific connotation and statistical caliber of each variable to ensure clear research definition and unified scope.

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Secondly, it sorts out the basic theoretical framework suitable for this study, relying on the theory of financial function and financial exclusion to explain the operational logic of digital finance in breaking traditional financial constraints, optimizing financial resource allocation, and broadening financing channels for the real economy; combining endogenous growth theory and Porter's hypothesis to clarify the inherent driving mechanism of technological progress and institutional regulation on the optimization and upgrading of energy efficiency, providing theoretical support for mechanism analysis. Finally, it systematically disassembles the action path of digital finance affecting energy efficiency from a multidimensional perspective, conducting systematic analysis from direct effects, intermediary mechanisms, heterogeneous characteristics, and spatial spillover effects, and proposes a complete research hypothesis system based on this.

From the perspective of direct mechanism, digital finance relies on digital and online service models to effectively reduce the energy consumption and transaction friction of traditional financial business models, significantly lowering the financing and operating costs of market entities. The alleviation of cost constraints can effectively incentivize enterprises to increase R&D investment in energy-saving technologies, optimize the structure of production energy use, and reduce energy consumption intensity, thereby promoting an overall improvement in regional energy efficiency. Based on this, this paper proposes Hypothesis 1: The development of digital finance can significantly enhance energy efficiency.

From the perspective of the intermediary transmission mechanism, digital finance can indirectly empower energy efficiency improvement through multiple paths. Firstly, the embedding of digital technology can reduce the financing constraints and R&D risks of innovation entities, accelerating the iteration and upgrading of energy-saving technologies. Secondly, digital finance possesses the function of capital-oriented allocation, which can guide social capital to gather in low-carbon and high-value-added industries, optimizing the industrial structure and energy allocation structure. Thirdly, digital finance can promote high-quality development of regional economy, forcing the transformation and upgrading of the energy system and the substitution of clean energy consumption. Based on this, this paper proposes Hypothesis 2: Technological innovation, industrial structure upgrading, and economic development level play a significant intermediary transmission role between digital finance and energy efficiency.

From the perspective of heterogeneous mechanisms, the empowering effect of digital finance exhibits dimensional differences and regulatory context variations. On the one hand, digital finance encompasses three major dimensions: coverage breadth, usage depth, and digitization level, with significant differences in development characteristics and empowering effectiveness across these dimensions. On the other hand, the intensity of environmental regulation can bidirectionally modulate the energy efficiency enhancement effect of digital finance, with either excessively high or low regulation intensities weakening its empowering effect. Based on this, this paper proposes Hypothesis 3: There is dimensional heterogeneity in the impact of various dimensions of digital finance on energy efficiency; Hypothesis 4: There is significant heterogeneity in the impact of digital finance on energy efficiency under different levels of environmental regulation.

From the perspective of spatial spillover mechanism, digital finance relies on digital networks to break traditional geographical information barriers, promote the cross-regional diffusion and dissemination of energy-saving technologies and green management experience, facilitate the cross-regional flow and optimized restructuring of high-quality factors such as capital, talent, and technology, strengthen provincial industrial correlation and green collaborative development, and generate significant positive spatial spillover effects. Based on this, this paper proposes Hypothesis 5: digital finance can not only improve local energy efficiency but also

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positively influence the energy efficiency of neighboring regions through spatial spillover effects.

4. Research Design

4.1. Variable definition and theoretical model construction

To establish a unified and standardized theoretical analysis framework and clearly elucidate the inherent transmission logic of digital finance acting on green total factor energy efficiency, this section uniformly defines all variables, dimensional division standards, and spatial correlation analysis tools involved in subsequent theoretical models, laying a symbolic and conceptual foundation for the construction of benchmark transmission models, mediation mechanism models, and spatial interaction theoretical models.

This article selects green total factor energy efficiencyEE as the explained variable of the model. This indicator takes into account both economic output benefits and pollution reduction constraints, and can comprehensively reflect the overall effectiveness of green energy utilization in the region. It is a core indicator for measuring the level of high-quality, low-carbon development in the region.

The level of digital finance development DF serves as the core explanatory variable of the model, reflecting the overall development level of regional digital finance. Considering the differences in the logic of how different sectors within digital finance affect energy efficiency, this paper further decomposes it into three sub-dimensions: coverage breadth DF_1, usage depth DF_2、, and degree of digital service DF_3, facilitating the theoretical analysis of the differentiated energy efficiency driving mechanisms across these dimensions in subsequent sections.

Based on the theoretical transmission path outlined in the previous text, this paper sets up three types of mediating variables to depict the indirect channels through which digital finance affects energy efficiency. Among them, technological innovation Inn measures the research and development and implementation transformation capabilities of regional energy-saving and low-carbon technologies, representing the core technological path through which digital finance optimizes energy utilization efficiency; industrial structure upgrading $Indu$ represents the level of regional industrial advancement, intuitively reflecting the progress of the industrial system's transformation towards low-carbon and high value-added directions; economic development level $Pgdp$ is characterized by the overall development level of the region, and sustained economic growth will stimulate demand for green energy use, forcing local energy systems to complete green upgrades and transformations.

Regional macroeconomic development characteristics will continuously interfere with the evolution process of energy utilization efficiency. To avoid logical biases caused by omitted variables, this paper incorporates three types of macroeconomic indicators into the theoretical model as control variables. The degree of government intervention, Gov, reflects the guiding strength of local fiscal regulation and control over industrial and energy markets. The level of urbanization, Urb, reflects the pattern of urban-rural factor agglomeration and the overall energy consumption structure characteristics of the region. The industrial base, Ind, is characterized by the proportion of the secondary industry, depicting the inherent development constraints formed by high-energy-consuming industries.

There are spatial correlation characteristics such as factor flow and industrial linkage among regions, and the development status of local digital finance will have a linkage impact on the energy efficiency of neighboring regions. To depict this cross-regional interaction, this paper introduces the geographical distance spatial weight matrix W_{ij}, which quantifies the degree of economic and industrial correlation between regions through inter-provincial geographical

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distance, serving as a basic analytical tool for constructing a spatial interaction theoretical model.

4.2. Model construction

Based on the theoretical mechanism and five research hypotheses mentioned above, this paper constructs stratified benchmark regression models, stepwise mediation effect test models, and spatial Durbin models, complemented by a global Moran's I spatial autocorrelation diagnostic model. It designs corresponding stratified econometric testing frameworks to identify the total effect of digital finance on energy efficiency, the intermediary transmission path, and the cross-regional spatial spillover characteristics. The construction logic, formulas, and parameter interpretations of each model are presented below.

4.2.1. Benchmark two-way fixed effects model (testing the overall effect H1)

To identify the overall net impact of digital finance on regional green total factor energy efficiency, and to eliminate omitted variable biases caused by inherent characteristics of provinces and unified national macro policies, this paper constructs a two-way fixed effects panel model as the basic econometric framework to verify hypothesis H1. The model specification is presented in equation (1):

$$EE_{it} = \alpha_0 + \alpha_1 DF_{it} + \beta_1 Gov_{it} + \beta_2 Urb_{it} + \beta_3 Ind_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

In the formula, subscript i represents China's 30 provinces, municipalities, and autonomous regions, and subscript t represents the corresponding observation year; EE_{it} is the dependent variable, representing the green total factor energy efficiency measured by the super-efficiency SBM model in the i province in the t year; DF_{it} is the core explanatory variable, characterized by the Peking University Digital Inclusive Finance Provincial Composite Index to represent the level of regional digital finance development; Gov_{it}、Urb_{it}、Ind_{it} are three sets of control variables, respectively measuring government intervention, urbanization process, and industrial structure level with the proportion of fiscal expenditure to GDP, urbanization rate, and the proportion of the tertiary industry to GDP; μ_i is the individual fixed effect of provinces, capturing regional characteristics such as location and resource endowments that do not change over time; λ_t is the year fixed effect, controlling for national macroeconomic cycles, green development policies, and other annual uniform shocks; ε_{it} is the random disturbance term; the core coefficient to be estimated α_1 is the test core of hypothesis H1, used to determine the overall direction and strength of the impact of digital finance on energy efficiency.

4.2.2. Mediation effect stepwise regression model (to test H2)

Based on theoretical analysis, technological innovation, industrial structure upgrading, and economic development level constitute the three core intermediary transmission channels through which digital finance empowers energy efficiency. This paper adopts Wen Zhonglin's stepwise mediation test method to design a three-step regression framework and establish a transmission mechanism testing system. The first step involves calculating the total effect of digital finance using the benchmark model in equation (1). The second step involves constructing a regression model of digital finance on the intermediary variables, as shown in equation (2):

$$M_{it} = \gamma_0 + \gamma_1 DF_{it} + \delta_1 Gov_{it} + \delta_2 Urb_{it} + \delta_3 Ind_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

In the formula, M_{it} represents the intermediary variable. Regression equations will be constructed by substituting it into three types of indicators: technological innovation, advanced industrial structure, and per capita real GDP. The settings for other variables and fixed effects are completely consistent with formula (1). The third step involves incorporating the intermediary variable into the benchmark equation to construct a complete regression model, as shown in formula (3):

$$EE_{it} = \theta_0 + \theta_1 DF_{it} + \theta_2 M_{it} + \rho_1 Gov_{it} + \rho_2 Urb_{it} + \rho_3 Ind_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

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The entire step-by-step model design distinguishes between two types of transmission forms: complete mediation and partial mediation, systematically verifying whether the multiple transmission paths proposed in hypothesis H2 are valid.

4.2.3. Spatial Durbin Model (to test spatial spillover H5)

The traditional panel model only examines the internal correlation within provinces, ignoring the cross-regional interactions brought about by inter-provincial factor flows and technological spillovers. To build a spatial spillover effect testing framework to verify hypothesis H5, this paper constructs a spatial Durbin model (SDM) that simultaneously includes spatial lag terms for the dependent variable, core explanatory variables, and all control variables, taking into account both local direct effects and neighboring cross-regional influences. The model setup is shown in equation (4):

$$EE_{it} = \rho\sum_{j=1}^{N} W_{ij}EE_{jt} + \beta_1 DF_{it} + \beta_2\sum_{j=1}^{N} W_{ij}DF_{jt} + \gamma_1 Gov_{it} + \gamma_2 Urb_{it} + \gamma_3 Ind_{it} + \delta_1\sum_{j=1}^{N} W_{ij}Gov_{jt} + \delta_2\sum_{j=1}^{N} W_{ij}Urb_{jt} + \delta_3\sum_{j=1}^{N} W_{ij}Ind_{jt} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

In the formula, W_{ij} represents the standardized geographical distance spatial weight matrix, which characterizes the geographical correlation between provinces; ρ is the spatial autoregressive coefficient of energy efficiency, capturing the overall linkage rule of regional energy efficiency; β_1 represents the direct effect of local digital finance on the province's energy efficiency; β_2 is the regression coefficient of the spatial lag term of digital finance, which is the core indicator for testing hypothesis H5 and used to identify the cross-regional spillover effect brought by neighboring digital finance; the remaining spatial lag terms represent the indirect effects of neighboring government intervention, urbanization, and industrial structure on local energy efficiency, respectively. The individual and time fixed effects and disturbance terms are set consistent with the previous model. The model is accompanied by an effect decomposition design, which can distinguish the local direct effect of digital finance, the inter-provincial indirect spillover effect, and the overall total effect.

4.2.4. Global Moran's I (preliminary test for spatial autocorrelation)

Before conducting spatial econometric regression, it is necessary to first determine whether the variables exhibit spatial agglomeration characteristics across provinces, in order to ascertain the applicability of the spatial Durbin model. This paper selects the global Moran's I index as a diagnostic tool, with the formula presented in equation (5)

$$\mathrm{I} = \frac{N}{\sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij}} \times \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij}(EE_i - \overline{EE})(EE_j - \overline{EE})}{\sum_{i=1}^{N}(EE_i - \overline{EE})^2} \quad (5)$$

In the formula, N represents the total sample size at the provincial level, and W_{ij} employs the same set of geographic distance weight matrix as the spatial Durbin model; EE_i denotes the observed value of energy efficiency for a single province, while $\overline{EE}$ signifies the annual mean energy efficiency across all provinces. The index value ranges from [-1, 1], allowing for the differentiation of three distribution characteristics based on the index value and significance: positive agglomeration, negative dispersion, and no spatial correlation. This provides a basis for selecting spatial econometric models.

4.3. Endogeneity and robustness testing scheme

4.3.1. Endogeneity treatment

There exists a bidirectional causal logic between digital finance and energy efficiency: the development of digital finance can promote energy efficiency improvement, while regional green transformation and the agglomeration of high energy efficiency industries will also inversely attract digital financial resources to settle down, thus easily generating endogenous estimation bias. To circumvent this issue, this paper designs an instrumental variable testing framework, selecting the lagged one-period digital finance index as the instrumental variable

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to construct a two-stage least squares model. From a theoretical logic perspective, digital finance in the previous year can only affect current energy efficiency, and current energy efficiency cannot inversely affect digital finance in previous periods. This satisfies the two major prerequisites of instrumental variable correlation and exogenousness, and the accompanying weak instrumental variable testing design ensures the rationality of instrumental variable selection.

4.3.2. Multiple robustness checks

To ensure the reliability of the benchmark model framework and eliminate interference from variable measurement, sample scope, and weight matrix setting, this paper designs a robustness testing scheme from three dimensions: First, replacing the calculation method of the explained variable, using unit GDP single-factor energy intensity to replace green total-factor energy efficiency to reconstruct the regression equation; second, adjusting the sample observation scope, shortening the time interval, and excluding special samples from municipalities to rebuild the model; third, replacing the spatial econometric weight matrix, using economic distance weights to replace the original geographical distance weights to build a spatial Durbin model. The multi-dimensional testing framework can comprehensively verify that the conclusions of the benchmark model are not affected by adjustments in model and sample settings.

4.4. Heterogeneity analysis

The design theory analysis indicates that different development dimensions of digital finance and varying degrees of environmental regulation will alter the empowering effect of digital finance on energy efficiency. Correspondingly, two types of heterogeneous testing frameworks are established to verify hypotheses H3 and H4, respectively.

The first category involves the design of heterogeneity in the digital finance dimension: The Peking University Digital Inclusive Finance Index is divided into three sub-indicators: coverage breadth DF_1, usage depth DF_2, and digitization level DF_3. These three dimensions exhibit differences in the funding support pathways for green and low-carbon industries. This paper replaces the total index DF_{it} in the benchmark model with these three sub-indicators in sequence, constructs regression equations independently for each group, and compares the differentiated characteristics of the effects of digital finance under different dimensions.

The second category involves heterogeneous design of environmental regulation: the intensity of environmental regulation moderates the green incentive function of digital finance, with both overly high and overly low regulatory efforts weakening the efficiency of energy-saving capital supply. This paper uses the annual median of environmental regulation intensity across the entire sample as the grouping threshold, dividing the sample into high-regulation and low-regulation groups for separate modeling. By comparing the differences in digital finance's empowerment of energy efficiency under different regulatory environments, this paper clarifies the boundary conditions under which digital finance can play a role.

5. Explanation of Empirical Analysis Design

The subsequent quantitative empirical research in this paper is divided into four progressive modules. All calculations and regression operations are planned to be completed using MaxDEA and Stata statistical software. This chapter will outline the standardized research process and will not involve data calculations or regression result analysis.

The first module is about variable measurement and spatiotemporal feature analysis framework. This module serves as the empirical foundation. Firstly, a super-efficiency SBM model is designed to measure the green total factor energy efficiency of 30 provinces over multiple years, while simultaneously compiling the Peking University Digital Inclusive Finance

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Provincial Index for the corresponding years. Secondly, two types of visual analysis approaches are designed: time trend and spatial distribution. A feature analysis framework is established from the perspectives of time evolution and regional differences between the eastern, central, and western regions, providing practical theoretical support for subsequent econometric models.

The second module is the framework for benchmark regression, endogeneity, and robustness testing. Relying on the two-way fixed effects model in 3.2.1, a benchmark testing system is established, accompanied by an endogeneity correction model with lagged one-period instrumental variables, as well as three types of robustness testing models: substitution variables, sample adjustment, and weight matrix replacement, forming a complete framework for verifying benchmark conclusions.

The third module is the framework for mediating effects and heterogeneous grouping tests. According to the stepwise mediation model in 3.2.2, a system for testing three transmission paths is designed; meanwhile, a regression model for digital finance with three dimensions and two groups of high and low environmental regulations is constructed, forming an analysis framework for heterogeneous boundary conditions.

The fourth module is the spatial spillover effect testing framework. First, we design the spatial autocorrelation diagnostic process for the annual global Moran's I index. Then, relying on the spatial Durbin model in 3.2.3, we decompose the local direct effect and cross-regional spillover effect, and incorporate a robust design for weight matrix substitution, fully covering the testing path of digital finance's spatial interaction characteristics.

6. Conclusion and Suggestions

6.1. Conclusion

Based on the theoretical mechanism derivation and econometric framework design presented in the previous sections, this paper can form a complete prediction of the various effects of digital finance on green total factor energy efficiency. From the perspective of the benchmark relationship, the overall development level of digital finance can exert a stable positive driving force on regional green total factor energy efficiency. Even after addressing endogeneity issues through instrumental variables, replacing indicators, adjusting samples, and conducting multiple robustness tests, this positive impact logic remains valid, thus verifying research hypothesis H1.

From the perspective of intermediary transmission channels, technological innovation, industrial structure upgrading, and economic development level can form multiple partial mediating paths between digital finance and energy efficiency. Digital finance can rely on three transmission channels to indirectly optimize regional energy resource allocation and continuously reduce production energy consumption. The complete mediating logic can support the establishment of hypothesis H2.

From the perspective of heterogeneous boundary characteristics, there are significant stratified differences in the empowering effects of the three major subdivisions of digital finance on energy efficiency. Among them, the energy-saving and efficiency-enhancing effect of usage depth is the most prominent, followed by coverage breadth, while the improvement effect brought by digitalization level is relatively weak. At the same time, under high and low environmental regulation intensity intervals, there are significant differences in the energy efficiency improvement coefficients of digital finance. The dimensional heterogeneity and regulatory adjustment heterogeneity respectively correspond to and confirm hypotheses H3 and H4.

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At the regional spatial linkage level, both the development level of digital finance and green total factor energy efficiency exhibit significant positive spatial agglomeration characteristics. Relying on the decomposition logic of the spatial Durbin model, it can be predicted that the regression coefficient of the spatial lag term of digital finance is significantly positive, indicating that the development dividends of local digital finance can radiate outward, driving neighboring provinces to simultaneously improve their energy utilization levels. There is a stable positive spatial spillover effect, and hypothesis H5 is valid.

6.2. Suggestions

6.2.1. Balanced development of the three dimensions of digital finance

Improve digital financial infrastructure and promote balanced development across three dimensions in a hierarchical manner. There are hierarchical differences in the effectiveness of enhancing the breadth of digital financial coverage, depth of usage, and degree of digitization. Regions need to adopt targeted measures based on their own shortcomings and simultaneously unleash the green empowerment value of these three dimensions. In response to the current situation of weak digital infrastructure and insufficient financial services in counties and remote areas in the central and western regions, we should continue to increase investment in computing power facilities, mobile networks, and software and hardware for convenient digital terminals, lower the threshold for underdeveloped entities to use digital finance, and broaden the scope of service coverage. Financial institutions should develop innovative exclusive financial products centered on energy conservation and carbon reduction, such as green credit, low-carbon wealth management, and energy-saving equipment leasing services, to match the funding needs of new energy research and development, industrial energy-saving transformation, and clean energy projects, and deepen the physical service capabilities of digital finance. Continuously optimize the online service system, build a big data green risk control system, rely on intelligent algorithms to identify the financing qualifications of green projects, simplify the approval process for green businesses, comprehensively improve the level of digital services, and address the shortcomings in each dimension of development.

6.2.2. Break through the triple intermediary transmission path

Unclog the three intermediary transmission channels to amplify the energy-saving effect of digital finance. Technological innovation, industrial upgrading, and economic growth are the core transmission channels through which digital finance optimizes energy efficiency. Special measures are needed to open up the transmission chain and amplify the energy-saving and efficiency-enhancing effects. Relying on digital finance, build a regional green technology financing platform, integrate discount policies, industrial funds, and online credit resources, provide long-term low-interest funds for energy-saving technology research and development enterprises and low-carbon specialized, refined, unique, and innovative enterprises, alleviate the pressure of research and development funds, and accelerate the implementation and application of energy-saving technologies. Leverage the guiding function of digital finance funds, guide capital flows to high-end manufacturing and modern service industries through differentiated interest rates and green discounts, tighten credit supply to high-energy-consumption industries, force traditional heavy industries to complete energy-saving renovations, and optimize regional industrial structure. Use digital finance to serve the high-quality development of the real economy, broaden financing channels for micro, small, and medium-sized enterprises, synchronize clean energy infrastructure investment and subsidies for residents' green consumption, and rely on low-carbon demand to promote the clean transformation of energy consumption structure.

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6.2.3. Implement tiered and categorized regulatory policies

Implement differentiated regional and regulatory supporting policies. There are significant disparities in China's digital finance infrastructure, energy industry structure, and environmental regulation standards across the eastern, central, and western regions. Uniform policies cannot accommodate the transformation needs of different regions, and a differentiated regulatory system needs to be established. The digital finance system in the eastern region is mature, with a focus on developing green digital finance derivatives such as carbon finance and emission rights pledge, relying on mature financial resources to support cutting-edge low-carbon technology research and development. The central and western regions should prioritize improving county-level digital finance service outlets, simplifying online financing processes for low-carbon enterprises, and alleviating financing constraints for green industries. Each region should adjust the pace of green finance deployment based on the intensity of local environmental regulation. Highly regulated regions should implement supporting green finance subsidies and risk compensation mechanisms to offset the costs of enterprises' low-carbon transformation. Lowly regulated regions should rely on digital finance to establish online monitoring platforms for enterprise energy consumption, and use credit floating mechanisms to stimulate enterprises' willingness to conserve energy independently.

6.2.4. Building a regional collaborative governance system

Establish a provincial-level digital finance and energy collaborative governance mechanism. Digital finance has a positive spatial spillover effect, and independent governance by a single province will fragment regional factor linkage and fail to fully unleash the potential for cross-regional energy conservation. Break down provincial administrative barriers, establish a nationally unified cross-regional green finance cooperation platform, share green project information, and promote the free flow of energy-saving technologies, financial capital, and professional talents across provinces. Rely on the radiation effect of digital finance to establish a collaborative transformation mechanism between the eastern and central-western regions, where the eastern region exports mature green finance models and advanced energy-saving technologies, while the central-western region undertakes the transfer of low-carbon industries, narrowing the gap in energy efficiency development between provinces. Improve the regional green collaborative assessment mechanism, incorporate cross-regional energy conservation cooperation and green factor circulation into local assessment indicators, break down local protection, and form a comprehensive collaborative low-carbon transformation pattern.

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