

UNLOCKING THE POTENTIAL OF THE NET-ZERO ENERGY TRANSITION: THE ENABLING ROLE OF GREEN FINANCE

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Abstract. Amid severe global climate change and environmental degradation, energy systems worldwide are undergoing a significant transformation from traditional, high-carbon, and inefficient energy structures to more efficient, secure, and sustainable ones. This study develops an indicator system for green finance and an Energy Net Zero Transition Potential (ENTP) index using data from 280 cities between 2004 and 2020 to examine how green finance development affects the net-zero transition of energy systems. The findings indicate that growth in green finance notably boosts the ENTP. Mechanism analysis shows that green finance promotes the ENTP by enhancing resource allocation efficiency and optimizing industrial structure. However, it has not effectively spurred green technological innovation to advance energy toward a net-zero goal. Heterogeneity analysis reveals that the positive impact of green finance development on the energy net-zero transition is stronger in resource-based cities, large cities, and provincial border regions. Additionally, this study verifies the robustness of its results through Difference-in-Differences (DID) analysis of green finance innovation pilot zones, lagged effects, two-stage least squares estimation, and spatial econometric analysis. These conclusions can guide policy recommendations for China's green finance reforms and address the global energy security challenge.

Keywords: energy net zero transition potential, green finance, resource allocation efficiency, industrial structure optimization, green technology innovation, spatial spillover effect.

JEL Classification: O21, Q41, R11.

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1. Introduction

Energy transition is crucial for global sustainability, aiming to reduce reliance on fossil fuels, shift to renewable and clean energy sources, and ultimately achieve low- or zero-carbon emissions to combat climate change, ensure energy security, and promote environmentally friendly economic growth. Amid rising global concerns about climate change and environmental issues, China, as one of the world's largest carbon emitters, is actively pursuing an energy transition, restructuring its energy system, and improving energy efficiency.

Data from China's National Bureau of Statistics shows that, although the share of renewable energy in China's energy consumption has continued to increase, fossil fuels still dominate as the primary energy source. In 2024, coal made up 53.2% of primary energy consumption, and oil accounted for 18.2%. Data indicate that China's energy production elasticity

coefficient was 0.81 in 2023, and it has remained below 1 for most of the past decade, emphasizing the urgent need for energy development to keep pace with sustainable growth. The process faces numerous challenges, including high costs of technological upgrades, which require accelerated R&D and deployment of new energy technologies. Significant investments are necessary for infrastructure upgrades, such as grid modernization and distributed energy systems. Additionally, there are shifts needed in employment within traditional energy sectors and concerns about social stability. Underdeveloped market mechanisms lead to unstable returns on green energy investments, and outdated policies and regulations lack effective incentives and exit strategies mechanisms.

In the face of persistent challenges in the energy transition, green finance can serve as a crucial tool for addressing them. By fostering innovation in financial products and services, optimizing resource allocation, enhancing risk pricing mechanisms, and raising environmental awareness, green finance supports the green transformation of enterprises. Furthermore, recent studies have demonstrated that the development of green finance can drive the green transformation of industrial enterprises in China (Zhao et al., 2024) and encourage firms to reduce carbon emissions (Chen et al., 2024a). As of the end of Q3 2024, China's total green loans reached 35.75 trillion RMB. This raises a critical question: Can the development of green finance genuinely optimize the energy structure, and through what mechanisms does it reshape the energy system? Answering these questions cannot only clarify the pathway for the energy transition but also strengthen policy recommendations for achieving carbon neutrality. This, in turn, promotes the balanced pursuit of economic growth and ecological protection, which is the central objective of this study.

Based on the research outlined above, the marginal contributions of this paper can be summarized as follows. First, this paper proposes a novel perspective on evaluating energy transition by applying the entropy weight method to three critical dimensions: energy structure, energy utilization efficiency, and path dependence. This approach allows for a more nuanced and comprehensive assessment and posits that a genuine transition is not merely an increase in renewable energy share, but a shift towards a system that is low-carbon, highly efficient, and has transformative potential. Second, this paper introduces a dynamic temporal analysis to disentangle the time-varying influence of green finance. Our methodology explicitly differentiates its short-term stimulative effects from its long-term structural impacts on the energy transition, offering new insights into its evolving role. Methodologically, we advance the field by employing a spatial econometric model to rigorously determine the spatial spillover effects of green finance. This approach allows us to transcend the limitation of conventional analyses that assume regional independence, and instead, quantitatively demonstrate how green finance in one region catalyzes energy structure optimization in neighboring regions, thereby establishing a new research direction on the interconnectedness of green finance policies.

2. Literature review and theoretical analysis

2.1. Literature review

The international community is actively exploring and implementing strategic pathways to transition from a reliance on traditional fossil fuels to a cleaner energy system in response to escalating environmental degradation, climate risks, and energy security concerns arising from the depletion of fossil fuel resources. This global process of energy structure adjustment

and upgrading has become a widely recognized strategic choice for nations worldwide, with a broad consensus reached in policy formulation and implementation. In 1982, the German Institute of Applied Ecology introduced the concept of “energy transition”, which defined the concept as “growth and prosperity without oil and uranium”, and advocating for a transition from energy systems dominated by oil and nuclear power to those predominantly fueled by renewable sources (Krause et al., 1982).

Over the subsequent decades, numerous scholars have explored the concept and impacts of the energy transition. For instance, Podobnik (2006) suggests that the transition to sustainable energy entails the replacement and widespread integration of alternative primary energy sources into human consumption patterns through technological advancement and the exploration and utilization of innovative energy reserves. Fouquet (2016) studied the historical experience of energy transformation from three perspectives: speed, price, and system change. In China, Qu (2004) examines the significance and measures of energy transition, advocating for China to pursue a diversified path to optimize its energy structure. He et al. (2022) analyze China’s low-carbon transition pathways and strategies, emphasizing the key is decarbonizing the energy mix. Lee et al. (2022) suggest that enhancing energy efficiency, advancing low-carbon energy sources, and streamlining energy infrastructure can enable the transition towards sustainable energy. In addition, some scholars have analyzed the factors influencing energy structure transformation. For example, some scholars believe that factors such as economic development (Belke et al., 2011), foreign investment (Azam et al., 2015), and environmental regulation policy (Ma & Li, 2024) have a significant impact on the energy structure.

GF represents an innovative financial model that integrates economic profitability with environmental protection objectives, aiming to maximize economic returns and sustainably safeguard ecosystems concurrently within financial resource allocation. In the international academic arena, Salazar (1998) was the first to introduce the concept of environmental finance in the 1990s, arguing that any financial innovations aimed at driving economic growth must be grounded in a profound commitment to and practical integration of environmental conservation. This notion laid the foundation for the nascent theory of GF, positing that the financial system should proactively establish a development model anchored in ecological protection. Subsequent research has further developed the understanding of GF, with Fatemi and Fooladi (2013) defining it as a new paradigm that addresses social and environmental challenges, and Ziolo et al. (2021) perceiving it as a system that encompasses various components to effectively enhance living conditions on Earth. In addition, studies have investigated its effects, demonstrating that it enhances corporate social value (Chami et al., 2002), provides advantages through diverse and intricate green financial products (Galema et al., 2008), encourages CO₂ emissions reductions in various industries (Wan et al., 2022), and serves as the most suitable financial policy for mitigating CO₂ emissions (Karim et al., 2022), with varying effects on greenhouse gas reduction depending on the financial structure of countries (market-based or bank-based) (Zhang et al., 2023). In China, Bai (1998) was among the first to introduce GF concepts, emphasizing the need for the financial system to adapt to societal and environmental advancements for sustained economic stability. Later, Ma Jun from the Research Bureau of the People’s Bank of China (Force, 2015) expounded on the necessity of building a GF system and offered recommendations.

Research on the impact of the advancement of GF has largely focused on two aspects: macro-level effects on the green economy and micro-level influences on corporate green transformation. Researchers have demonstrated that it can bolster high-quality economic

growth by facilitating economic greening (Liu et al., 2019). And on this basis, balance environmental development and economic quality (Zhou et al., 2020). At the micro-level, GF has been shown to effectively motivate companies to adopt green technology innovation strategies (Zhou et al., 2023), and specifically, green credit has been shown to enhance green innovation (Hu et al., 2021).

While these studies extensively investigate the impact of GF on the macroeconomy and corporate performance, there's little literature on the impact of it on energy structures, with only a few scholars studying the relationship between the two. For example, Wang and Zhi (2016) proved that developing green finance through green loans, green securities, insurance tools, and increasing financial support for green industries can promote the expansion of green industries and ultimately optimize the energy consumption structure. Sun and Chen (2022) discover that the advancement of GF efficaciously promotes adjustments in energy consumption structures. Chishti et al. (2023) reveal positive influences of green financing, green technologies, and relational environmental policies on energy transition. Hosan et al. (2024) show that increased funding for energy innovation directly or indirectly fosters equitable energy transition in developed economies. These findings suggest a possible association between GF and energy transition. Several crucial issues remain unaddressed in existing research. First, there is a dearth of literature on the construction of evaluation indicators for net-zero energy transition, coupled with an incomplete definition of energy transition. Most scholars build an index system based on the energy consumption structure, such as Shen et al. (2025). From the perspective of energy consumption structure, the production part of energy and the different dependence effects of industrial development on energy are ignored. Secondly, many scholars have restricted their GF research in green credit (Lv et al., 2023). He discussed the micro -mechanism of GF through the differentiated impacts of the green credit policy. When the assessment and quantification of statistical indicators in the green financial field are involved, the current literature system is very scarce. Finally, the impact of the space for GF was ignored. GF has strengthened regional interconnection and produce space overflow through reasonable financial resources, environmental improvement and demonstration effects. When solving these research gaps, this article studies the impact of the advancement of GF on zero net energy transition potential.

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These findings suggest a possible association between GF and energy transition. However, several crucial issues remain unaddressed in existing research. First, there is a dearth of literature on the construction of evaluation indicators for the net-zero energy transition, coupled with an incomplete definition of energy transition. Most scholars build an index system based on the energy consumption structure, such as Shen et al. (2025). This perspective on energy consumption structure ignores the production side of energy and the varying dependence

of industrial development on energy. Second, many scholars have restricted their research on GF to green credit (Lv et al., 2023). The micro-mechanisms of GF are often discussed only through the differentiated impacts of green credit policy. When it comes to the assessment and quantification of statistical indicators in the green financial field, the existing literature is very scarce. Finally, the spatial impacts of GF have been ignored. GF can strengthen regional interconnection and produce spatial spillovers through the reasonable allocation of financial resources, environmental improvement, and demonstration effects.

To address the aforementioned shortcomings, this study constructs an Energy Net-Zero Transition Performance (ENTP) index from three dimensions: Energy Structure, Energy Use Efficiency, and Path Dependence. Correspondingly, a Green Finance Development Index is developed across seven aspects to provide a comprehensive evaluation framework. The research investigates both the direct impact of GF on the ENTP and its spatial spillover effects. The findings indicate that GF significantly facilitates the transition toward net-zero energy systems. Mechanism analysis further reveals that such promotion occurs primarily through improved resource allocation efficiency and industrial structure optimization. Nevertheless, it is noteworthy that GF has not effectively driven green technological innovation to further advance the net-zero energy transition. Additionally, significant spatial spillover effects are observed.

2.2. Theoretical analysis

2.2.1. Theoretical foundations

1. Signaling Theory

Signaling theory posits that in imperfectly competitive markets, information asymmetry exists, leading to reduced market efficiency and causing market failures. Consequently, the transmission of reliable signals is widely regarded as an effective tool for countering information asymmetry and enhancing transparency, as the process weakens or eliminates information barriers. GF, with its distinctive state-oriented and targeted nature, implicitly provides a clear directional indicator for the flow and concentration of capital. By providing tools such as transparent information disclosure, risk management, and innovative financial instruments, GF helps investors better identify and assess the risks and returns of energy projects. This, in turn, guides capital toward more sustainable energy initiatives, corrects failures within the energy market, and ultimately promotes the net-zero energy transition.

2. Externality Theory

Externality theory emphasizes that the environment is a public good, characterized by its non-excludable nature and the fact that it can be used free of charge. This allows any individual or firm to utilize and degrade it without limit and at no cost. The consequence of this behavior is that total carbon emissions remain uncontrolled and environmental pollution worsens. To address this, internalizing the environmental costs of firms can reduce their negative external diseconomies. GF facilitates this by internalizing the external costs of polluting firms, guiding them to recognize their negative externalities. Through incentive and constraint mechanisms, it integrates environmental and social factors into investment decisions, pushing energy projects to become environmentally friendly and socially responsible. This reduces the negative externalities of energy projects and fosters the net-zero energy transition.

3. Sustainable Development Theory

The theory of sustainable development calls for the coordinated development of the economy, society, and the environment. It encourages behaviors that are conducive to the

long-term health of resources and the environment while penalizing actions that are destructive. This principle lays the essential theoretical foundation for actively developing GF to promote sustainable economic and social progress. GF contributes to this by fostering the optimization and transformation of the energy structure and promoting the widespread application of clean energy and low-carbon technologies, thereby helping to achieve the net-zero energy transition and reduce greenhouse gas emissions. Simultaneously, GF also addresses social and environmental factors, driving energy projects toward social equity and environmental sustainability, which helps to achieve the overarching goals of sustainable development and promotes harmony between the economy, society, and the environment.

2.2.2. Mechanisms of action

Based on the above theoretical foundations, this paper summarizes three mechanisms through which GF influences the net-zero energy transition.

1. The Mechanism of Resource Allocation Efficiency

First, through clear policy guidance, mandatory information disclosure requirements, and standards for green financial products, GF sends a strong market signal to “develop the green economy and curb polluting activities.” This guides the market to respond to policy cues, steering societal investment toward green industries aligned with future development trends. Second, GF directly internalizes corporate environmental externalities through differentiated financial instruments, which helps investors better identify and assess the environmental risks and long-term value of projects. By providing market-based rewards for the positive externalities of green projects and imposing penalties on the negative externalities of polluting ones, this process directly corrects market failures caused by environmental externalities. This optimizes the overall allocative efficiency of economic resources, thereby guiding capital more precisely toward sustainable energy projects.

2. The Mechanism of Green Technology Innovation

First, GF uses differentiated financial instruments to internalize the externalities of corporate innovation, incentivizing green R&D while imposing constraints on polluting activities. This provides a direct market-driven impetus for technological advancement. Second, the GF framework is designed to identify and reward the positive signals sent by corporate innovation, helping investors assess firms’ long-term growth potential and optimizing the allocation of innovation capital. This, in turn, guides funding toward sustainable technological pathways. However, the transmission of this ideal mechanism often faces real-world challenges and may even have an inhibitory effect. First, information asymmetry and moral hazard. “Greenwashing” can distort market signals, leading capital to be misallocated and preventing genuinely innovative firms from securing funding. Second, financing constraints. Excessive financing constraints can “crowd out” R&D investment. Furthermore, lenders’ risk aversion may cause them to favor large, established firms over smaller, more innovative ones, thus stifling breakthrough technologies.

3. The Mechanism of Industrial Structure

First, by implementing differentiated policies for resource allocation and innovation support, GF encourages the development of green, low-carbon strategic emerging industries and modern service industries, while restricting traditional secondary industries characterized by high pollution and high energy consumption. Second, when firms demonstrate a commitment to green practices, such as optimizing resource allocation and

promoting technological innovation, they enhance their ability to secure financing in alignment with market signals. This outcome allows potential investors to recognize a firm's growth potential and long-term value, which are aligned with future trends. This, in turn, accelerates the shift of production factors from high-pollution, high-energy-consumption sectors to green, low-carbon fields. This process creates both a forcing mechanism for industrial transformation by curbing the unchecked expansion of high-pollution and high-energy industries and an incentive mechanism for industrial upgrading by generating market space and capital support for green industries. Consequently, this accelerates the green transformation of the overall industrial structure, laying a solid foundation for achieving long-term sustainable development goals.

In summary, GF enhances the prospects of achieving a net-zero energy transition through direct effect and three synergistic mechanisms: optimizing resource allocation, fostering green innovation, and restructuring industrial frameworks. On account of the above analysis, this article proposes:

H1: The advancement of GF can improve the potential for net-zero energy transition.

H2: The advancement of GF influences the potential for net-zero energy transition through mechanisms including improving resource allocation efficiency, optimizing industrial structure, and affecting green technological innovation.

3. Research design

3.1. Model construction

To analyze the implications of the development of GF for the transition to net-zero energy, we set up the following baseline model:

$$\text{ENTP}_{it} = \alpha + \beta \text{GF}_{it} + \delta X_{it} + \mu_i + \lambda_t + \varepsilon_{it}. \quad (1)$$

To empirically evaluate the impact of GF on the energy transition, we employ a two-way fixed effects panel regression model as our baseline specification. In the model, i and t denote city and year, respectively. The dependent variable is the Energy Net-zero Transition Potential (ENTP), and the core explanatory variable is GF. We include a set of control variables (X_{it}) comprising the level of environmental regulation (ER), technology input (TI), fiscal decentralization (FD), regional informatization (RI), industrial structure (IS), degree of openness (FRATIO), and marketization (MARKET). The terms μ_i and λ_t represent city and year fixed effects, respectively, while ε_{it} is the random error term.

The choice of this model is based on two key considerations. First, the inclusion of city-specific fixed effects controls for time-invariant unobserved heterogeneity, such as persistent differences in resource endowments or institutional environments. Concurrently, year-specific fixed effects account for common shocks affecting all cities, like national policy changes or macroeconomic cycles, thereby yielding more accurate and reliable estimates. This choice is further supported by the results of the Hausman and F-tests, which indicate that the fixed effects specification is appropriate. Second, the high-dimensional fixed effects regression is well-suited for large panel datasets like ours, which feature multiple sets of fixed effects.

3.2. Variable

3.2.1. Dependent variable

The dependent variable for this study is the Energy Net-zero Transition Potential (ENTP), a composite index designed to measure a region's capacity for transitioning its energy system toward net-zero emissions. We construct our ENTP indicator system by building on the frameworks of Ding et al. (2023). This index incorporates three key dimensions: energy structure, energy use efficiency, and dependence on the energy supply industry. The specific procedure for calculating this indicator using the entropy method is detailed below.

First, positive indicators and negative indicators are standardized separately, with the formulas shown in Eqs. (2) and (3) respectively:

$$X'_{ij} = \frac{X_{ij} - \min X_{ij}}{\max X_{ij} - \min X_{ij}}; \quad (2)$$

$$X'_{ij} = \frac{\max X_{ij} - X_{ij}}{\max X_{ij} - \min X_{ij}}, \quad (3)$$

where i and j represent the i sample value of the j indicator, respectively. Then, calculate the proportion p_{ij} of the i sample value to the sum of all sample values of the j indicator, with the formula shown in Eq. (4):

$$p_{ij} = \frac{X'_{ij}}{\sum_{i=1}^n X'_{ij}}. \quad (4)$$

Next, calculate the information entropy e_j and the information redundancy degree:

$$e_j = -\frac{1}{\ln k} \sum_{i=1}^n p_{ij} \ln p_{ij}; \quad (5)$$

$$d_j = 1 - e_j. \quad (6)$$

Calculate the weight of each indicator w_j :

$$w_j = \frac{d_j}{\sum_{j=1}^m d_j}. \quad (7)$$

Finally, the comprehensive score is obtained by weighting. The specific indicator system for the ENTP is presented in Table 1.

Table 1. Energy Net Zero Transition Potential (ENTP) Index System

Main Indicator	Sub-Indicator	Variable Measure	Symbol
Energy Structure	Fossil fuel consumption share	The proportion of coal consumption to energy	-
	Carbon Emissions	Carbon emissions decline rate year-on-year	+

End of Table 1

Main Indicator	Sub-Indicator	Variable Measure	Symbol
Energy Use Efficiency	Coefficient of elasticity of energy	Energy consumption growth rate/GDP growth rate	–
	Energy Use Intensity	Total energy consumption/ industrial value added	+
	Dependence on the Energy Extraction Industry	Ratio of mining employment to total employment	–
Path Dependence	Dependence on Energy Supply Industry	Employees in electricity, gas and water production/total employees	–
	Energy consumption per capita	Total energy consumption/ total population	–

Note: Symbol “+” indicates a positive indicator, and symbol “–” denotes a negative indicator.

3.2.2. Explanatory variable

The core explanatory variable in this study is GF, which measures the level of GF development. Following the methodology of Chen et al. (2024b), we construct the GF index using the entropy method. The specific indicators comprising this index are detailed in Table 2.

Table 2. Index System of GF

Main Indicator	Sub-Indicator	Variable Measure	Symbol
Green Credit	Share of environmental projects in lending	Provincial ratio of environmental project credit to total credit	+
Green Investment	Investment in environmental protection as a percentage of GDP	Environmental protection investments/GDP	+
Green Insurance	Level of support for environmental liability insurance	Environmental pollution liability insurance receipts/total insurance receipts	+
Green Bonds	Level of development of green bonds	Total issuance of green bonds/ total bond issuance	+
Green Support	Proportion of fiscal environmental protection expenditure	Environmental protection spending / total government spending	+
Green Funds	Share of green funds in total funds	Market value of ecological funds/total market value of funds	+
Green Equity	Extent of green equity development	(Carbon trading volume + energy use right trading volume + pollution right trading volume) stock market transaction volume	+

3.2.3. Control variables

Drawing from the existing literature, we include a series of city-level control variables that may influence the net-zero energy transition. These variables are defined as follows:

Environmental Regulation Level (ER): Measured by the frequency of environment-related terms appearing in municipal government work reports.

Technology Input Level (TI): Calculated as the proportion of research and development (R&D) expenditure to total fiscal expenditure, reflecting a region's commitment to technological innovation.

Fiscal Decentralization (FD): Defined as the ratio of local fiscal revenue to local fiscal expenditure, indicating the degree of fiscal self-sufficiency.

Regional Informatization Level (RI): Proxied by the total revenue from telecommunications and postal services as a share of GDP.

Industrial Structure (IS): Measured as the ratio of the value-added of the tertiary industry to that of the secondary industry, indicating the prominence of the service sector.

Degree of Openness (FRATIO): Calculated as the proportion of actual foreign investment relative to GDP, reflecting the region's economic integration.

Marketization Level (MARKET): Represented by the Fan Gang Marketization Index for each city, which measures the development of the market economic system.

3.2.4. Diagnostic tests

We conducted a series of diagnostic tests on the data to ensure its suitability for our econometric analysis. Firstly, this study assessed multicollinearity using the Variance Inflation Factor (VIF). All values were below 5, confirming the absence of severe collinearity among the explanatory variables. Secondly, the Levin Lin Chu (LLC) test was used to check for unit roots, and the results led to the rejection of the null hypothesis of a common unit root for all variables at the 1% significance level, indicating stationarity. Furthermore, the Friedman test revealed a significant cross-sectional correlation within the data. Finally, the Pedroni test rejected the null hypothesis of no cointegration, confirming the existence of a long-run relationship among the variables. Taken together, these diagnostic results validate our data and methodological choices, supporting the reliability of our subsequent analysis.

4. Empirical analysis

4.1. Baseline regression

This study examines the impact of GF development on the energy net-zero transition potential using the baseline model. Table 3 presents the regression results, with Column (1) showing the model without control variables and Column (2) including them. The findings are consistent across both specifications: the coefficient on GF is positive and statistically significant at the 5% level, regardless of whether control variables are included.

This result supports Hypothesis 1, indicating that the growth of GF has a significant, positive impact on the energy net-zero transition. It underscores the proactive role of GF in promoting changes in the energy structure, improving energy use efficiency, and reducing path dependence, thereby facilitating a smoother transition of the energy system. These findings provide strong empirical evidence that GF is a key driver of energy transformation. This is consistent with previous studies by scholars on this topic (Chen et al., 2024a; Lee et al., 2024). To ensure the robustness of our findings, this study conducts a series of robustness tests using four methods: (1) Treating potential endogeneity using the instrumental variables approach; (2) Accounting for time lag effects; (3) Removing disturbance from key policy; (4) Reconstructing indicators using PCA. The results from these tests confirm the robustness of our benchmark regression.¹

¹ For the sake of brevity, the corresponding results are presented in the Appendix.

Table 3. Baseline regression

Variable	(1)	(2)
GF	0.112** (0.047)	0.103** (0.047)
Constant	0.176*** (0.014)	0.168*** (0.022)
Control variable	NO	YES
Year fixed effect	YES	YES
City fixed effect	YES	YES
Observations	4760	4760
Adjusted R-squared	0.688	0.689

Note: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.2. Long-term and short-term analysis

To investigate the dynamic impact of GF, this article conducted a short- and long-term analysis by estimating the effect of the explanatory variable lagged from one to ten periods. The coefficients from these regressions are visualized in Figure 1. The plot shows that the coefficient fluctuates around a stable, positive level for the first seven periods but begins to decrease in the eighth period. This indicates that the beneficial influence of GF, while immediate and lasting for several years, may gradually weaken over a longer time horizon.

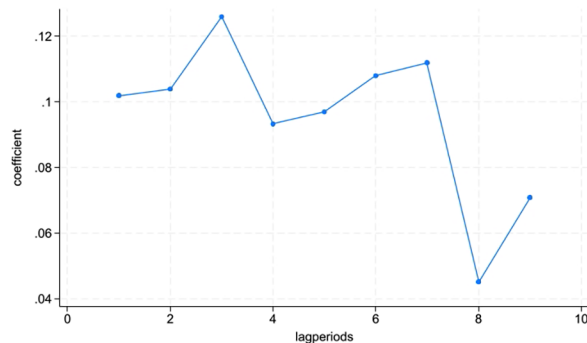


Figure 1. Long term and short-term analysis

4.3. Mechanism testing

4.3.1. Resource allocation efficiency

This study follows the methodology of Liu and Xia (2023), the inverse variable of the degree of factor market distortion is used as our proxy variable for resource allocation efficiency.² Table 4, Column (1) illustrates the effects of GF on resource allocation, with its coefficient being markedly positive. Furthermore, this study employed the bootstrap mediation effect test

² For the sake of brevity, the corresponding calculation process is provided in the Appendix.

to examine the significance of the three mediating variables. The procedure was set to 1000 bootstrap samples with a 95% confidence interval. An indirect effect was considered significant if its 95% confidence interval did not contain zero, which we interpreted as evidence of full mediation. The result shows that the 95% confidence interval of bootstrap mediation effect test is [0.0015, 0.0081], excluding 0. This indicates that GF facilitates a net-zero energy transition by optimizing the distribution of resources.

This process operates through two primary channels. First, GF instruments, such as green credit guidelines and environmental, social, and governance (ESG) investing, help mitigate information asymmetries in the market. They act as a signaling mechanism, systematically identifying and directing capital, talent, and technological resources toward projects and sectors with high environmental benefits and long-term sustainability. Concurrently, GF restricts or increases the cost of capital for polluting and energy-intensive industries, thereby crowding out inefficient investments locked in carbon-intensive pathways. Second, the price discovery function embedded in green financial markets ensures that resources flow to their most productive and environmentally compatible uses (Lin & Zhong, 2024). By valuing environmental performance and future climate risks, GF effectively re-prices economic activities, making clean energy investments more attractive and fossil-fuel-dependent projects less viable. This market-driven selection process continuously optimizes the portfolio of societal resources.

The enhanced allocation efficiency serves as a critical mediator for net-zero transition. It accelerates the development and deployment of key low-carbon technologies by ensuring they receive adequate and timely funding. Furthermore, by channeling resources directly into the net-zero energy system—including generation, grid modernization, and demand-side management—it elevates the overall productivity of the energy sector per unit of input. Consequently, a more efficient resource allocation system, orchestrated by GF, lowers the societal cost of the energy transition and speeds up the structural shift toward a net-zero economy.

4.3.2. Green technological innovation

In this study, the annual count of green invention applications is employed as a proxy variable for green technological innovation. The regression results for green technological innovation, as shown in Column (2) of Table 4, indicate that the development of GF significantly suppresses green technological innovation. However, bootstrap analysis confirms a statistically significant mediating effect, with a 95% confidence interval of [0.0274, 0.0497] excluding zero. This pattern suggests a possible suppression effect, whereby the positive total effect of GF on the energy transition is partially offset by its negative indirect pathway through innovation.

One plausible explanation for this suppression effect lies in the characteristics of GF policies and practices at the current stage. GF implementation may inadvertently increase corporate compliance and operational costs, crowding out resources that could otherwise be allocated to R&D and innovation. Moreover, some GF standards tend to favor mature, low-risk environmental projects over exploratory and high-risk frontier green technologies. As a result, financial resources may not be efficiently channeled into technological innovation, ultimately weakening GF's overall driving force for transition.

That said, the innovation that still progresses within the GF framework tends to be highly targeted and application-oriented—often developed to meet clear emission reduction targets or energy efficiency goals. Such innovation demonstrates well-defined commercial pathways and strong systemic compatibility, facilitating its practical deployment. Although quantitatively constrained by limited resources, these innovations exert a substantial transformational impact, enabling them to integrate more directly and effectively into the low-carbon transition of the energy system, thereby still contributing to a significant mediating effect overall.

4.3.3. Industrial structure

For this analysis, the tertiary-to-secondary sector ratio is used as a proxy for industrial structure. The results, presented in Column (3) of Table 4, reveal a coefficient for GF that is significant and negative at the 1% level, and bootstrap test shows a significant mediating effect. This suggests that by optimizing the industrial structure, GF facilitates the transition to net-zero energy.

As GF matures, financial institutions and enterprises increasingly prioritize sustainable development and environmental protection. This leads to a gradual shift of resources—including capital, technology, and talent—toward environmentally friendly and clean energy sectors, spurring the growth of the tertiary sector (Xiong et al., 2023). Concurrently, GF restricts funding to highly polluting and energy-intensive industries, compelling them to either undergo a green transformation or face obsolescence. Under these circumstances, the industrial structure undergoes a metamorphosis. This transformation of the industrial structure has a catalytic effect on the transition to net-zero energy (Dong et al., 2024). First, the growth of clean energy and ecological conservation sectors within the tertiary industry directly contributes to this transition. Technologies and products from these sectors provide critical support for renewable energy generation and improvements in energy efficiency, thereby helping to reduce fossil fuel consumption and carbon emissions. Second, the contraction or greening of the secondary sector inherently curtails overall energy consumption and carbon emissions. Heavy industry and manufacturing, which are major consumers of energy and emitters of carbon, are concentrated in the secondary sector. As these industries decline or transform, aggregate energy demand and carbon emissions fall accordingly.

Table 4. Mechanism analysis

Variable	(1)	(2)	(3)
	Resource Allocation Efficiency	Green Technology Innovation	Industrial Structure
GF	1.348* (1.750)	-1.092*** (0.365)	0.228* (0.120)
Constant	-1.028** (-2.000)	4.248*** (0.206)	0.114 (0.090)
Control Variables	YES	YES	YES
Year Fixed Effects	YES	YES	YES
City Fixed Effects	YES	YES	YES
Observations	4743	4486	4443
Adjusted R-squared	0.519	0.919	0.819

4. Further analysis

4.1. Heterogeneity analysis

Prior research has demonstrated the pivotal role of GF in facilitating the transition to net-zero energy. However, given the inherent diversity among cities, it is plausible that the impact of GF on this transition may vary. To investigate this, we examine how the effectiveness of GF in promoting the transition to net-zero energy is influenced by city-level heterogeneity, analyzing this from three perspectives: natural resource endowments, city size, and provincial border regions.

4.1.1. Natural resource endowment

This paper categorizes cities into resource-based and non-resource-based types, based on the 126 prefecture-level administrative regions identified in China's "National Sustainable Development Plan for Resource-Dependent Cities (2013–2020)," and conducts separate panel regression analyses for each group. The results, presented in Columns (1) and (2) of Table 5, show that GF development significantly promotes the transition to net-zero energy in resource-based cities, while its impact on non-resource-based cities is not statistically significant. This disparity may arise because resource-based cities typically have greater resource endowments, with economies dominated by heavy industry and extractive sectors that often exert considerable environmental pressure. Consequently, these cities face greater environmental pressures and transformation needs, which are compounded by path dependency issues that lead to undiversified industrial structures, an over-reliance on resource-dependent industries, and severe pollution (Li et al., 2024). GF provides the financial support and technological guidance these cities need to shift toward green, low-carbon, and circular economies, thereby driving a more pronounced transition to net-zero energy.

4.1.2. Economies of scale

The 280 cities in this study were classified by size, based on the list of 70 big and medium-sized cities published by the National Bureau of Statistics of China. The results of the grouped regressions are presented in Columns (3) and (4) of Table 5. These results demonstrate that GF development has a significant positive impact on the transition to net-zero energy in big cities, but no discernible effect in non-big cities. This is consistent with the research results of Zhang et al. (2024). This may be explained by several factors. First, the advanced financial systems and higher level of financial development in big cities facilitate the effective implementation of GF policies, enabling capital to shift to environmentally friendly enterprises and promote the transition to net-zero energy. Additionally, the extensive markets and resource channels in large cities support the growth of green industries, making it easier for green enterprises to secure funding and expand, thereby driving the transition to net-zero energy. To optimize the role of GF, efforts must focus on improving financial market environments, technological innovation capabilities, and resource acquisition channels, especially in non-big cities.

4.1.3. Border wasteland effect

Cities are classified into two categories: those situated in provincial border regions and those located in non-border regions. This classification is based on geographical boundaries, and separate regressions are conducted for each category. The results, presented in Columns (5) and (6) of Table 5, show that the coefficient for GF is significantly positive at the 5% level in non-provincial border regions, with a value of 0.123. In contrast, the effect of GF on provincial border regions is not statistically significant. The reasons for this may be due to three factors. First is the "border wasteland effect," which impedes economic spillovers from core areas, resulting in weaker economic zones with underdeveloped financial markets. Second, geographical boundaries restrict the mobility of resources and exacerbate inefficiencies in resource allocation, which is often due to neglected development in border areas. Third, the cross-jurisdictional nature of pollution externalities in border regions increases the cost and difficulty of intervention, leading to a lack of incentive for governments to address pollution effectively.

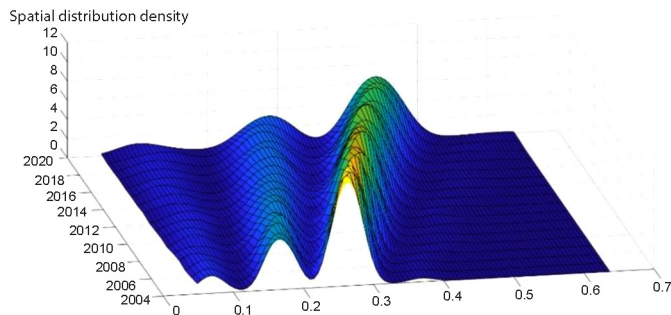
Table 5. Heterogeneity analysis

Variable	(1) Resource-based cities	(2) Non-resource-based cities	(3) Big cities	(4) Other cities	(5) Border regions of provinces	(6) Non-border Regions of Provinces
GF	0.156** (0.065)	0.079 (0.0527)	0.314*** (0.071)	0.028 (0.049)	0.100 (0.088)	0.123** (0.054)
Control variables	YES	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES	YES
Observations	1904	2856	1105	3655	1700	3060
Adjusted R-squared	0.681	0.697	0.777	0.665	0.663	0.710

4.2. Spatial effect analysis

4.2.1. Selection of spatial models

To analyze these spatial effects, this study employs spatial panel econometric methods. The spatial and density plots are presented in Figure 2. First, global Moran's I indices were calculated, yielding a value of 0.158 for the ENTP Moran's I and 0.635 for the GF Moran's I, both of which are statistically significant. This finding indicates the presence of spatial autocorrelation in both the explanatory and dependent variables, necessitating the use of a spatial panel model. To determine the most appropriate spatial econometric model, this study employs a Lagrange Multiplier (LM) test and the robust LM-lag test, the result indicates that the Spatial Error Model (SEM) is the appropriate model for this analysis.³

**Figure 2.** The spatial and density plots

4.2.2. Spatial effect analysis of green finance

As shown in Table 6, the spatial error term coefficient (SE) is 0.142 and is statistically significant. This indicates a spatial correlation in the factors affecting the transition to net-zero energy across prefecture-level cities, suggesting that the transition in these cities also exhibits spatial spillover effects. At the same time, the coefficient for GF is 0.0818 and passes the 5% significance test, indicating that GF has a significant positive influence on the ENTP even after accounting for spatial effects.

³ For the sake of brevity, the corresponding results are presented in the Appendix.

These findings indicate that the development of municipal GF has a significant impact on the local transition to net-zero energy, while also generating a notable positive spatial spillover effect. This implies that GF development not only fosters the optimization of local energy structures and environmental protection but also positively influences the transition to net-zero energy in neighboring regions. The presence of such spatial spillovers suggests potential “path dependence” or “lock-in effects,” making successful GF practices more likely to diffuse and propagate spatially, which highlights the regional interconnectedness and collaboration crucial to GF development. These spatial spillovers may arise from close spatial interactions and cooperative mechanisms between a city’s GF initiatives and its surrounding areas, as well as through channels such as technology diffusion, policy transmission, and economic cooperation.

The spatial correlation of GF manifests primarily in four aspects. Firstly, GF must address regional differences by supporting projects with environmental benefits that are often location-dependent; for example, wind farm construction is contingent on wind resource distribution, while the placement of pollution control facilities is influenced by the location of emission sources. GF must also consider the spatial dynamics of technology transfer and application to promote the adoption of advanced technologies tailored to the unique needs of each region. Second, GF has cross-regional impacts, meaning that green investments in one area can affect other regions—enhancing environmental quality, boosting economic development, or even creating social conflicts. It is therefore necessary to consider these broader impacts and interconnections in project assessments. Third, GF exhibits spatial spillover effects, as green investments can generate externalities in adjacent areas (Zhang et al., 2024). For instance, a clean energy project might reduce emissions in neighboring regions, but if mishandled, it could cause environmental issues and create negative spillovers, a phenomenon demonstrated by the significant positive spatial correlation of haze pollution. Fourth, policy orientation varies by jurisdiction, which influences the allocation of GF resources. For example, governments may establish pilot zones with specific incentives to attract green investments. This spatial correlation underscores the importance of considering spatial factors when evaluating GF’s role in the transition to net-zero energy to ensure both policy effectiveness and sustainable development.

Consequently, when formulating and implementing relevant policies, policymakers must thoroughly consider these spatial interactions and potential spillover effects, tailoring more targeted policy measures to the specific circumstances and characteristics of each region. This approach will support holistic GF development and the broader attainment of environmental protection and economic sustainability goals, ensuring that the benefits of GF development extend to a wider range of regions.

Table 6. Spatial model regression results

Variable	(1) Main	(2) Spatial
GF	0.082** (0.040)	
SE		0.142*** (0.019)
Observations	4760	4760
Adjusted R-squared	0.034	0.034

5. Conclusion and policy recommendations

This study explores the potential of GF in driving the net-zero transition of the energy system. The findings of this study are as follows: (1) Using the entropy method, this study establishes a multi-indicator framework to evaluate the impact of GF development on the potential for a net-zero energy transition. The results reveal that advancements in GF significantly enhance the capacity for achieving this transition. (2) GF exerts its influence through two critical pathways, improving resource allocation efficiency and optimizing industrial structures. However, it does not primarily drive the net-zero transition by directly stimulating green technological innovation. (3) Spatial econometric analysis indicates that GF exhibits spatial autocorrelation. At the municipal level, GF development not only significantly impacts the local transition to net-zero energy but also displays substantial positive spatial spillover effects.

In light of these research conclusions, the following policy recommendations are proposed.

First, based on the benchmark regression and the analysis of lagged effects, the government needs to strengthen the role of GF in the energy transition by formulating regulations that combine short-term incentives with long-term support. Second, concerning industrial structure, it is necessary to establish differentiated financial support mechanisms for industries, accelerating the transformation and upgrading of the secondary sector and implementing distinct GF strategies for high-energy-consumption industries versus green, low-carbon industries. Third, to improve resource allocation efficiency, financial institutions should be encouraged to develop diversified green financial tools, such as green asset securitization, to guide private capital into the energy transition and improve the efficiency of fund utilization and resource allocation. Fourth, it is necessary to tailor policies to local conditions by improving GF incentive mechanisms for regions at different developmental stages and with different characteristics, such as resource-based cities, small and medium-sized cities, and provincial border areas, and by guiding financial institutions to support a variety of green projects. Fifth, based on the spatial econometric results, a cross-regional platform for resource sharing and cooperation on large-scale clean energy projects should be established. This platform should incorporate GIS in planning for green energy infrastructure, account for spatial spillover effects, and use big data to regularly evaluate and dynamically adjust policies, thereby promoting the energy system's transition toward the net-zero target.

In addition, while the sample period of this study concluded in 2020, it demonstrates that GF promotes the ENTP mechanism by optimizing resource allocation and industrial structure—a dynamic that has not only persisted in subsequent practice but has also been reinforced, as exemplified by China's introduction of transformational finance in 2024. Therefore, these findings remain highly relevant, providing both a theoretical benchmark and practical reference for evaluating the effectiveness of contemporary green finance policies.

However, this study also has certain limitations. First, regarding variable measurement, future scholars could expand the green finance evaluation system from multiple perspectives and conduct more in-depth research on its impact mechanisms. Second, future research could explore the specific roles and potential moderating effects of mediating variables such as technological innovation and policy support. Third, this article focuses primarily on the macroeconomic impact of green finance on the energy transition. Further research could be conducted from the micro-level perspectives of firms and households.

Based on the limitations of the current study, we propose the following suggestions for future research. First, future studies could integrate multi-source data to develop a more

comprehensive and multi-level green finance evaluation framework. For instance, incorporating indicators such as corporate ESG ratings could better reflect the level of green finance development from the perspective of borrowers in green lending. Second, it is recommended to further investigate the specific pathways through which mediating variables such as technological innovation and policy support operate. For example, when technological innovation serves as a mediator, it may be subject to moderating effects, meaning its role could vary across regions and types of enterprises. Additionally, exploring potential threshold effects in the mediating role of technological innovation would be valuable. Third, future research could examine the applicability of findings across multiple levels, such as industrial, firm, and household perspectives, to enhance the generalizability and practical relevance of the conclusions.

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Author contributions

All authors contributed to the study. Qiaoru Wang: Supervision, Visualization, Writing – review & editing, Funding acquisition; Wenhui Fang: Conceptualization, Methodology, Data curation, Writing – original draft; Tingyu Liu: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. Peng Huang: Writing – review & editing.

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APPENDIX

Robustness tests

1. Endogeneity treatment

When examining the impact of GF development on the transition to net-zero energy, the baseline model established in this study may be susceptible to endogeneity arising from reverse causality, which could lead to biased parameter estimates. To mitigate this endogeneity, this study aggregates GF data to the provincial level and then uses an interaction term between provincial-level GF and the average city gradient (GRADIENT) as an instrumental variable (IV). The average city gradient, as an inherent geographical feature of a city, is naturally exogenous. Incorporating GF aggregated at the provincial level introduces a time-varying characteristic that effectively captures the changing nature of urban GF development over time, without being influenced by net-zero transition indicators at the prefecture-level

city scale. As shown in Table A1, the first-stage F-statistic exceeds 10, indicating a strong correlation between the chosen IV and the endogenous variable. This result passes the weak instrument test, confirming the validity of the instrument. Furthermore, the second-stage coefficient for GF remains significantly positive, consistent with the direction of the coefficients obtained from the baseline regressions. This consistency supports the robustness of the results.

Table A1. Robustness test: endogeneity treatment

Explained Variable	(1) 1st-stage GF	(2) 2nd-stage ENTP
GF*GRADIENT	0.002*** (0.000)	
GF		0.778*** (0.169)
Control Variables	YES	YES
Year Fixed Effects	YES	YES
City Fixed Effects	YES	YES
F-Statistic	293.540	4.110
Observations	4709	4709

2. Accounting for time lag effects

Considering the potential lagged effect of GF development on the net-zero energy transition, this study conducts a regression analysis with the explanatory variable lagged by one period, the results of which are presented in Column (1) of Table A2. The regression results indicate a significantly positive coefficient for the explanatory variable, suggesting that the development of GF in the previous year can promote the net-zero energy transition in the following year. Moreover, to address potential endogeneity issues associated with the control variables, this study also lags all control variables by one period. As shown in Column (2) of Table A2, the results remain statistically significant, and the regression coefficient for the GF Index is similar to that of the baseline regression, indicating that the selected control variables are robust.

3. Removing disturbance from key policy

During the advancement of GF, government-initiated pilot policies may introduce regional heterogeneity. Notably, in 2017, China's State Council launched GF innovation and reform trials in eight cities (or districts) across five provinces or regions: Zhejiang, Jiangxi, Guangdong, Guizhou, and Xinjiang. To account for the potential confounding impact of these specific policy interventions, we incorporate a Difference-in-Differences (DID) variable for the GF trials into our regression model. As shown in Column (3) of Table A2, the results demonstrate that the coefficient for GF development remains significant after incorporating this policy variable, thereby confirming the robustness of this study's findings.

4. Constructing indicators using PCA

Given that Principal Component Analysis (PCA) can compress high-dimensional data into a lower-dimensional space while preserving the primary information, this study uses PCA

instead of the entropy method to recalculate the indicators for the regression. The results are presented in Column (4) of Table A2, which shows that the findings of this study remain robust.

Table A2. Robustness test: lagged period and GF experiment

Variable	(1) Lagged by One Period	(2) Controlled Variable Lag	(3) Key Policy	(4) PCA Method
ENTP	0.102** (0.051)	0.095** (0.048)		0.007** (0.003)
DID			0.019 (1.880)	
Constant	0.162*** (0.023)	0.169*** (0.026)	0.198*** (11.500)	0.198*** (0.017)
Control variables	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES
Observations	4480	4480	4760	4760
Adjusted R-squared	0.693	0.693	0.689	0.668

Method for calculating resource allocation efficiency

This study uses the degree of factor market distortion as an inverse proxy for resource allocation efficiency. The specific calculation process is as follows: We begin with a log-linearized Cobb-Douglas production function. Assuming market prices for capital and labor are r and w respectively, this study calculates the degree of market distortion by measuring the deviation between the marginal product of each factor and its price. The individual distortions for capital and labor are then aggregated to obtain a total factor market distortion index. After inputting the actual data for each city, we can derive this distortion index for each city in each year. To create a standardized measure, we define the degree of resource misallocation as the ratio of a city's distortion index to the maximum value observed across all cities in that year. Finally, the inverse of this resource misallocation measure is used as our proxy variable for resource allocation efficiency.

LM test

To determine the most appropriate spatial econometric model, this study employs a Lagrange Multiplier (LM) test, the results of which are presented in Table A3. Both the LM-lag and LM-error tests are significant, indicating the need for further analysis using the robust versions of the LM tests. The robust LM-error test is found to be significant, while the robust LM-lag test is not. This indicates that the Spatial Error Model (SEM) is the appropriate model for this analysis.

Table A3. Result of LM test

Test method	(1) Test statistic	(2) p-value
LM-error	345.113	0.000
Robust LM-error	213.357	0.000
LM-lag	131.806	0.000
Robust LM-lag	0.050	0.823