RESEARCH ARTICLE

Green Finance and Low-Carbon Economic Development: Moderating Roles of Green Technology Innovation and Government Intervention in China

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Abstract

Using balanced panel data for 30 Chinese provinces from 2005 to 2022, this study investigates the impact of green finance (GF) on low-carbon economic development (LCE), with particular attention to the moderating roles of green technology innovation (GTI) and government intervention intensity (GII). A two-way fixed effects model is employed to control for regional heterogeneity and time effects. The results show that GF significantly promotes LCE. Moreover, GTI strengthens the positive effect of GF on LCE, whereas GII weakens this relationship, indicating that excessive government intervention may reduce the effectiveness of GF in supporting low-carbon development. These findings remain robust across alternative specifications and measurements, and provide policy implications for improving green financial systems and advancing low-carbon transitions in emerging economies.

Keywords: green finance, low-carbon economic development, green technology innovation, government intervention.

1 Introduction

The transition toward a low-carbon economy represents a cornerstone of sustainable development and climate mitigation strategies internationally. As concerns over environmental degradation and climate change intensify, governments and scholars alike have underscored the need for financial systems to support green transformation pathways. In this context, green finance (GF) — encompassing instruments such as green credit, green bonds, and environmentally focused investment and insurance products — is increasingly seen as a vital mechanism to steer capital toward low-carbon projects and technologies that can decouple economic growth from carbon emissions [1]. Empirical research suggests that GF can significantly facilitate the shift to LCE by allocating financial resources toward more sustainable sectors and incentivising innovation [2, 3].

Despite rapid scholarly growth in this area, several key issues remain unresolved. Prior studies have documented positive associations between GF and various environmental outcomes, including reduced carbon intensity and improved LCE

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metrics [4]. However, empirical findings vary considerably depending on measurement approaches, geographic scope, and analytical frameworks. Moreover, while green technological innovation (GTI) has been recognised as a pathway through which GF influences environmental outcomes (e.g., green patenting), and government intervention intensity (GII) as a potential shaping force, few studies have systematically examined how these factors moderate the GF-LCE nexus across China's diverse provinces [5]. This gap limits understanding of the conditions under which GF is most effective and the mechanisms driving its impact.

This study addresses these gaps by investigating the effect of GF on LCE using provincial panel data from 30 Chinese provinces over 2005–2022. A composite GF index serves as the main explanatory variable, while a multidimensional LCE index captures regional performance in achieving carbon-efficient growth. To unpack heterogeneous effects and underlying channels, we introduce green patent authorisations as a measure of GTI and a proxy for GII as moderating variables in a moderated regression framework. Control variables include labor force level (LAB), social consumption level (CON), urbanization level (UBL), degree of openness (OPN) to the outside world, which have been frequently employed in empirical models of regional economic and environmental outcomes.

This study contributes to the literature in three principal ways. First, it expands the empirical focus beyond carbon emissions alone to a comprehensive LCE construct that better reflects policy objectives and multidimensional outcomes. Second, by incorporating moderating effects of GTI and GII, the study sheds light on contingent mechanisms that shape the GF-LCE linkage, thereby enriching theoretical understanding. Third, the long time span and cross-provincial data enable a nuanced analysis of regional dynamics within China's green transition. These insights can inform both academic discourse and policymaking in other emerging economies seeking to leverage financial policy for sustainable development.

The remainder of the paper is structured as follows. Section 2 reviews relevant literature and develops hypotheses. Section 3 describes data, variable construction, and methodology. Section 4 presents empirical results, including moderation analyses. Section 5 discusses robustness checks and additional findings. Finally, Section 6 concludes with policy implications and avenues for future research.

2 Literature Review

2.1 GF and LCE

The academic literature increasingly recognises GF as a critical policy instrument for supporting the transition to low-carbon economies. Conceptually, GF comprises financial mechanisms—including green credit, green bonds, and environmentally oriented investment—that reallocate capital toward projects with positive environmental externalities and reduce reliance on carbon-intensive activities [6]. This reallocation has been posited to correct market failures in environmental externalities and to internalise environmental costs, thereby facilitating low-carbon transformation [7].

Empirically, a growing body of research has documented a significant positive relationship between the development of GF and various dimensions of LCE progress. For instance, recent provincial-level evidence from China shows that GF significantly and positively affects LCE, with mechanisms linked to industrial upgrading, technological innovation, and foreign direct investment inflows; positive effects are particularly pronounced in less developed regions [8]. Studies focusing on carbon emissions also support this linkage: research synthesising global and Chinese contexts finds that GF reduces carbon emissions through policy guidance, improved resource allocation, and technical support [9].

Moreover, green finance-driven capital orientation can alleviate financing constraints for clean energy and low-carbon projects, thus enabling structural shifts in energy and industrial sectors that are essential for sustainable growth [10]. Scholars analysing dynamic models further show that green finance not only promotes local LCE construction but also exerts spatial spillover effects on neighbouring regions, underscoring the systemic influence of green financial development [11].

Despite these advances, several empirical gaps remain. First, much of the existing literature has examined the impact of GF on carbon emissions intensity or broad environmental outcomes rather than on a composite index of LCE that integrates economic efficiency, structural change and sustainability objectives [12]. While carbon emissions remain critical, LCE encompasses broader socio-economic transformations, including productivity shifts

and industrial restructuring. Second, although mechanisms such as technological innovation and industrial upgrading are often discussed, relatively few studies have formally tested their moderating roles within a unified empirical framework at the provincial level over a long time span. This limits understanding of how and under what conditions GF influences LCE. Third, heterogeneity across regions — a key feature of China's vast and diverse economy — is underexplored in most existing research designs.

The importance of clarifying the relationship between GF and LCE extends beyond academic curiosity: it directly informs the design of climate-aligned financial policies. If GF can demonstrably enhance low-carbon outcomes, then policy efforts to deepen financial markets and integrate environmental considerations into financial decision-making are justified [13]. Conversely, ambiguous empirical results could indicate the need for complementary policies to strengthen transmission mechanisms. In light of these considerations, the first hypothesis of this study is proposed:

Hypothesis 1: Green finance development has a positive effect on low-carbon economic development.

2.2 The moderating effect of GTI on GF and LCE

The impact of GF on LCE is inherently conditioned by regional technological capabilities. While GF facilitates the reallocation of financial resources toward environmentally friendly activities, its effectiveness depends on whether regions possess sufficient green technological capacity to absorb and deploy such resources efficiently. GTI, which reflect validated and legally protected green innovation outputs, provide a reliable indicator of realised green technological capacity [14].

Existing studies show that GF can stimulate GTI by easing financing constraints and encouraging investment in low-carbon technologies [15]. More importantly, empirical evidence suggests that technological innovation conditions the environmental and economic effects of GF. Using regional data from China, several studies find that the carbon-reduction and efficiency-enhancing effects of GF are significantly stronger in regions with higher levels of green patent activity, indicating a positive interaction between financial development and technological capacity [16, 17].

From a theoretical perspective, regions with higher levels of authorised green patents are better equipped to transform green financial inputs into substantive low-carbon outcomes through technological upgrading, productivity improvements, and structural transformation [18]. In contrast, in regions with weaker green innovation foundations, the marginal contribution of GF to LCE may be limited due to insufficient technological absorption capacity.

Despite these insights, most existing studies focus on carbon emissions or carbon intensity and rarely examine LCE as a multidimensional outcome. Moreover, green innovation is often treated as a mediating mechanism rather than as a moderating factor that shapes the strength of the GF–LCE relationship. Addressing this gap is essential for identifying the boundary conditions under which GF is most effective. Accordingly, this study proposes the following hypothesis:

Hypothesis 2: Green technological innovation plays a significant moderating role in the relationship between green finance and low-carbon economic development.

2.3 The moderating effect of GII on GF and LCE

Institutional factors critically shape the effectiveness of GF in promoting LCE. In this context, GII reflects the intensity of local government involvement in economic activities, including fiscal expenditure, regulatory oversight, and policy guidance. While moderate intervention can correct market failures, reduce information asymmetry, and facilitate green investment [19], excessive intervention may distort financial resource allocation, crowd out private capital, and reduce the efficiency of market mechanisms [23].

Empirical studies provide evidence for the conditional effects of GII. Research based on Chinese provincial data shows that the effectiveness of GF in reducing carbon intensity and improving environmental performance varies significantly with institutional characteristics [20]. In regions where GII is high, green financial resources may be allocated toward politically or administratively favoured projects rather than those with the highest low-carbon potential. Consequently, the positive effect of GF on LCE can be weakened, indicating a negative moderating effect of GII on this relationship.

Theoretically, excessive GII can limit firms' responsiveness to green financial incentives by constraining market-based decision-making, reducing competition, and lowering the incentive to adopt innovative low-carbon technologies [21, 22]. Moreover, overly interventionist policies may slow structural

upgrading and resource reallocation, reducing the efficiency gains that GF is intended to promote. These mechanisms provide a plausible explanation for why empirical analyses often find that higher GII dampens the positive impact of GF on LCE.

Despite these insights, most studies treat GII as a control variable or focus on its direct effects rather than its conditional role. Investigating GII as a moderator allows for identification of institutional boundary conditions that shape the effectiveness of GF, offering valuable guidance for policy design and regional implementation strategies. Based on these arguments and the empirical evidence, the following hypothesis is proposed:

Hypothesis 3: Government intervention degree plays a significant moderating role between GF and LCE.

3 Data and Methodology

3.1 Sample and data sources

This study investigates the correlation between GF and LCE, with particular attention to the moderating roles of GTI and GII. The analysis focuses on Chinese provinces and is conducted as follows: provinces with significant missing data were excluded, and remaining missing values were interpolated. Consequently, the final sample comprises 30 provinces from 2005 to 2022, yielding 540 observations. Tibet, Taiwan, Hong Kong, and Macau were excluded due to data unavailability. The time span 2005–2022 is selected because it encompasses key policy and economic developments that have shaped the green finance landscape in China, including the launch of the Green Credit Guidelines (2007), the establishment of the National Green Finance Pilot Zones (2017), and the acceleration of carbon peaking and carbon neutrality initiatives in 2020, providing a comprehensive period to capture the evolution of both GF and LCE.

Data for the main variables were collected from authoritative sources including the National Bureau of Statistics, Ministry of Science and Technology, People's Bank of China, and a range of provincial and sectoral statistical yearbooks. The GF index and LCE index were constructed using a multi-indicator system and calculated through the entropy method, which assigns higher weights to indicators with greater dispersion, thereby reflecting their relative contribution to the overall index. Moderating variables, GTI and GII, were obtained from the China Statistical Yearbook, while control variables included LAB, CON, UBL and OPN. Data processing was performed using SPSS and Excel, and regression analyses, including moderation testing, were conducted using Stata software.

3.2 Variables

3.2.1 Dependent variable (GF)

Drawing on the China Green Finance Development Report and existing GF evaluation frameworks [24–26], a comprehensive provincial-level GF evaluation system was constructed to reflect the actual development status of GF across China. This indicator system is designed to provide a holistic assessment of the effectiveness and depth of GF implementation. The specific indicators and calculation methodology

Table 1. Green finance evaluation indicator system.

First-level index	Sub-level index	Calculation explanation
Green finance	Green credit	Total credit for regional environmental protection projects / Total regional credit
	Green investment	Investment in environmental pollution control as a percentage of GDP
	Green insurance	Environmental pollution liability insurance income / Total premium income
	Green bonds	Total amount of green bonds issued / Total amount of all bonds issued
	Green support	Fiscal expenditure on environmental protection / Total fiscal budget expenditure
	Green Fund	Total market capitalization of green funds / Total market capitalization of all funds
	Green rights	Total transaction volume of carbon trading, energy use rights trading, and pollution rights trading/emissions trading market.

Table 2. Low-carbon economic development evaluation indicator system.

Target Level	First-level index	Sub-level index	Calculation explanation	Direction
Level of low-carbon economic development	Low-carbon output indicators	Carbon productivity	GDP/Carbon Emissions	+
		Energy processing and conversion efficiency	Energy input / Energy output	+
	Low-carbon consumption indicators	Household consumption carbon emissions	Carbon emissions/household consumption expenditure	-
		Government consumption carbon emissions	Carbon emissions / Government consumption expenditure	-
	Low-carbon resource indicators	Share of zero-carbon energy	Zero-carbon energy consumption / Total energy consumption	+
		Energy carbon emission coefficient	Carbon emissions/Energy consumption	-
		Carbon sink density	Carbon sequestration amount/area	+
	Low-carbon policy indicators	Low-carbon economic development plan	With or without	+
		Establish a system for monitoring, reporting, and regulating carbon emissions.	With or without	+
		The level of public awareness of low-carbon economy concepts.	Penetration rate (%)	+
		Compliance rate with environmental protection and energy saving standards	Execution rate %	+
		Carbon tax policy	With or without	+
	Low-carbon environmental indicators	Carbon emission intensity of waste	Carbon emissions from waste / Amount of waste generated	-
		Industrial waste treatment index	Processing rate (%)	+

are detailed in Table 1.

3.2.2 *Independent variable* (*LCE*)

The LCE is a new development paradigm characterized by low energy consumption, low pollution, and low emissions. It promotes a deep decoupling of economic and social development from carbon emissions through energy structure innovation, low-carbon technological upgrades, and the construction of a circular economy system. To comprehensively and scientifically measure the level of LCE, this study, drawing on the research of Zhongyu et al. [27], constructs a comprehensive evaluation index system for the level of LCE from five dimensions: low-carbon output, low-carbon consumption, low-carbon resources, low-carbon policies, and the low-carbon environment (see Table 2).

3.2.3 *Moderating variables* (*GTI and GII*)

Green technology innovation (GTI). The level of green technology innovation is expressed by the number of green patents granted in each province. The development of GF will support companies in increasing their exploration of environmentally friendly technologies, which will help reduce innovation risks for businesses and thus reduce carbon emissions [28].

Government intervention intensity (GII). The government intervention degree is measured by the proportion of government fiscal expenditure to regional GDP in each province. GII influences the allocation of financial resources and the implementation efficiency of GF policies. Appropriate intervention can guide capital toward low-carbon sectors through subsidies, regulations, and public investment, while excessive intervention may distort market mechanisms and weaken the incentive effects of green finance, thereby constraining its effectiveness in promoting LCE [29].

3.3 Control variables

To ensure the accuracy and robustness of the model estimation results, this study incorporates four control variables that may influence the relationship between GF and LCE: labor force level, social consumption level, urbanization level, and degree of openness.

Labor force level (LAB). In the context of rapid population aging, China's labor market has undergone profound structural transformations in recent years [11]. Increasing mismatches between labor supply and demand may affect production efficiency, industrial structure, and energy consumption patterns, thereby exerting indirect effects on both economic performance and environmental outcomes. Accordingly, LAB is measured as the natural logarithm of the total number of employed persons in each province.

Social consumption level (CON). Social consumption reflects the overall scale of consumer goods supplied to residents and society through various distribution channels across industries and serves as an important indicator of economic vitality [10]. Higher consumption levels may stimulate economic growth while simultaneously influencing energy demand and carbon emissions. In this study, CON is measured as the ratio of total retail sales of consumer goods to GDP.

Urbanization level (UBL). Urbanization fundamentally reshapes population distribution, industrial agglomeration, and infrastructure development, all of which have important implications for LCE. On the one hand, urbanization can improve resource allocation efficiency and facilitate the diffusion of green technologies; on the other hand, rapid urban expansion may intensify energy consumption and environmental pressure [12]. UBL is measured by the proportion of the urban population to the total population in each province.

Degree of openness (OPN). A higher degree of openness enables regions to absorb advanced foreign technologies, management experience, and green development concepts, thereby fostering international cooperation in the green economy. Empirical evidence suggests that trade openness significantly affects carbon intensity and environmental performance [13]. Accordingly, OPN is measured as the ratio of total imports and exports of goods to GDP.

3.4 Model design

This study examines the relationship between GF and LCE across Chinese provinces using a two-way fixed effects panel regression model. As specified in Equation (1), province and year fixed effects are incorporated to control for unobserved heterogeneity arising from time-invariant regional characteristics and common temporal shocks. By accounting for both spatial and temporal variations, the two-way fixed effects model enables a more precise identification of the effect of GF on LCE.

To further explore the underlying mechanism, this study investigates the moderating roles of GTI and GII in the relationship between GF and LCE. Specifically, interaction terms between GF and GTI, as well as between GF and GII, are introduced to examine whether and how these factors condition the impact of GF on LCE. Accordingly, Equations (2) and (3) present the moderation models. This specification accounts for time-series dependence and cross-sectional heterogeneity, while highlighting the heterogeneous effects of GF under different levels of GTI and GII. The analysis thus provides new empirical insights into the pathways through which GF contributes to LCE.

$$LCE_{i,t} = \alpha_0 + \alpha_1 GF_{i,t} + CV_{i,t} + \theta_t + \mu_i + \varepsilon_{i,t}, \quad (1)$$

$$LCE_{i,t} = \beta_0 + \beta_1 GF_{i,t} + \beta_2 GTI_{i,t} + \beta_3 GF_{i,t} * GTI_{i,t} + CV_{i,t} + \theta_t + \mu_i + \varepsilon_{i,t}, \quad (2)$$

$$LCE_{i,t} = \gamma_0 + \gamma_1 GF_{i,t} + \gamma_2 GII_{i,t} + \gamma_3 GF_{i,t} * GII_{i,t} + CV_{i,t} + \theta_t + \mu_i + \varepsilon_{i,t}. \quad (3)$$

where $LCE_{i,t}$ shows the low-carbon economic development level of province i in year t. $GF_{i,t}$ indicates the green finance index of province i in that year. $CV_{i,t}$ includes labour force level, social consumption level, Urbanization level and degree of openness. Province-fixed effects μ_i and year-fixed effects θ_t are involved. $\varepsilon_{i,t}$ denotes the error term. Descriptive statistics of the variables and the correlation matrix are shown in Tables 3 and 4, respectively.

4 Empirical results

4.1 Descriptive statistics and correlation analysis

The outcomes of the descriptive statistics can be seen from Table 3. A total of 540 sets of data are included in the analysis. It presents the descriptive statistics of

Table 3. Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
LCE	540	0.4777	0.2668	0.0640	1.0648
GF	540	0.2983	5548.2830	2	45359
GTI	540	2995.02	1.7700	0.6931	10.7224
GII	540	0.2376	0.1068	0.0919	0.7583
LAB	540	7.5782	0.7858	5.5452	8.8639
CON	540	0.3745	0.0572	0.1796	0.5044
UBL	540	0.5635	0.1397	0.27	0.9
OPN	540	0.3527	0.0861	0.1001	0.5738

the variables. The data exhibit sufficient dispersion to support subsequent empirical analysis.

Table 4 reports the Pearson correlation coefficients among the main variables. GF is significantly and positively correlated with LCE, providing preliminary support for the hypothesized relationship. GTI also exhibits a strong positive association with LCE, while GII is negatively correlated with LCE. Importantly, none of the pairwise correlation coefficients exceed the commonly accepted threshold, suggesting that multicollinearity is unlikely to be a serious concern. This conclusion is further supported by the VIF test results. The negative correlation between GII and both GF and LCE is consistent with the view that excessive GII may distort market-based GF mechanisms and impede LCE.

Table 5 reflects Variance Inflation Factor (VIF) values for the key variables. Although the VIF values for GTI and UBL are relatively higher, they remain below the critical value of 10, suggesting that multicollinearity does not materially affect the reliability of the regression estimates.

4.2 Regression results and analysis

4.2.1 Baseline model regression

Table 6 presents the baseline regression estimates of the impact of GF on LCE under a two-way fixed effects framework. Column (1) shows that the coefficient on the GF is positive and highly significant at the 1% level, indicating that higher levels of GF development are associated with enhanced LCE. This finding is consistent with existing empirical evidence that GF facilitates structural transformation and technological upgrading, thereby promoting regional low-carbon transitions [3]. In Column (2), after including control variables, the positive effect of GF remains robust, and the OPN exhibits a significant negative coefficient, suggesting that higher OPN may be associated with greater exposure to carbon-intensive external pressures, in line with studies showing mixed effects of trade openness on environmental performance [13].

Column (3) further replaces GF with its lagged term to address potential dynamic impacts, and the lagged GF coefficient remains significantly positive, reinforcing the notion that the development of GF systems has a persistent and favourable influence on LCE. Across all specifications, the inclusion of both province and year fixed effects helps mitigate concerns about omitted time-invariant regional heterogeneity and common temporal shocks, thereby enhancing the credibility of the estimated relationships. Overall, the baseline results provide robust empirical support for the hypothesis that GF contributes positively to LCE.

4.2.2 Moderating model regression

Table 7 presents the moderating effect results, examining how GTI and GII condition the relationship between GF and LCE. In Column (1), the interaction term GF*GTI is positive and significant at the 1 % level, indicating that provinces with higher levels of green patent authorizations strengthen the positive impact of GF on LCE. This finding is consistent with previous studies showing that technological innovation enhances the effectiveness of green finance in promoting LCE [6].

In Column (2), the interaction term GF*GII is negative and highly significant, suggesting that higher GII weakens the positive effect of GF on LCE. The main effect of GII is also significantly negative, implying that excessive government intervention may distort market signals and reduce the efficiency of GF allocation, consistent with evidence that institutional factors can condition the effectiveness of market-based environmental policies [18].

Overall, these results highlight the contingent nature of GF's impact on LCE: while GTI enhances the translation of GF into low-carbon development, GII can impede this effect. The findings underscore the importance of fostering supportive innovation environments and calibrating institutional involvement to maximize the environmental benefits of GF.

Figure 1 illustrates the moderating effects of GTI and GII on the relationship between GF and LCE. As shown in Figure 1(A), the positive association between GF and LCE is significantly stronger when GTI is at a higher level, as evidenced by the steeper slope for regions with higher GTI. This pattern indicates that green technological innovation

Table 4. Correlations Matrix.

	LCE	GF	GTI	GII	LAB	CON	UBL	OPN
LCE	1.000							
GF	0.747***	1.000						
GTI	0.638***	0.616***	1.000					
GII	-0.527***	-0.351***	-0.357***	1.000				
LAB	0.385***	0.343***	0.525**	-0.650***	1.000			
CON	0.393***	0.438***	0.441*	-0.219***	0.275***	1.000		
UBL	0.584***	0.460***	0.634***	-0.152***	-0.143***	0.256***	1.000	
OPN	0.483***	0.312***	0.293***	-0.394***	0.0163	0.150***	0.681***	1.000

Table 5. VIF test results.

Variables	VIF	1/VIF
GF	1.79	0.5595
GTI	8.32	0.1202
GII	2.58	0.3876
LAB	6.36	0.1572
CON	1.32	0.7578
UBL	8.11	0.1233
OPN	2.43	0.4112
Mean VIF	4.42	

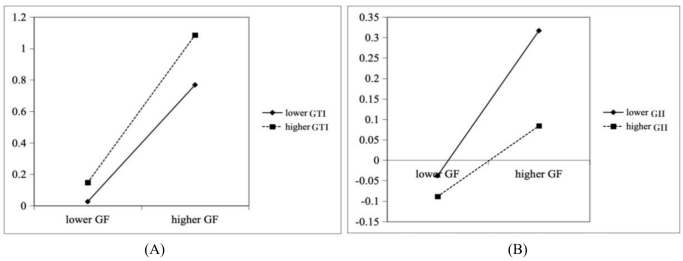


Figure 1. (A)Regulation effect diagram of GTI, (B)Regulation effect diagram of GII.

enhances the effectiveness of GF in promoting LCE by improving the capacity to absorb and transform financial resources into low-carbon outcomes. In contrast, Figure 1(B) reveals a negative moderating effect of GII. Although GF remains positively related to LCE under both low and high levels of GII, the slope is markedly flatter when GII is higher, suggesting that excessive government intervention weakens the marginal effect of GF. This finding implies that strong administrative involvement may distort market-based financial allocation mechanisms, thereby reducing the efficiency with which GF contributes to low-carbon economic development. Overall, the interaction plots visually corroborate the regression results and highlight the heterogeneous roles of innovation capacity and institutional intervention in shaping the effectiveness of GF.

4.3 Robustness test results

To assess the robustness of the baseline findings, this study conducts two sets of additional tests, as reported in Tables 8 and 9. First, Table 8 presents results using the one-period lagged dependent variable (L.LCE) to account for potential dynamic effects and temporal dependence. The coefficient on lagged GF remains positive and highly significant across specifications, while the interaction terms GF*GTI and GF*GII retain their signs and significance. Specifically, the positive interaction between GF and GTI persists, and the negative interaction between GF and GII continues to be strongly significant, corroborating the moderating roles of GTI and GII under alternative temporal assumptions. Similar approaches using lagged variables have been employed in the GF literature to mitigate concerns related to endogeneity and dynamic adjustment processes [23].

Second, Table 9 introduces industrialization level (INL) as an additional control to address potential omitted variable bias. Although the inclusion of INL slightly alters the magnitudes of some coefficients, the core results remain robust: GF's positive effect on LCE is sustained, GTI positively moderates this relationship, and GII's moderating effect remains negative and significant. The significance of INL itself in some specifications underscores the importance of controlling for broader structural economic conditions. The robustness of key relationships to both alternative model specifications and additional controls enhances confidence in the stability of the estimated effects, consistent with robustness practices in related studies that employ expanded control sets to validate GF-LCE linkages.

4.4 Heterogeneity Analysis

Different provinces exhibit distinctive characteristics in terms of population size and geographical location, and these characteristics also affect the effectiveness

Table 6. Baseline regression results.

	(1)	(2)	(3)
	LCE	LCE	LCE
GF	1.5597*** (0.0435)	1.4988***(0.0910)	
L.GF			1.4787***(0.0971)
LAB		0.0297(0.0226)	0.0229(0.0236)
CON		-0.0730(0.0637)	-0.0772 (0.0647)
UBL		0.0193(0.0617)	0.0429 (0.0659)
OPN		-0.0428**(0.0214)	-0.0406** (0.0228)
Cons	0.0126 (0.0347)	-0.1646(0.1747)	-0.1064 (0.1834)
Year FE	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Obs	540	540	540
R2	0.5576	0.5440	0.5463

Note: The standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. It also applies to the following tables.

Table 7. Moderating effect results.

	(1)	(2)
	LCE	LCE
GF	0.8735*** (0.1539)	1.6005*** (0.0927)
GTI	0.0310*** (0.0080)	
GF*GTI	0.1035*** (0.0219)	
GII		-0.1879*** (0.0627)
GF*GII		-1.5962*** (0.3517)
LAB	0.0322 (0.0245)	0.0145 (0.0224)
CON	-0.0452 (0.0634)	-0.0228 (0.0649)
UBL	-0.1064 (0.1191)	-0.0333 (0.0652)
OPN	-0.0043 (0.0233)	-0.0341 (0.0214)
Cons	-0.1727 (0.1941)	-0.0341 (0.1737)
Year FE	Yes	Yes
Province FE	Yes	Yes
Obs	540	540
R2	0.5822	0.440

of GF. Therefore, this study further analyzes the heterogeneity of GF's impact on LCE from the perspectives of population size and geographical location.

4.4.1 Population size heterogeneity

Table 10 presents regional heterogeneity analysis across China's eastern, central, and western regions[1]. GF positively affects LCE in all regions, with the effect strongest in the eastern and central regions (1.6268 and 1.6072, $p < 0.01$) and weaker in the western region (0.3647, $p < 0.05$). The stronger effects in more developed regions may be due to better financial infrastructure and higher technological adoption, which allow GF to more efficiently channel resources into low-carbon projects [9].

LAB shows a positive association in the western region, while UBL and OPN exhibit heterogeneous effects across regions, highlighting that local structural and economic conditions shape the translation of GF into LCE. Overall, the results suggest that GF's effectiveness is conditioned by regional characteristics, reinforcing the need for tailored policy interventions.

4.5 Geographical location heterogeneity

Table 11 presents the heterogeneity analysis based on population size, dividing provinces into three categories: permanent resident population $\geq$ 80 million, 30–80 million, and $\leq$30 million[2]. Across all groups, GF exerts a consistently positive and significant effect on LCE, indicating that the

[1]According to the "Seventh National Population Census Communique" released by the National Bureau of Statistics in 2021, the eastern region refers to 11 provinces (cities) including Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Liaoning, Guangdong, and Hainan; the central region refers to 6 provinces including Shanxi, Anhui, Jiangxi, Henan, Heilongjiang, Jilin, Hubei, and Hunan; and the western region refers to 11 provinces (autonomous regions, cities) including Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. https://www.stats.gov.cn/sj/tjgb/rkpcgb/qgrkpcgb/202302/t20230206_1902008.html

[2]According to the "Seventh National Population Census Bulletin" released by the National Bureau of Statistics in 2021, provinces with a permanent resident population of $\geq$80 million include Guangdong, Henan, Jiangsu, Shandong, and Sichuan. Provinces with a population of 30 to 80 million include 15 provinces: Anhui, Fujian, Guangxi, Guizhou, Hebei, Heilongjiang, Hubei, Hunan, Jiangxi, Liaoning, Shanxi, Shaanxi, Yunnan, Zhejiang, and Chongqing. Provinces with a population of $\leq$30 million include 10 provinces: Beijing, Gansu, Hainan, Jilin, Inner Mongolia, Ningxia, Qinghai, Shanghai, Tianjin, and Xinjiang. https://www.stats.gov.cn/sj/tjgb/rkpcgb/qgrkpcgb/202302/t20230206_1902008.html

Table 8. Robustness test results (One-period lagged LCE).

	(1)	(2)	(3)
	L.LCE	L.LCE	L.LCE
GF	1.5159*** (0.0948)	0.8532*** (0.1563)	1.5976*** (0.0958)
GTI		0.0359*** (0.0082)	
GF*GTI		0.1102*** (0.0225)	
GII			-0.1546*** (0.0664)
GF*GII			-1.5243*** (0.3653)
LAB	0.0364 (0.0231)	0.0313 (0.0247)	0.0216 (0.0229)
CON	-0.0436 (0.0635)	-0.0030 (0.0629)	-0.0066 (0.0654)
UBL	-0.0041 (0.0647)	-0.1928 (0.1251)	-0.0500 (0.0670)
OPN	-0.0401** (0.0223)	0.0031 (0.0242)	-0.0338 (0.0225)
Cons	-0.2340 (0.1794)	-0.1769 (0.1954)	-0.1059 (0.1779)
Year FE	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Obs	540	540	540
R2	0.5405	0.5661	0.5762

Table 9. Robustness test results (Add INL as a control variable).

	LCE	LCE	LCE
GF	1.4558*** (0.0970)	0.7846*** (0.1605)	1.5364*** (0.0974)
GTI		0.0341*** (0.0081)	
GF*GTI		0.1059*** (0.0219)	
GII			-0.2105*** (0.0633)
GF*GII			-1.6808*** (0.3438)
LAB	0.0353 (0.0230)	0.0372 (0.0247)	0.0245 (0.0223)
CON	-0.1021 (0.0677)	-0.0836 (0.0664)	-0.0632 (0.0680)
UBL	0.0113 (0.0620)	-0.1569 (0.1215)	-0.0417 (0.0654)
OPN	-0.0344 (0.0224)	0.0115 (0.0248)	-0.0199 (0.0222)
INL	-0.0939 (0.0739)	-0.1404* (0.0735)	-0.1454** (0.0735)
Cons	-0.1486 (0.1750)	-0.1170 (0.1961)	-0.0192 (0.1709)
Year FE	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Obs	540	540	540
R2	0.5494	0.5773	0.6024

Table 10. Population size heterogeneity analysis results.

	Chinese eastern region	Chinese central region	Chinese western region
GF	1.6268*** (0.1368)	1.6072*** (0.0779)	0.3647** (0.1523)
LAB	0.0247 (0.0287)	0.0092 (0.0149)	0.0726** (0.0338)
CON	0.0319 (0.0975)	-0.0073 (0.0996)	-0.0941 (0.0933)
UBL	0.2236* (0.1155)	0.0150 (0.1008)	0.3332*** (0.0791)
OPN	-0.0157 (0.0241)	0.0006 (0.1161)	0.5103*** (0.0747)
Cons	-0.2490 (0.2303)	-0.0392 (0.1308)	-0.5529** (0.2459)
Year FE	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Obs	198	144	198
R2	0.7299	0.8758	0.4917

development of green finance effectively promotes LCE regardless of demographic scale. The impact is largest in medium-sized provinces (1.4984, $p < 0.01$), suggesting that these regions may combine adequate

Table 11. Geographical location heterogeneity analysis results.

	Permanent resident population ≥80 million	Permanent resident population: 30-80 million	Permanent resident population ≦30 million
GF	1.0663*** (0.2352)	1.4984*** (0.1857)	1.4026*** (0.1222)
LAB	-0.0406 (0.0592)	0.0414 (0.0500)	0.0874** (0.0351)
CON	-0.7646*** (0.2200)	-0.1163 (0.0992)	-0.2739*** (0.0966)
UBL	0.9372*** (0.1877)	0.0311 (0.1415)	-0.1832** (0.0731)
OPN	-0.0075 (0.0276)	-0.8447 (0.0661)	-0.0198 (0.0302)
Cons	0.4003 (0.5065)	-0.2629 (0.3941)	-0.3471 (0.2306)
Year FE	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Obs	90	270	180
R2	0.9295	0.3444	0.4727

financial resources with sufficient market flexibility to translate GF into tangible LCE improvements. The slightly lower coefficients in the largest (1.0663, $p < 0.01$) and smallest provinces (1.4026, $p < 0.01$) imply that very large populations may face coordination or implementation challenges, while smaller populations may have limited resource mobilization capacity.

The results also highlight the role of control variables in shaping LCE. LAB positively contributes to LCE in smaller provinces, suggesting that labor availability can facilitate low-carbon initiatives where resources are limited. UBL enhances LCE in the largest provinces but is negatively associated in the smallest, reflecting the differing capacity of urban infrastructure to support green transitions. CON exhibits negative effects in the largest and smallest provinces, indicating that high consumption levels may temporarily counteract LCE [15]. Overall, the findings underscore that while GF is the key driver of LCE, its effectiveness is conditioned by population size, emphasizing the need to design population-sensitive GF policies to maximize low-carbon outcomes.

5 Discussion

This study provides robust empirical evidence that the development of GF significantly promotes LCE across Chinese provinces. The positive association between GF and LCE is consistent with recent findings in the literature, which highlight that GF instruments can facilitate the transition to LCE by reallocating capital toward sustainable investments and supporting energy structure transformation [28].

Importantly, the moderating analyses reveal that GTI enhances the beneficial effect of GF on LCE. The positive and significant interaction term (GF*GTI) suggests that provinces with stronger green innovation capabilities are better positioned to absorb and translate green financial resources into tangible low-carbon outcomes. This result aligns with studies demonstrating that technological innovation interacts with financial support mechanisms to reduce emissions and improve environmental performance [15, 27]. These findings underscore that innovation ecosystems can amplify the efficacy of green finance, highlighting the importance of policies that simultaneously cultivate technological capacity while expanding financial support for low-carbon projects.

In contrast, GII exhibits a negative moderating effect on the GF–LCE relationship. The negative interaction (GF*GII) indicates that more intensive intervention may attenuate the positive influence of GF on LCE. This aligns with theoretical arguments that excessive administrative involvement can distort market signals and impede efficient resource allocation, even within sustainability-oriented frameworks [20]. It suggests that while some level of intervention may be necessary to correct market failures, an overemphasis on direct government control could reduce the catalytic impact of market-based GF instruments.

The heterogeneity analyses further reveal that the positive effect of GF on LCE is context-dependent. Regional disparities and population size differences condition the strength of the association, reflecting variations in financial market depth, institutional

capacity, and the structural readiness of local economies. Prior studies similarly report spatial heterogeneity in the environmental effectiveness of green finance policies, with stronger impacts in regions with advanced financial systems and innovation capacities [5, 6]. This body of evidence suggests that one-size-fits-all policy designs may be suboptimal; instead, tailored strategies that consider regional characteristics, demographic scale, and institutional contexts are essential for maximizing LCE outcomes.

6 Policy Implications and Recommendations

The findings yield several important policy implications. First, the consistently positive effect of GF on LCE indicates that expanding green financial instruments—such as green credit, green bonds, and sustainability-linked financing—remains a critical pathway for promoting low-carbon economic transformation. Policymakers should therefore continue improving the institutional framework of GF, particularly by enhancing information disclosure standards and strengthening risk-sharing mechanisms, to ensure that financial resources are effectively directed toward low-carbon activities.

Second, the positive moderating role of GTI suggests that the effectiveness of GF is highly contingent on regional innovation capacity. This implies that GF policies should be coordinated with innovation-oriented strategies, including support for green R&D, intellectual property protection, and technology diffusion platforms. Strengthening the linkage between financial capital and green technological progress can significantly amplify the contribution of GF to LCE.

Third, the negative moderating effect of GII highlights the potential crowding-out or distortion effects associated with excessive government intervention. While government involvement is essential for correcting market failures and guiding green transitions, overly direct or rigid intervention may weaken market incentives embedded in GF. This finding underscores the need for a balanced governance framework in which the government acts primarily as a rule-setter and facilitator rather than a direct allocator of financial resources.

Finally, the observed regional and population-scale heterogeneity implies that green finance policies should be tailored to local conditions. Regions with weaker economic foundations or smaller population sizes may require complementary policies—such as capacity building and institutional support—to fully leverage the benefits of GF for LCE.

Future policy design should prioritize strengthening the coordination between GF and GTI by fostering innovation-friendly financial instruments that explicitly support green patent commercialization. At the same time, governments should recalibrate GII toward a facilitative and regulatory role, minimizing direct intervention that may distort market signals. Further research may extend this framework by incorporating firm-level data or dynamic spatial interactions to better capture cross-regional spillover effects of GF on LCE.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

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Not applicable.

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