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Green Finance-Driven and Low-Carbon Energy Transition: A Tripartite Game-Theoretic and Spatial Econometric Analysis Based on Evidence from 30 Chinese Provinces

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Abstract

Addressing climate change and achieving carbon neutrality are urgent global responsibilities, with China's "dual carbon" goals presenting a significant challenge and opportunity for its energy sector. Green finance, as a pivotal driver for fostering low-carbon and high-quality development in the energy industry, significantly accelerates its green transition. Employing an integrated micro-macro framework, this study first develops a tripartite evolutionary game model involving government, local energy enterprises, and external energy enterprises to analyze the micro-mechanisms of corporate low-carbon decision-making under green finance policies. Subsequently, utilizing panel data from 30 Chinese provinces (2013–2021), it empirically examines the macro impact of green finance on the industry's low-carbon, high-quality development using a spatial Durbin model (SDM). Key findings include the following: (1) Game analysis reveals that local enterprises' low-carbon transition propensity and emission reduction returns increase with R&D investment but are negatively moderated by the tax rate level within green finance policies. (2) Spatial econometric results demonstrate that green finance significantly facilitates local energy industry low-carbon transition via technological progress, confirming a significant negative spatial spillover effect on neighboring regions, with notable regional heterogeneity. (3) The effectiveness of green finance policy exhibits significant regional disparity, being markedly stronger in eastern China compared to central and western regions. The findings provide a theoretical and practical foundation for improving market mechanisms and regional coordination in China's green finance policies, offering a valuable reference for the design of green finance systems in other major emerging and developing economies.



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1. Introduction

Addressing climate change and achieving carbon neutrality are urgent global priorities. In recent years, international climate finance has seen significant milestones, including developed countries meeting the long-standing USD 100 billion annual climate finance goal and the agreement at COP29 to establish a new collective quantified goal for climate finance post-2025. Parallel to these efforts, global carbon markets are expanding, with initiatives such as the European Union's Carbon Border Adjustment Mechanism (CBAM) driving the adoption of carbon pricing schemes worldwide. As the world's largest emitter, accounting for approximately 30% of global carbon emissions, China's "dual carbon" commitments are of paramount importance.

Currently, traditional energy sources (e.g., oil, coal, natural gas) remain key pillars of China's energy industry, but their utilization generates serious atmospheric pollution, imposing huge pressure on the natural environment. At present, China's total carbon emissions account for approximately 30% of global carbon emissions, making it the world's largest energy consumer and carbon emitter. Reducing greenhouse gas emissions and protecting the ecological environment thus constitute a shared global responsibility. When the environment is damaged and energy sources are depleted, sustainable economic development will be ultimately impeded [1]. The 2020 Central Economic Work Conference emphasized carbon peaking and carbon neutrality efforts, formally establishing the "30–60 Dual Carbon target" (to peak carbon dioxide emissions by 2030 and reach carbon neutrality by 2060). Despite rapid growth in the new energy sector, persistent challenges include inadequate infrastructure and the need for enhanced innovation capabilities. Therefore, fostering low-carbon, high-quality development of the energy industry is essential for achieving China's "Dual Carbon" goals.

The term "green finance" is defined in China's "Guiding Opinions on Building a Green Financial System" (issued in 2016) as "economic activities targeting environmental improvement, climate change response and resource conservation and efficient utilization, specifically, financial services supporting project investment and financing, project operation, risk management in environmental protection, energy conservation, clean energy, green transportation, green building sectors". As an important instrument for promoting sustainable development and low-carbon transition, green finance has received increasing attention from scholars. In recent years, it has received widespread attention as a key mechanism for promoting sustainable development. Nguyen et al. [2] pointed out that green finance plays a significant role in promoting green energy and green production and can effectively improve the quality of green economic growth. Wang et al. (2024) [3] empirically analyzed the role of green finance in promoting low-carbon energy transition from the perspective of supply and demand and found that green finance can not only improve the financing structure but also stimulate clean energy investment, thus promoting the optimization of energy structure. Additionally, the evolution of green finance research has attracted attention in the academic community. For example, Wang et al. (2025) [4] found that green finance research is gradually expanding from the conceptualization stage to comprehensive assessment and policy orientation, with the core issues focusing more and more on climate finance, green credit and carbon market mechanisms. On this basis, Dhayal et al. (2025) [5] combined text and network analysis methods to further clarify the conceptual boundaries of green finance and to reveal the knowledge structure of green finance in academia along with its interdisciplinary characteristics. In addition, the relationship between green finance and energy efficiency improvement has also been empirically verified. Liu et al. (2024) [6] found that green finance significantly improves energy efficiency by promoting green technology innovation and optimizing the energy structure, simultaneously promoting environmental quality and economic benefits. In summary, current studies generally agree green finance's multi-dimensional effects, including promoting green transition, optimizing energy structure and advancing high-quality development. Future research should further deepen the design of green finance policy tools and analyze the effects of regional differences to better serve the goal of the "dual-carbon" strategy.

China's policy system for the low-carbon and high-quality development of the energy industry has undergone significant evolution. From the 11th Five-Year Plan to the 14th Five-Year Plan, China's energy policy has gradually shifted from focusing on energy saving and emission reduction to green and low-carbon transition and has further deepened the policy system for green and low-carbon development of energy since the proposal of dual carbon goal in 2020. Policies have gradually promoted the transition of the energy

structure towards clean and low-carbon directions, with the proportion of non-fossil energy consumption continuing to increase. For example, targets reaching 20% for non-fossil energy consumption and 39% for non-fossil energy power generation by 2025. At the same time, policies support the development of new energy sources such as wind power and photovoltaic, and other new energy sources drive large-scale industry development via subsidized tariffs and consumption guarantees (Yu, S. et al., 2022) [7]. These policies encourage energy technology innovation and promote the cleaner transition of traditional energy sources and the application of new energy technologies. Specifically, they support new sectors like hydrogen and biomass while accelerating deployment of energy storage and smart grid technologies.

This study makes a methodological contribution by integrating game theory with spatial econometrics, a combination that is rarely employed in the existing literature on green finance. Previous research has tended to rely either on (i) game-theoretic models to examine strategic behavior among governments, enterprises, and financial institutions, or (ii) econometric models to quantify the macro-level impacts of green finance on energy transition. However, these two approaches have largely developed in parallel, leaving a gap in understanding how micro-level strategic interactions translate into macro-level outcomes across regions.

The originality of our study lies in bridging this divide. First, the tripartite evolutionary game model allows us to reveal the micro-foundations of decision-making, showing how green finance policies alter cost–benefit structures and reshape the incentives of governments, local enterprises, and external enterprises. This captures dynamic behavioral adjustments that cannot be observed from aggregate data alone.

Second, the spatial Durbin model (SDM) enables us to empirically test whether these micro-level mechanisms scale up to the regional level and whether green finance exhibits spatial spillover effects—positive (technology diffusion, demonstration) or negative (industrial relocation, pollution haven). This spatial perspective has been largely absent from international studies, despite the cross-regional nature of energy markets and financial capital flows.

By combining game theory and spatial econometrics, we not only provide a consistent micro-to-macro analytical framework but also offer new insights into the mechanisms of green finance. Specifically, this approach uncovers how strategic responses at the firm level aggregate into heterogeneous regional outcomes and how these outcomes propagate through spatial linkages. In doing so, our study contributes both theoretical innovation and policy-relevant evidence, extending the relevance of China's experience to broader global discussions on sustainable finance and low-carbon transition.

2. Literature Review

Although an expanding international literature documents that green finance mobilizes capital for renewable energy and can improve firms' access to cheaper or targeted funding, this body of work remains fragmented across market-level, firm-level and policy-practice strands. Policy initiatives such as the European Green Deal have reoriented public policy and capital-market regulation toward sustainability, creating taxonomy, disclosure and industrial coordination instruments that shape where and how green capital flows, according to the European Commission (2019) [8]. At the market level, studies on green bonds and certification demonstrate that labelled debt can affect issuance volumes, pricing and investor engagement—yet results on pricing “green premia/discounts” are mixed and appear sensitive to certification, issuer type and market structure.

At the public-finance end, “green bank” models and public de-risking facilities in the U.S. and elsewhere illustrate how limited public capital can crowd in private investors for

early-stage clean projects, but the distributional consequences of these instruments across regions and firm sizes are understudied (U.S. EPA, 2018) [9].

2.1. *Game Analysis of Green Finance Influencing the Behavior of Energy Industry Players*

Early studies, based on the traditional game framework, focused on the two-body interactions between governments and enterprises. For example, Madani and Rasti-Barzoki [10] constructed a government-enterprise decision-making model using Stackelberg game theory, and through system dynamics simulation, found that differentiated green credit policies can accelerate the diffusion of green technologies. With the market-oriented transition of China's green financial system, the research perspective gradually expands to encompass collaborative mechanisms among multiple players. Wang et al. [11] innovatively constructed a tripartite evolutionary game model involving financial institutions, core enterprises, SMEs, revealing how supply chain finance drives technological innovation through risk sharing mechanism via its dynamic equilibrium path. To address the policy synergy challenges, Zhao et al. [12] introduce Lyapunov stability theory to verify that the coupling mechanism of environmental risk premium and policy incentives is necessary for the balanced development of green finance market. Wang and Liu [13] quantitatively analyzed the "market failure" mechanism of green technological innovation by incorporating the R&D investment elasticity coefficient into a government-firm-consumer tripartite game. In addition, Li [14] demonstrated the threshold effect of regulatory intensity and green credit supply using an evolutionary game theory.

2.2. *Empirical Research on the Impact of Green Finance on the Development of the Energy Industry*

Recent studies have highlighted the significant role of green finance in promoting the energy transition in China. Li et al. [15] found that Chinese power enterprises' sustainable energy investments through green finance channels can substantially increase the share of clean energy, thereby facilitating the green upgrade of the energy system. Using panel data from 30 Chinese provinces, Ma et al. [16] empirically demonstrated that the expansion of green finance, particularly green credit and green bonds, effectively supports the development of non-hydro renewable energy industries. From the perspective of resource policy, Chen and Bian [17] explored the relationship between green finance and renewable energy resource allocation. Their findings reveal that green finance can optimize resource use efficiency through market-based mechanisms, thereby advancing national sustainable development goals. Xu et al. [18] further examined how green finance influences energy transition. Using econometric models, they found that green finance significantly promotes the reconstructing of China's energy industry toward low-carbon sources. In addition, Du et al. [19] studied the impact of green finance on the resilience of China's energy system, revealing that green finance not only helps mitigate energy supply shocks but also enhances the overall flexibility and adaptive capacity of the energy system.

2.3. *Review and Contributions of This Study*

While the existing literature about green finance and the energy industry is extensive, research specifically addressing its role in driving LCHQD (the low-carbon, high-quality development) of the energy sector remains relatively scarce. Consequently, critical research gaps persist, prompting the following questions:

- (1) How does green finance drive the low-carbon transition in energy enterprises by measures such as altering cost–benefit structures and strategic interactions?
- (2) Does technological progress play a mediating effect in green finance's impact on the LCHQD of the energy industry?
- (3) Does green finance exert spatial spillover effects on energy industry development in geographically neighboring regions?

This study makes three primary contributions:

(1) It develops a tripartite evolutionary game model involving the government, local energy enterprises, and external energy enterprises. This model elucidates the micro-foundations of enterprise decision-making in response to green finance policies, specifically examining how changes in cost–benefit structures and strategic interactions facilitate low-carbon transitions.

(2) Theoretically, it derives the mediating role of technological progress in green finance’s pathway to influence the LCHQD of the energy industry, and empirically validates this mediation using a spatial Durbin model.

(3) It explicitly complements existing research by incorporating spatial spillover effects through which green finance affects energy industry development in surrounding regions, thereby mitigating potential estimation biases caused by overlooking spatial spillover effects.

3. Tripartite Game Model

3.1. Model Hypotheses

Hypothesis 1: Construct a tripartite game model consisting of the government (G), local energy enterprises (LE) and external energy enterprises (EE). In the model, there is a strategy interaction mechanism based on the green tax system, which is shown as follows: the government regulates the behavior of enterprises by implementing differential green tax rate policies, while enterprises face two strategic choices: (1) green technology innovation path: increasing the R&D investment to improve energy efficiency, reduce the carbon emission intensity per unit of energy consumption, thus reducing the taxable emissions; (2) spatial arbitrage path: outsourcing the pollution-intensive production process to enterprises in regions with lower environmental regulation intensity, but have to bear the transfer costs including investments in pollution treatment facilities and technology transfer expenses (Figure 1).

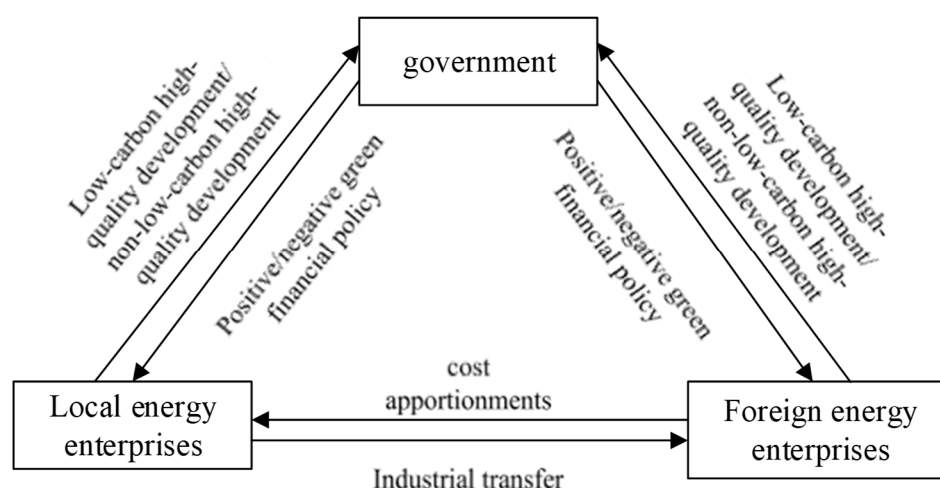


Figure 1. Game analysis diagram.

Hypothesis 2: The strategy space of each player is defined as follows:

Government (G) strategy space: $sg = \{\text{positive green finance policy (A1), negative green finance policy (A2)}\}$, with strategy selection probabilities x ($0 \leq x \leq 1$) and $1 - x$, respectively;

Local energy enterprise (LE) strategy space: $sle = \{\text{low carbon high quality development (B1), non-low carbon high quality development (B2)}\}$, with strategy selection probabilities y ($0 \leq y \leq 1$) and $1 - y$, respectively;

Strategy space of external energy enterprises (EEs): $SFE = \{\text{Low-carbon high-quality development (C1), non-low-carbon high-quality development (C2)}\}$, with strategy selection probabilities z ($0 \leq z \leq 1$) and $1 - z$, respectively.

Hypothesis 3: *There is a significant difference in the fiscal effects of government policy implementation. The implementation of green tax policy will generate additional tax revenue W , while the implementation of standard tax policy only receives regular tax revenue and generates no net incremental revenue. Furthermore, the implementation of green financial policies will lead to service costs, mainly including the policy implementation costs (e.g., the construction of the regulatory system), the financial institutions' product R&D costs, and the training expenditures of practitioners.*

3.2. Modeling and Solving

Based on the above hypotheses, the payoff matrix of the “government—local energy enterprises—external energy enterprises” tripartite game can be obtained by analogy (Table 1), and the related parameter descriptions are shown in Table 2.

Table 1. Parameter description.

Parameter	Description
i_g	Green tax rate, %
i_n	Traditional tax base rate, %
I_j ($j = 1, 2$)	Costs of low-carbon, high-quality development by local and external energy enterprises, USD
R_j ($j = 1, 2$)	Corporate gains when local and external energy companies undertake low-carbon, high-quality development, USD
E_j ($j = 1, 2$)	Additional revenues from carbon credits, etc., received by local and external energy enterprises for low-carbon, high-quality development, USD
ω	Additional tax revenues from government development of green taxes, dollars
α	Indirect benefits, such as environmental benefits, received by energy enterprises, USD
γ	Probability of risk of loss due to failure of an energy enterprise to meet expectations, %, $0 < \gamma < 1$
β	Cost-sharing ratio, %, $0 < \beta < 1$
δ	Proportion of compensation received by external energy enterprises for cost-sharing, %, $0 < \delta < 1$

Table 2. Game payoff matrix.

Strategic Choice		Governments	
		Active Green Finance Policies x	Negative Green Finance Policies $1 - x$
External energy enterprises	Low-carbon, high-quality development z	Low-carbon, high-quality development y	$\frac{(1+i_g)(I_1+I_2)+\omega}{(1-\lambda)(R_1+R_2)-(1-\beta)(1+i_g)I_1+\alpha, (1-\lambda)(R_2+E_2+\delta E_1)-(I_2+\beta I_1)(1+i_g)+\alpha}$
		Non-low-carbon, high-quality development $1-y$	$\frac{(1+i_g)I_2}{R_1-\alpha}$
	Non-low-carbon, high-quality development $1-z$	Low-carbon, high-quality development y	$\frac{(1+i_g)I_1+\omega}{(1-\lambda)(R_1+R_2)-(1-\beta)(1+i_g)I_1+\alpha, R_2+(1-\lambda)\delta E_1-\beta(1+i_g)I_1-\alpha}$
		Non-low-carbon, high-quality development $1-y$	$\frac{R_1-\alpha}{R_2-\alpha}$

Where U_{11} is the expected return of local energy enterprises adopting the strategy of “low-carbon and high-quality development” based on the game return matrix; U_{12} is the expected return of local energy enterprises adopting the strategy of “non-low-carbon and high-quality development”; and $\bar{U}_1$ is the average return of the local energy industry, that is:

$$U_{11} = zx[(1-\lambda)(R_1 + E_1) - (1-\beta)(1+i_g)I_1 + \alpha] + z(1-x)[(1-\lambda)(R_1 + E_1) - (1+i_g)I_1 + \alpha] + (1-z)x[(1-\lambda)(R_1 + E_1) - (1-\beta)(1+i_g)I_1 + \alpha] + (1-z)(1-x)[(1-\lambda)(R_1 + E_1) - (1+i_g)I_1 + \alpha] \quad (1)$$

$$U_{12} = zx(R_1 - \alpha) + z(1-x)(R_1 - \alpha) + (1-z)x(R_1 - \alpha) + (1-z)(1-x)(R_1 - \alpha) \quad (2)$$

$$\bar{U}_1 = yU_{11} + (1-y)U_{12} \quad (3)$$

where U_{21} is the expected return of external energy enterprises adopting the strategy of “low-carbon and high-quality development”, U_{22} is the expected return of external energy enterprises adopting the strategy of “non-low-carbon and high-quality development”, and $\bar{U}_2$ is the average return of external energy enterprises, that is:

$$U_{21} = yx[(1-\lambda)(R_2 + E_2 + \delta E_1) - (I_2 - \lambda I_1)(1+i_g) + \alpha] + y(1-x)[(1-\lambda)(R_2 + E_2) - (1+i_n)I_2 + \alpha] + (1-\alpha)yx[(1-\lambda)(R_2 + E_2) - (1+i_g)I_2 + \alpha] + (1-y)(1-x)[(1-\lambda)(R_2 + E_2) - (1+i_n)I_2 + \alpha] \quad (4)$$

$$U_{22} = zx(R_1 - \alpha) + z(1-x)(R_1 - \alpha) + (1-z)x(R_1 - \alpha) + (1-z)(1-x)(R_1 - \alpha) \quad (5)$$

$$\bar{U}_2 = zU_{21} + (1-z)U_{22} \quad (6)$$

From Equations (1)–(6), the replication dynamics equation for local energy enterprises is obtained as:

$$F(y) = dy/dt = y(U_{11} - \bar{U}_1) = y(1-y)\{xI_1[1+i_n - (1-\beta)(1+i_g)] + (1-\lambda)(R_1 + E_1) - (1+i_n)I_1 - R_2 + 2\alpha\} \quad (7)$$

Let $F(y)=0$, we obtain $y=0$, $y=1$ and $y=y^* = x = [y(R_1 + E_1) - 2\alpha - E_1 + (1+i_n)I_1] / \{[1+i_n - (1-\beta)(1+i_g)]I_1\}$. The strategy of the local energy enterprise is not affected by the system, and the system is in a stable state at any time, and the stable strategy is an arbitrary strategy. When $y > y^*$, $F'(y)|_{(y=0)} > 0$, $F'(y)|_{(y=1)} < 0$, then $y=1$ (the local energy enterprise carries out the low-carbon and high-quality development), and the strategy of the local energy enterprise is a stable strategy. When $y < y^*$, $F'(y)|_{(y=1)} > 0$, $F'(y)|_{(y=0)} < 0$, then $y=0$ (local energy enterprises undergo low-carbon and high-quality development), the strategy of local energy enterprises is a stabilization strategy.

Based on the above analysis, the following game results can be derived:

(1) There is a significant positive correlation between the propensity of local energy enterprises to undergo low-carbon transition and their emission reduction benefits. This study shows that when enterprises obtain marginal gains through the application of low-carbon technologies, they will correspondingly increase the technology R&D investments, forming a positive feedback mechanism of “emission reduction and efficiency enhancement—R&D reinforcement”, thus enhancing the motivation of low-carbon transition.

(2) The tax rate regulation in the government’s green financial policy tools has a structural impact on enterprises’ low-carbon decision-making. The empirical results show that the level of tax rate is significantly negatively correlated with the willingness of enterprises to low-carbon development, and when the tax rate exceeds a specific threshold, the willingness of enterprises to choose a low-carbon development path shows a precipitous decline. Accordingly, Proposition 1 is proposed: Improving the level of green finance will effectively promote the development of energy enterprises.

(3) The distribution of regional risks is characterized by significant spatial heterogeneity, and its differentiation pattern is mainly influenced by the dual impact of the stage of regional economic development and the structure of fixed asset investment. Regions with higher levels of economic development and better capital factor allocation efficiency tend to show stronger risk resistance. This brings about Proposition 2: the role of green finance in promoting the development of energy enterprises has regional heterogeneity.

(4) We appreciate this insightful comment. Indeed, our game-theoretic model assumes that governments and enterprises behave as rational, profit-maximizing actors. While this assumption is standard in evolutionary game theory, it inevitably overlooks behavioral and normative drivers such as corporate social responsibility (CSR), managerial values, and reputational concerns.

We have addressed this limitation in the revised Conclusions Section. Specifically, we note that real-world enterprises may adopt low-carbon strategies not only for profit motives but also to comply with stakeholder expectations, improve brand reputation, or align with global ESG (environmental, social, and governance) standards. Such bounded rationality and socially oriented behavior may accelerate green transitions even when short-term financial incentives are weak.

Therefore, while our rational-choice framework provides a clear baseline for understanding strategic interactions, future research could enrich the analysis by integrating behavioral game theory or institutional perspectives, which capture the role of CSR, investor activism, and normative pressures in shaping green finance outcomes.

4. Empirical Design

4.1. Research Hypotheses

4.1.1. Direct Impact of Green Finance on the Low-Carbon, High-Quality Development of the Energy Industry

Green finance plays a pivotal role in mitigating financial constraints on clean energy development by injecting capital into clean energy technology innovation. This financial support helps address technological bottlenecks in both the development and promotion stages, reduces the cost of clean energy deployment, and accelerates the substitution of traditional fossil fuels with clean alternatives, while maintaining energy security. In this way, green finance contributes significantly to the low-carbon and high-quality transition of the energy industry. In addition, green finance also influences the demand side by facilitating green consumption through financial incentives. As highlighted by Zheng [20], such mechanisms not only increase consumers' access to green products, but also raise environmental awareness across society. As the concept of green, low-carbon living becomes more prevalent, consumer preferences are exerting increasing pressure on producers to adopt cleaner energy sources and environmentally sustainable production methods. This dual-channel effect—supply-side support for innovation and demand-side preference shifts—creates a positive feedback loop that drives the energy industry toward a low-carbon and high-efficiency trajectory.

Based on the above analysis, we propose the following hypothesis:

Hypothesis 1. *Green finance can promote the low-carbon and high-quality development of the energy industry.*

4.1.2. The Mediating Role of Technological Progress in the Impact of GREEN Finance on the Low-Carbon, High-Quality Development of the Energy Industry

Under the guidance of green finance, capital increasingly flows toward green technologies, fostering the low-carbon and high-quality development of the energy industry [21].

As a policy instrument of environmental regulation [11], green finance imposes cost pressures on high-polluting sectors, thereby incentivizing enterprises to pursue technological innovation as a pathway toward low-carbon transition [22]. Enterprises that achieve advancements in low-carbon technologies may benefit from market-based mechanisms, such as trading surplus emission quotas, which in turn generates further investment in energy-saving and emission-reducing innovations. Moreover, green capital, driven by technological progress, serves as a catalyst for integrating enterprises, financial institutions, and consumers through digital platforms. The development of technologies such as artificial intelligence and big data is enhancing the effectiveness of environmental regulation, overcoming the limitations of traditional oversight mechanisms that often suffer from inefficiency and imprecision. These smart regulatory tools enable real-time monitoring and adaptive regulation, thereby reinforcing enterprises' incentives to adopt sustainable production practices.

Based on the above transmission mechanism, we propose the following hypothesis:

Hypothesis 2. *Green finance promotes the low-carbon and high-quality development of the energy industry through the channel of technological progress.*

4.1.3. Spatial Spillover Effects of Green Finance Affecting the Low-Carbon, High-Quality Development of the Energy Industry

Green finance exhibits distinct spatial correlation characteristics [23], meaning that its impact on the low-carbon and high-quality development of the energy industry is not limited to the local region, but also extends to neighboring areas through spatial spillover effects. However, the direction and magnitude of these spillover effects remain uncertain. On the one hand, the development of green finance in a given region may create a demonstration effect, encouraging neighboring regions to follow suit. Technological advancements facilitated by green finance often carry positive externalities, leading to spillovers through interregional technology exchanges and collaborative innovation. In addition, the expansion of green financial networks promotes the cross-regional allocation and optimization of financial resources, facilitating green investment and financing activities for enterprises beyond administrative boundaries. On the other hand, green finance, when acting as a form of environmental regulation, may induce polluting industries to relocate from regions with stringent green finance policies to those with laxer environmental oversight [24]. This “pollution haven” effect may hinder the low-carbon transition in recipient regions. In contrast, regions with robust green finance frameworks may attract environmentally friendly industries from surrounding areas, thereby strengthening local green development. Taken together, the spatial spillover effects of green finance on the energy industry are complex and may vary depending on regional regulatory environments, industrial structures, and the degree of financial integration.

Based on the above analysis, we propose the following hypothesis:

Hypothesis 3. *Green finance exhibits spatial spillover effects on the low-carbon and high-quality development of the energy industry in neighboring regions, but the direction of these effects is uncertain.*

4.2. Research Design

This study utilizes panel data from 30 provincial-level administrative regions in China (excluding Tibet, Hong Kong, Macao, and Taiwan) over the period 2013–2021. The data sources are as follows:

(1) Energy industry-related data are obtained from the Provincial Energy Statistical Yearbooks;

(2) Green finance development indicators are compiled from the China Financial Yearbook, the China Science and Technology Statistical Yearbook, and official Environmental Status Bulletins issued by individual cities;

(3) Data on green invention patents are sourced from the State Intellectual Property Office;

(4) City-level macroeconomic variables are primarily drawn from the China Urban Statistical Yearbook, with missing values supplemented using linear interpolation.

4.2.1. Explanatory Variable

The core explanatory variable is the Energy Industry Low-Carbon and High-Quality Development Index (EIO), which is constructed using the entropy weighting method and comprises two dimensions: low-carbon development and high-quality development (see Table 3 for details).

Table 3. Indicator system for low-carbon and high-quality development of the energy industry.

Level I Indicators	Level II Indicators	Level III Indicators	Description of Indicators	Indicator Properties	Weights
Level of low-carbon, high-quality development of the energy industry	Low carbon development levels	Raw coal production as a percentage of carbon intensity	Raw coal production/total primary energy production	-	0.102
		Sulfur dioxide per capita	Total CO ₂ emissions/GDP	-	0.026
			Total sulphur dioxide emissions/population	-	0.016
	High-quality level of development	Energy supply losses	Losses from energy processing and conversion	+	0.416
		Installed capacity of new energy generation		+	0.116
		Number of green patent applications		+	0.324

The low-carbon development dimension is evaluated using three sub-indicators:

Coal consumption share, calculated as the proportion of raw coal in total energy production [25]; carbon emission intensity, measured by the ratio of total CO₂ emissions to GDP [26]; per capita sulfur dioxide emissions, measured by the ratio of total SO₂ emissions to population [27]. These three indicators are classified as negative indicators, as higher values indicate lower levels of low-carbon development.

The high-quality development dimension consists of the following three indicators:

Energy supply loss, measured by the amount of energy lost during processing and conversion, [28]; installed capacity of new energy, which captures the energy sector's transition and modernization efforts [29]; Green patents can effectively enhance energy conversion efficiency and resource utilization, promoting low-carbon and high-quality development of the energy industry [30]. These indicators are classified as positive indicators, where higher values represent greater progress toward high-quality development. The entropy method is applied to assign objective weights to all sub-indicators and synthesize them into the composite EIO index.

The Green Financial Development Index (GF) is constructed based on four core dimensions: green credit, green securities, green investment, and green insurance, following the framework of Zhu and Wang [31]. The composite index is generated using the entropy weighting method, which objectively determines the weight of each level III indicator based on its variability (see Table 4 for variable details).

Table 4. Green Finance Indicator System.

Level I Indicators	Level II Indicators	Description of Indicators	Indicator Properties	Weights
Green finance	Green credit	Borrowing size of environmentally listed companies (A-share environmentally listed company borrowing/A-share listed company borrowing)	+	0.587
	Green Securities	Market capitalization share of environmental protection enterprises (total output value of environmental protection enterprises/total market capitalization of A-shares)	+	0.176
	Green investment	Percentage of investment in environmental pollution control (investment in environmental pollution control/GDP)	+	0.071
	Green insurance	Depth of agricultural insurance (agricultural insurance income/gross agricultural output)	+	0.165

Green Credit is measured by the ratio of borrowings by A-share listed environmentally friendly enterprises to the total borrowings of all A-share listed enterprises. This indicator reflects the scale of green credit available to enterprises engaged in environmental protection.

Green Securities, serving as a gauge of capital market commitment to green development, are quantified by the market capitalization share of green-industry firms within China's A-share market.

Green Investment is evaluated by the ratio of government expenditure on environmental pollution control, reflecting the fiscal policy's inclination toward environmental governance.

Green Insurance is proxied by the ratio of agricultural insurance revenue to total agricultural output, representing financial support mechanisms for environmental and climate-related risks in the agricultural sector.

These four indicators are positive indicators, where higher values indicate more advanced levels of green financial development. The entropy method is applied to calculate the individual weights and synthesize the indicators into a comprehensive GF index for each region and year.

4.2.2. Intermediate Variables

Technological Progress (RD). Technological progress is introduced as an intermediate variable that captures the mechanism through which green finance may influence the low-carbon and high-quality development of the energy industry. Following Li et al. [32], we measure technological progress by the ratio of regional R&D expenditure to gross domestic product (GDP). A higher RD ratio indicates a greater investment in innovation capacity, which can facilitate energy efficiency improvements and industrial transition.

4.2.3. Control Variables

To account for other factors potentially affecting the development of the energy industry, we introduce the following control variables at the regional level:

Degree of Openness (OD). Greater openness to international trade can enhance technological exchange and capital inflow, which supports green technological advancement and industrial upgrading. OD is measured as the ratio of the total value of goods imports

and exports (In RMB, converted using the annual average USD to RMB exchange rate) to Gross Regional Product (GRP) [33].

Urbanization Level (UL). Urbanization contributes to economic growth but also intensifies energy demand and environmental pressure. It is measured as the proportion of urban population to the total population [34]. A higher UL may reflect more developed infrastructure and potentially more advanced environmental management capacity.

Industrial Structure (IS). The transition of industrial structure plays a key role in promoting low-carbon development. We measure IS using the ratio of tertiary industry output to secondary industry output [35]. A higher value indicates a shift toward a service-oriented economy, which generally features lower energy intensity.

Environmental Regulation (ER). Environmental regulation can incentivize cleaner production practices and attract green investment. Following Zheng et al. [36], ER is proxied by the ratio of completed investment in industrial pollution control to the value added of the industrial sector. This indicator reflects the intensity of government and enterprise efforts toward pollution mitigation.

The definitions and summary statistics of all variables used in the analysis are presented in Table 5.

Table 5. Descriptive statistics of variables.

Variables	Sample Size	Average Value	(Statistics) Standard Deviation	Minimum Value	Maximum Values
EIO	270	0.266	0.146	0.033	0.886
GF	270	0.191	0.136	0.001	0.784
RD	270	0.018	0.012	0.004	0.065
OD	270	0.253	0.264	0.008	1.342
UL	270	0.601	0.106	0.379	0.896
IS	270	1.324	0.717	0.572	5.297
ER	270	0.003	0.004	0	0.031

4.3. Baseline Modeling

Spatial spillover effects have often been neglected in previous studies of the impact of green finance on the energy industry. To address this gap, this paper constructs a spatial econometric model for empirical investigation. Different with spatial lag model (SLM) and spatial error model (SEM), spatial Durbin model (SDM) is regarded as a comprehensive framework and standardized method for spatial economic analysis. Therefore, this paper establishes the following SDM:

$$EIO_{i,t+1} = \alpha_0 + \rho_1 W.EIO_{j,t+1} + \alpha_1 GF_{it} + \rho_2 W.GF_{jt} + \alpha_2 Control_{it} + \rho_3 W.Control_{jt} + v_i + u_t + \varepsilon_{it} \quad (8)$$

In Equation (8), i, j represent cities, α_0 represents the constant term, α_1 and α_2 represent the coefficients, and ρ_1 — ρ_3 represent the estimated coefficients of the spatial lag term. Furthermore, we use the indicator of low-carbon and high-quality development of energy industry in period $t + 1$, $EIO_{i,t+1}$, to alleviate the endogeneity problem caused by the correlation of variables in the same period. GF is the core explanatory variable, green financial development level. W is the spatial adjacency matrix, and $Control_{it}$ denotes the control variable. v_i is the region fixed effect, u_t is the time fixed effect, and ε_{it} denotes the random disturbance term.

5. Analysis of Empirical Results

5.1. Baseline Regression Analysis

To further assess the spatial effects of green finance on the low-carbon and high-quality development of the energy industry, we compare the estimation results from non-spatial models (OLS and fixed effects, FE) with those from the Spatial Durbin Model (SDM). The results are reported in Table 6.

Table 6. Green finance impacts low carbon high quality development of the energy industry: baseline regression.

	(1) Non-Space OLS	(2) Non-Space Panel FE	(3) Space SDM
W.EIO			0.145 *** (0.850)
GF	0.472 *** (5.036)	0.564 *** (6.036)	0.566 *** (15.946)
W.GF			−0.053 *** (−0.063)
control variable	YES	YES	YES
Area, time fixed effects	YES	YES	YES
N	270	270	270
R ²	0.758	0.970	

Note: ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively, with t-values in parentheses. Same as the tables below.

The coefficient of the spatial lag term of the dependent variable (W.EIO) is significantly positive at the 1% level, indicating a clear positive spatial spillover effect. This suggests that improvements in the low-carbon and high-quality development of the energy industry in one province can positively influence neighboring provinces. Such a pattern is likely driven by inter-regional production linkages and the diffusion of green technologies and best practices across administrative boundaries. Consistent with theoretical expectations and the results from the baseline regression, the significantly positive green finance (GF) coefficient confirms that green finance development has a significant promoting effect on the local energy industry's transition to low-carbon and high-quality growth. These findings provide robust empirical support for Hypothesis 1. However, the estimated coefficient of the spatial lag of green finance (W.GF) is significantly negative, indicating a negative spatial spillover effect. In other words, while green finance promotes energy transition within the local region, its development may exert a suppressing influence on the neighboring regions' energy industries. This result validates Hypothesis 3 and suggests a form of industrial displacement: stricter environmental standards in regions with strong green finance mechanisms cause pollution-intensive energy enterprises to relocate to neighboring areas with less stringent regulatory and financial environments. Together, these findings highlight the dual spatial effects of green finance: a positive spillover in terms of industrial development momentum and innovation diffusion, but a negative spillover in terms of potential pollution transfer or industrial relocation. These effects underscore the necessity of coordinated regional green finance policies to prevent interregional inequality in environmental and industrial upgrading efforts.

To further investigate the spatial mechanisms through which green finance influences the low-carbon and high-quality development of the energy industry, we adopt the partial differential decomposition approach to decompose the total effects into direct and indirect (spillover) components. The decomposition results are reported in Table 7.

Table 7. Decomposition of spatial effects of green finance affecting low-carbon and high-quality development of energy industry.

Variables	Direct Effect	Indirect Effect	Total Effect
GF	0.935 *** (0.00)	−0.005 (0.93)	0.930 *** (0.00)
OD	0.069 *** (0.00)	0.205 *** (0.00)	0.274 *** (0.00)
UL	−0.156 *** (0.00)	−0.496 *** (0.00)	−0.652 *** (0.00)
IS	−0.028 *** (0.00)	−0.060 *** (0.00)	−0.089 *** (0.00)
ER	−2.537 ** (0.01)	0.656 (0.82)	−1.881 (0.53)
N	270	270	270
R ²	0.796	0.796	0.796

The direct effect captures the influence of green finance on the development of the local energy industry. The results show that green finance exerts a significantly positive direct effect, suggesting that green financial policies—such as green credit, green bonds, and sustainable investment incentives—enhance the capacity of local enterprises to undertake technological innovation, upgrade industrial structures, and improve energy efficiency. For instance, access to green financing channels can facilitate the adoption of clean energy technologies and the replacement of high-emission equipment, thereby reducing carbon emissions and fostering the transition to a low-carbon economy.

In contrast, the indirect effect, or the spatial spillover effect, reflects the extent to which the low-carbon transition of the energy industry in one region influences neighboring regions. The positive and significant indirect effect indicates that the green financial development in one province can generate beneficial spillovers—such as knowledge diffusion, joint R&D, and supply chain synergy—which encourage surrounding regions to follow similar paths of green development. These spillovers may arise from demonstration effects, policy learning, or interregional business collaboration.

Taken together, the decomposition results confirm that green finance not only serves as a direct driver of local industrial transition but also contributes to a regional virtuous cycle of green development through spatial externalities. These findings underscore the importance of policy coordination and regional integration in designing green financial frameworks that can maximize both local and cross-regional impacts on sustainable energy transition.

5.2. Robustness Tests

5.2.1. Replacement of the Space Weight Matrix

To test whether the baseline results are sensitive to the choice of spatial weight structure, we replace the traditional contiguity-based spatial adjacency matrix with a composite spatial weight matrix that incorporates both geographic proximity and economic similarity. Specifically, the new matrix is constructed by taking the average of the inverse geographic distance and the inverse of the GDP gap between provinces. This approach accounts not only for physical closeness but also for economic linkages, better capturing the actual intensity of interregional interactions. The regression results remain consistent in terms of sign and significance, indicating the robustness of the spatial spillover effect of green finance.

5.2.2. Winsorization of Extreme Values

To reduce the potential distortion from extreme outliers, we apply a 1% Winsorization at both tails of all continuous variables. The regression is re-estimated using the Winsorized data. The signs, magnitudes, and significance levels of the coefficients remain stable compared to the baseline estimation. This confirms that the results are not driven by outliers and further supports the robustness of the finding that green finance significantly promotes low-carbon and high-quality development in the energy industry.

5.2.3. Exclusion of Contemporaneous Policy Interference

Considering that other concurrent national or regional energy policies may confound the estimated effect of green finance, we exclude provinces that are heavily influenced by such policies to isolate the net effect. Specifically, we remove provinces with strong reliance on coal (e.g., Hebei, Shanxi, Inner Mongolia, Jiangsu, Shandong, Henan, Shaanxi) and those receiving focused support for new energy development (e.g., Qinghai, Yunnan, Xinjiang, Ningxia, Gansu) due to their inclusion in pilot programs for energy conservation and emission reduction initiated by the Ministry of Finance and the National Development and Reform Commission in 2011–2014. After excluding these provinces, the regression results remain robust, with the coefficient of green finance still significantly positive, confirming its independent role in promoting the low-carbon transition of the energy industry (Table 8).

Table 8. Green finance influences low-carbon and high-quality development of energy industry: robustness test.

	(1) Replacement of the Spatial Weight Matrix	(2) Indentation	(3) Exclusion of Contemporaneous Policy Interference
W.EIO	0.1639 *** (11.618)	0.1574 *** (11.619)	0.2765 *** (3.641)
GF	0.5539 *** (16.292)	0.5256 *** (14.888)	0.7351 *** (35.904)
W.GF	−0.2106 * (−1.806)	−0.0578 ** (−2.453)	−0.2649 *** (−3.078)
Control variable	YES	YES	YES
Area, time fixed effects	YES	YES	YES
N	270	270	270
R ²	0.758	0.970	

5.3. Mechanism Testing

To further explore how green finance influences the low-carbon and high-quality development of the energy industry, we conduct a mechanism analysis. Specifically, we examine whether this effect is transmitted through technological progress, which is widely regarded as a key driver of industrial transition. Following the classic mediation approach, we construct and estimate a mediation effect model, as shown in Equations (9) and (10).

$$RD_{i,t+1} = \alpha_0 + \rho_1 W.RD_{j,t+1} + \alpha_1 GF_{it} + \rho_2 W.GF_{jt} + \alpha_2 Control_{it} + \rho_3 W.Control_{jt} + v_i + u_t + \varepsilon_{it} \quad (9)$$

$$EIO_{i,t+1} = \alpha_0 + \rho_1 W.EIO_{j,t+1} + \alpha_1 GF_{it} + \rho_2 W.GF_{jt} + \alpha_2 RD_{it} + \alpha_3 Control_{it} + \rho_3 W.Control_{jt} + v_i + u_t + \varepsilon_{it} \quad (10)$$

The estimation results are presented in Table 9. The coefficient of green finance remains significantly positive when technological progress is included as a mediator, and technological progress itself is also significantly associated with improvements in the low-carbon and high-quality development of the energy industry. These findings suggest that technological innovation serves as an important channel through which green

finance promotes industrial upgrading and emission reduction. Therefore, Hypothesis 2 is empirically supported.

Table 9. Green finance influences low-carbon and high-quality development of the energy industry: a mechanism test.

	RD	EIO
W.RD	0.0023 *** (11.548)	
W.EIO		0.0451 ** (2.172)
GF	0.0335 *** (3.068)	0.5677 *** (15.946)
W.GF	0.0064 ** (1.972)	−0.8508 *** (9.970)
RD		2.1824 *** (7.853)
Control variable	YES	YES
Area, time fixed effects	YES	YES
Observed value	270	270

In addition to the direct and mediated effects within a region, we also examine the spatial spillover mechanism by which green finance affects neighboring regions. The results show that local green financial development may induce a relocation of high-emission energy industries to adjacent areas, thereby inhibiting the low-carbon transition in these neighboring regions. This result highlights the negative spatial spillover effects of green finance, suggesting that while green financial instruments promote environmental upgrading locally, they may also exacerbate unintended regional disparities due to industrial migration pressures. This finding further corroborates the spatial dynamics discussed in Hypothesis 3.

5.4. Heterogeneity Analysis

To further explore regional heterogeneity, this study divides the 30 provincial level regions into eastern, central, and western regions and applies the Spatial Durbin Model (SDM) to examine the differential effects of green finance on the low-carbon and high-quality development of the energy industry across these regions. The estimation results, presented in Table 10, show that green finance significantly promotes energy industry development in all three regions at the 1% significance level, with corresponding coefficients of 0.7148, 0.5542, and 0.2194 for the eastern, central, and western regions, respectively. These findings indicate that although green finance positively contributes to the transition to low-carbon and high-quality energy development nationwide, its effectiveness exhibits a clear regional gradient—strongest in the eastern region, moderately strong in the central region, and weakest in the western region. This regional disparity may be attributed to differences in financial infrastructure, policy implementation capacity, and industrial bases among the three regions.

In summary, the empirical findings reveal significant regional heterogeneity in the effectiveness of green finance in promoting the development of the energy industry. Specifically, the eastern region exhibits the strongest positive impact, followed by the central region, while the western region shows the weakest effect. This regional disparity may be attributed to differences in the maturity and diffusion of low-carbon technologies, as well as the varying capacities for industrial transition across regions. In the central and western regions, the technological upgrading process is more time-consuming, and the entrenched issues of lower development quality and higher carbon intensity present greater

challenges to rapid transition. In contrast, the eastern region benefits from relatively better environmental quality, more advanced industrial structures, and greater access to green financial resources. These advantages enable green finance to play a more pronounced role in accelerating the low-carbon and high-quality transition of the energy industry in this region.

Table 10. Green finance influences low-carbon and high-quality development of the energy industry: A heterogeneity analysis.

	Eastern Region	Central Region	Western Region
	EIO	EIO	EIO
W.EIO	−0.3227 *** (−3.298)	−0.3378 *** (−2.614)	−0.7215 *** (−4.927)
GF	0.7148 *** (11.742)	0.5542 *** (10.276)	0.2194 *** (2.834)
W.GF	0.0990 * (1.890)	0.6925 ** (2.547)	0.2987 * (1.765)
Control variable	YES	YES	YES
Area, time fixed effects	YES	YES	YES
N	108	81	81
R ²	0.658	0.847	0.725

6. Conclusions and Policy Recommendations

This study constructs a tripartite game model involving the government, local energy enterprises, and external energy enterprises to analyze the strategic interactions among these stakeholders before and after implementing green financial policies. Through this theoretical framework, it reveals the micro-level mechanisms by which green finance promotes the transition and upgrading of the energy industry. Furthermore, using provincial panel data from 2013 to 2021, a spatial Durbin model is employed to empirically test the impact of green finance on the low-carbon and high-quality development of the energy industry. The key findings are as follows:

(1) Green finance significantly promotes the development of energy enterprises. The theoretical analysis shows that under the green financial policy framework, an increase in the green tax rate enhances the expected benefits of industrial transition, thereby incentivizing both local and external energy enterprises to shift toward greener practices.

(2) While green finance fosters the low-carbon and high-quality development of the local energy industry, it exerts a negative spillover effect on neighboring regions. This adverse effect arises primarily from the relocation of high-pollution enterprises, leading to a spatial mismatch in the burden of environmental externalities.

(3) Technological progress serves as an important mediating channel through which green finance influences the energy industry. By lowering the cost of innovation and encouraging R&D investment, green finance accelerates technological advancement within the energy sector, thereby enhancing both the efficiency and sustainability of energy production and consumption.

(4) The impact of green finance exhibits pronounced regional heterogeneity. The eastern and central regions experience stronger promotion effects due to better institutional foundations, more mature financial markets, and greater innovation capacity, whereas the western region lags behind.

Our findings, particularly those related to the interplay between government policy, corporate strategy, and regional spillovers, offer valuable lessons for other large, resource-rich emerging economies. While China's institutional context is unique, the core challenges of financing a low-carbon energy transition in a state-led system with significant regional disparities are highly relevant.

Specifically, countries like those in Central Asia and the Middle East can replicate key experiences from our study:

Strategic Use of State-Led Green Finance: Countries with strong central governments can utilize state-backed green funds and sovereign guarantees to de-risk green projects and attract private capital, a model that has proven effective in China.

Coordinated Regional Governance: The negative spillovers we identified underscore the need for a coordinated approach to green policy. Resource-rich nations with diverse sub-national regions should implement inter-provincial or inter-regional environmental agreements and compensation mechanisms to prevent polluting industries from simply relocating to areas with weaker regulations.

Digital Infrastructure for Transparency: The development of digital platforms, like those based on blockchain, for tracking green finance flows and carbon emissions is a replicable and essential practice for building a credible and transparent green financial system.

By distilling these replicable experiences, our study provides a valuable reference point for policymakers in other major emerging economies as they navigate their own low-carbon transitions.

Based on these findings, the following policy recommendations are proposed to enhance the effectiveness of green finance in advancing the low-carbon and high-quality transition of the energy industry:

(1) Expand green finance support tools and promote green platform construction. Government agencies should actively develop green financial service platforms to facilitate enterprise access to instruments such as green bonds and sustainability-linked loans. Additionally, fostering intermediary institutions to bridge ecological projects and financial markets can reduce information asymmetries and mobilize broader private capital participation.

(2) Strengthen the supervision and support of green projects to accelerate progress toward dual-carbon goals. Fiscal incentives such as tax reductions and financial subsidies should be provided to certified green projects. At the same time, a robust risk monitoring mechanism must be established to prevent misallocation of green credit toward environmentally damaging or technologically outdated projects. More targeted support should be directed toward the western region to address regional imbalances and promote equitable green development.

(3) Promote investment in green technology R&D to enhance industrial competitiveness. Policymakers should encourage collaboration between energy enterprises and research institutions to accelerate the development and commercialization of low-carbon technologies. A dedicated green innovation fund could be established to support pilot projects and scale up successful applications, thereby strengthening the technological resilience of the energy industry.

(4) Implement sound environmental regulatory instruments to optimize industrial structure. In light of the observed negative spatial spillover effects, coordinated inter-regional governance mechanisms are needed to prevent inefficient competition and avoid “race-to-the-bottom” scenarios. Green finance should align with long-term structural goals and be used strategically to steer industrial upgrading and optimize regional energy mixes.

(5) We propose establishing a carbon fiscal transfer system where provinces with a strong green finance policy and significant emission reductions (the “polluter pays” principle) would provide financial compensation to provinces that receive relocating industries and, as a result, face increased carbon emissions. This system would function similarly to existing environmental fiscal transfers but would be specifically tied to carbon emissions data.

(6) To address the regional heterogeneity found in our analysis, particularly the weaker impact of green finance in central and western regions, we recommend a more targeted approach. Instead of traditional green bonds that may struggle to attract investment in these areas due to perceived higher risks, we suggest the issuance of green bonds with sovereign guarantees. This mechanism would involve the central government or a state-backed entity providing a guarantee for green bonds issued by or for projects in these underserved regions. The sovereign guarantee would mitigate default risk, lower the cost of capital, and attract a broader range of investors who might otherwise be hesitant to invest in these areas. This would directly support the development of green projects—such as renewable energy farms, ecological restoration efforts, and green infrastructure—that are crucial for these regions’ low-carbon transition but lack sufficient private funding.

7. Limitations and Future Research Directions

Despite its contributions, this study has several limitations. First, it focuses exclusively on China, which may limit the generalizability of the findings to other countries with different financial structures and regulatory regimes. Second, although we employ spatial econometric techniques to mitigate omitted variable bias, potential endogeneity issues—such as reverse causality between green finance and energy transition—cannot be fully ruled out. Third, our measure of green finance primarily captures formal financial instruments, while informal financing channels or international capital flows may also play important roles.

Future research could address these limitations by (1) conducting comparative studies across different institutional contexts (e.g., Europe, U.S., emerging economies) to test the external validity of our findings; (2) employing quasi-natural experiments (e.g., pilot policies or international shocks) to better identify causal effects; and (3) extending the analysis to include cross-border spillovers, given the global nature of energy trade and climate finance. Such work would not only strengthen the empirical robustness but also deepen the relevance of green finance research for global sustainability transitions.

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