RESEARCH ARTICLE

The impact of local government competition and green technology innovation on economic low-carbon transition: new insights from China

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Abstract

The government-led Chinese economic development system determines that local government competition is a significant factor affecting the economic low-carbon transition. Driving an economic development mode with green technology innovation as the core is the critical path to realizing an economic low-carbon transition. Consequently, it is of significant practical relevance to investigate the impact of local government competition and green technology innovation on the economic low-carbon transition under the government-led Chinese economic development system. This paper systematically explores the nexus between green technology innovation and economic low-carbon transition in terms of local government competition perspective using the system generalized method of moments, panel threshold model, and geographically weighted regression on the basis of a dataset of 30 provincial administrative areas in China from a period of 2006–2019. The results indicate that green technology innovation significantly promotes the economic low-carbon transition. Local government competition not only significantly dampens the economic low-carbon transition but also considerably inhibits the positive effect of green technology innovation on the economic low-carbon transition. A significant N-shaped association is evident between green technology innovation and the economic low-carbon transition when green technology innovation is applied as a threshold, while such association is insignificant when local government competition is used as a threshold. Compared with high-competition intensity areas, green technology innovation promotes economic low-carbon transition weaker in low- competition intensity areas, while local government competition inhibits economic low-carbon transition stronger. However, local government competition significantly inhibits the positive effect of green technology innovation on the economic low-carbon transition in low-competition intensity areas, while insignificant in high-competition intensity areas. The geographically weighted regression technique as a whole also verified the above results. Therefore, policymakers should not only increase research and development investment in green technologies, but also develop a regionally linked low-carbon emission reduction system to avoid ineffective competition among governments to facilitate the earlier fulfillment of the "dual carbon" goal.

Keywords Economic low-carbon transition · Green technology innovation · Local government competition · High-quality development

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Introduction

As the world economy recovers from COVID-19, carbon emissions linked to energy are rebounding rapidly (Shah et al. 2022; Ray et al. 2022; Razzaq et al. 2020). It is estimated that China will contribute over 11.9 billion tons of carbon emissions in 2021, which is 33% of the global total, according to the latest analysis by the International Energy Agency (IEA).[1] Meanwhile, National Bureau of Statistics data reveal that Chinese raw coal production volume reached 4.13 billion tons in 2021, up 55.7% year-on-year, and coal consumption increased by 4.6%.[2] The disorderly expansion of China's economic development has destroyed enormous amounts of natural resources and exacerbated ecological degradation, posing a great threat to environmental protection and sustainable economic development (Zahoor et al. 2022; Xu et al. 2022; Jia et al. 2022). China explicitly introduced the goals of "carbon peak" by 2030 and "carbon neutral" by 2060 at the 75th session of the United Nations General Assembly in September 2020 (Shi and Xu 2022; Xin et al. 2022; Zhao et al. 2022). Subsequently, in October 2021, the Chinese government promulgated the "Opinions on Complete and Accurate Implementation of the New Development Concept to Do a Good Job of Carbon Peaking and Carbon Neutral Work"; since then, the low-carbon transition and high-quality development of the economy under the double carbon goal has gradually emerged as a consensus society (Chen et al. 2022a, b).

Simultaneously, green technology innovation plays an increasingly vital role in economic low-carbon transition as an essential driver of low-carbon economic transition (Razzaq et al. 2022; Hao et al. 2022). Green technology is a universal designation for all processes and technologies that can minimize energy and resource consumption and reduce environmental pollution (Gao et al. 2022; Cao et al. 2021). Compared with general technological innovation, green technology innovation emphasizes resource conservation and environmental protection, which can effectively strengthen resource and energy utilization efficiency (Wicki and Hansen, 2019). Also, green technology innovation is widely applied in enterprises, and micro-individuals will boost enterprises' clean production and drive residents' green consumption to realize an economic low-carbon transition from the production and consumption sides (Liao and Li 2022). Moreover, green technology innovation in the energy sector is beneficial to the extrusion induced by the consumption of traditional energy sources, reducing the cost

of green energy usage and transitioning the energy consumption structure to low-carbon and clean energy (Dong et al. 2022). Thus, exploring economic low-carbon development powered by green technology innovation has been an essential path for the Chinese economic low-carbon transition.

As for the green technology innovation level enhancement and innovation capacity intensification, local governments' support is indispensable. The Chinese government, as the leader of regional economic and social development, can allocate factors and guide industrial transition through various ways such as policy formulation, tax relief, and financial support, and its competitive behavior and intensity will influence local green technology innovation development, which in turn will have appropriate effects on economic low-carbon transition (Feng et al. 2022; Sovacool 2021). On the one hand, under the context of economic performance as the key political incentive, local officials may, to maximize jurisdictional interests, distort the fiscal expenditure structure and increase investment in projects that can stimulate economic growth in the short term (Wang et al. 2022; Yan et al. 2022). Meanwhile, policy incentives related to green technology innovation with high risks and long payoff cycles are lessened, resulting in a lack of motivation for green technology innovation in research and development, universities, and enterprises (Shang et al. 2022). On the other hand, local governments are competing for green technology innovations that can yield environmental benefits as political incentives gradually shift to eco-efficiency. Research and development activities associated with green technology innovation are also gradually gaining attention from local governments, which are strengthening their innovation-driven development strategies to enhance green technology innovation performance (Chen et al. 2022a, b).

As the Chinese government is an influential practitioner and participant in global ecological civilization, it is economical, and social low-carbon development efforts have already formed an increasingly significant part of the global climate governance system. Thus, it is of practical meaning to consider the impact of green technology innovation on the economic low-carbon transition. So, what is the potential effect of green technology innovation on the economic low-carbon transition? Considering that the natural characteristics and socio-development differ significantly from one area to another in China, and the economic base and the development level also differ, what is the role of green technology innovation in the process of economic low-carbon transition in different areas? What is the role of local government competition in the economic low-carbon transition through intensified competition in the market economy? Under the current innovation-driven development strategy, answering the above questions can be used as an empirical reference

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[1] See more detail: https://www.iea.org/reports/global-energy-review-2021?language=zh

[2] http://www.stats.gov.cn

for China to address the energy and environmental constraints and fulfill the "double carbon" goal, while simultaneously contributing to the development of low-carbon transition in economies similar to China. As such, this paper systematically explores the nexus between green technology innovation and economic low-carbon transition in terms of local government competition perspective using the system generalized method of moments (SYS-GMM), panel threshold model, and geographically weighted regression on the basis of a dataset of 30 provincial administrative areas in China from a period of 2006–2019.

This paper mainly broadens the scope of existing research with regard to the following dimensions. First, unlike previous studies, this paper incorporates local government competition, green technology innovation, and economic low-carbon transition into one integrated analytical framework to investigate the association among the three, to generate empirical evidence for a low-carbon transition in China. Second, the influence of green technology innovation on economic low-carbon transition under local government competition in different areas is evaluated in the light of regional heterogeneity to identify a more target-oriented and appropriate path for low-carbon governance. Thirdly, using SYS-GMM, panel threshold model, and geographically weighted regression to quantitatively evaluate the three associations, which serve as valuable guidelines for adjusting local government competition and rationally utilizing green technology innovation to boost low-carbon economic transition.

The remainder of the article is organized as follows: the second section is the "Literature review," which aims to review the current research findings on local government competition, green technology innovation, and economic low-carbon transition, drawing on the lessons learned from previous research and identifying the shortcomings of previous studies. The third section is "Theoretical analysis and research hypothesis," which introduces this paper's mechanism and research ideas. The fourth section is a description of the methodology and data. The fifth section furnishes the study's results and a detailed discussion of the results. The final section concludes with recommendations and identifies the limitations and deficiencies of the paper.

Literature review

Local government competition, green technology innovation, and economic low-carbon transition are popular issues discussed by scholars. However, there are short

works to classify the three in a common framework. This paper is devoted to sorting out the available studies on green technology innovation and economic low-carbon transition and local government competition, and economic low-carbon transition to establish a research basis for further analysis.

Research on green technology innovation and economic low-carbon transition

Technological progress is the root of energy saving and emission control, while green technological innovation is crucial to economic low-carbon transition (Ikram 2022; Sun et al. 2021). As early as the late nineteenth century, scholars from the neoclassical school of economics had already identified the significant role of production technology on economic growth. Along with economic development, technological progress is emerging as a core driver of stable economic growth and the optimal way to guide changes in economic growth patterns (Xie et al. 2021; Sadik-Zada 2021). Hasanov et al. (2021), for example, reveal that technological progress facilitates carbon mitigation while GDP growth aggravates carbon emissions. The literature on green technology innovation and economic low-carbon transition is categorized into the following fields.

First, a definition is given to the green technology concept. The formal concept of green technology is derived from Braun and Wield's (1994) definition, which considers green technology as a general term for processes and technologies that can minimize adverse environmental effects by saving resources, reducing pollution and carbon emissions, resulting in a natural link between green technology innovation and low-carbon development (Nazir, 2021). Later, scholars such as Rennings and Zwick (2002) incorporated sustainable development into their definition of green technology innovation and diversified its connotation. As green development evolves, scholars have classified green technologies in terms of cleaner production, pollution control, and environmental protection (Arslan et al. 2022; Demirel and Kesidou 2011; Varbanov et al. 2021), broadened their connotation and scope of application, and developed them to micro-enterprise level research, arguing that enterprises are subject to green technological innovation development and are the starting point for technology diffusion (Lu et al. 2022). Second, research on green technology innovation assessment. Measuring green technology innovation is mainly divided into surveying its level and dynamic mechanism, and scholars usually quantify its level using technology input (Costa-Campi et al. 2017) or patent grants (Cai et al. 2020) and utilize approaches such as structural equations to survey the dynamic mechanism affecting its change.

Ikram et al. (2021) evaluate green technology indicators in several dimensions and identify energy utilization, recycling, and ecological agriculture as critical factors influencing green technology.

Finally, exploring the association between green technological innovation and low-carbon transition. The promotion of technological innovation in economic low-carbon transition has been more widely proven by scholars (Dong et al. 2022; Sovacool et al. 2022). Li et al. (2019) suggest that technological progress can effectively boost industrial sectors' green development and economic low-carbon transition. Scholars such as Ghisetti and Quatraro (2017) also point out that technological innovation significantly contributes to the green economy and low-carbon development. Pradhan and Ghosh (2022) argue that endogenous technological innovations in new energy sources facilitate low-carbon goals, while green innovations represented by carbon capture and storage technologies contribute to carbon abatement at a lower economic cost. Moreover, Shan et al. (2021) reveal that green technology innovation reduces carbon emissions. However, some scholars hold different opinions. They believe that the precise impacts of green technology innovations on carbon productivity are still unknown. For example, Eikeland and Skjærseth (2021) argue that corporate technological innovation does not significantly impact green, low-carbon development. It can be noted that, in general, scholars believe that green technological innovation can facilitate economic low-carbon transition by enhancing resource and energy utilization. However, many current studies only substitute technological innovation for green technological innovation for research, resulting in poor representation of green features in green technological innovation.

Research on local government competition and economic low-carbon transition

Local government competition is defined as the cross-regional competition among local governments in economic, environmental, and social services to attract labor, capital, and other production factors (Zavadskaya and Shilov 2021; Zhang et al. 2021). Local governments in China are the tangible implementers of the central government's environmental governance policies (Beck 2022). Local governments are influenced both politically and economically by the central government. Political centralization forces local governments to preserve the environment during economic development (Liu et al. 2022b), while economic decentralization empowers local governments with a certain degree of autonomy that can trigger competition among local governments by biasing them toward

economic development (Wu et al. 2020a). However, as the central government pays more attention to environmental protection, environmental performance will bring new incentives to reduce the competitive strength of local governments for economic growth (Yang et al. 2020).

The idea of government competition can be traced back to Adam Smith's "Wealth of Nations," in which government competition is given in terms of the effect of tax differentials between governments on factor flows (Aschenbrenner, 2021). Later, Tiebout (1956) introduces the concept of "voting by feet," in which local governments adjust government tax rates to induce factor inflows and enhance the well-being of regional residents. Subsequently, Owens (2022) also examines the impact of local government competition on regional services from fiscal and taxation perspectives. As can be observed, early competition research on government has mainly emphasized fiscal and social welfare aspects (Murshed et al., 2022). Breton and Breton (1997), who first presented the concept of "government competition" as a whole, argued that governments compete for resources, control, and public services. Omodero (2022) identifies that fiscal decentralization positively reflects on residents' social welfare. After entering the twenty-first century, the concepts of green, low-carbon, and sustainable development have been deeply rooted, and the concept of government competition has been gradually introduced into the research on the local environment and ecological protection (Gan et al. 2021; Li 2022). On the whole, research on local government competition and economic low-carbon transition is categorized into two main aspects: the promotion theory and the inhibition theory. Nie et al. (2022), for example, finds that local government competition on the environment has a positive impact on green innovation, and there is a significant spatial spillover effect. Moreover, some scholars hold different views, such as Liu et al. (2022b) and Yang et al. (2022a). The latter argue that the GDP-oriented view of performance and official promotion tournaments make local governments actively reduce environmental protection, exacerbate the existence of regional market segmentation of "beggar-thy-neighbor," worsen the competitive relationship between local governments, and crowd out the cost of technological innovation, and weaken the ability of local economies to make a low-carbon transition. Deng et al. (2019) confirm that the inverted U-shaped relationship between political competition and enterprises' optimal level of green technology innovation is related to the incentive coefficient of local government investment behavior set by the central government.
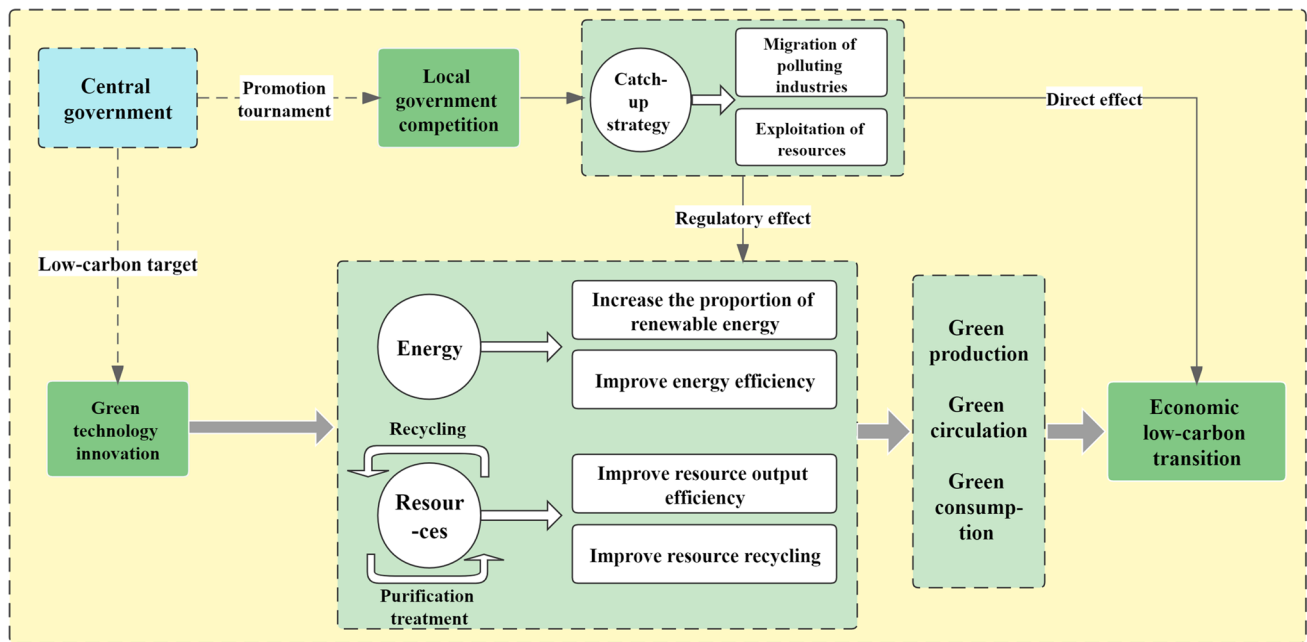
Fig. 1 Mechanism analysis diagram

Reviewing the literature on local government competition and economic low-carbon transition shows that more scholars have focused on the impact of local government competition on green development. At the same time, there are still relatively few systematic studies on local government competition and economic low-carbon transition. Although numerous scholars have conducted normative and empirical studies on local government competition, technological innovation, and low carbon, there are still some limitations. For example, few scholars have included these themes within a unified research framework, and there are earlier definitions and evaluation methods on green technology innovation that are not precise. Based on this, this paper redefines the level of green technology innovation and low-carbon economic transition. It examines the relationship between local government competition, green technology innovation, and economic low-carbon transition by integrating them into a unified analytical framework through both normative and empirical aspects.

Mechanistic analysis and research hypothesis

Low-carbon development is the essence of improving the efficiency of energy and resource utilization, and green technology innovation capability is undoubtedly the most effective way to increase energy utilization efficiency and tackle resource shortage (Dong et al. 2022).

From the energy utilization scenario, green technology innovation can drive extensive use of green renewable energy and enhance the development and application of clean energy (Razzaq et al. 2021; Xin et al. 2022). Meanwhile, it will also impel to reduce the proportion of fossil energy in energy consumption, boost the adjustment and optimization of regional energy structure, and curb the pollution caused to ecology and environment during energy production and utilization. Moreover, the advancement of green technology innovation may boost the development of production processes and applications, and improve traditional energy utilization efficiency (Gao et al. 2022). Considering resource utilization, the development of green technology innovation advances the areas to reshape the regional production model through high technology to strengthen the output rate of resources and recycling rate (Hasanov et al., 2021). Furthermore, this will also form a development system of green production, green distribution, and green consumption, which will in turn influence the change of residents' lifestyles and values, and ultimately promote the low-carbon transition of the regional economy (see Fig. 1). Based on this, the following hypotheses are put forward:

H1: green technology innovation plays a significant role in promoting economic low-carbon transition.

The Chinese decentralization model has the characteristics of the principal-agent relationship, which leads

to the information asymmetry between the central and local governments (Yang et al. 2022a; Zhao et al. 2021). Therefore, the superior government often selects some explicit indicators to assess the lower-level government officials. The relatively easy to judge economic development has become the main basis for assessing the lower-level officials (Hao et al. 2021). Under this decentralized mode, local governments, as the "agent" of economic development, have economic development autonomy, and form "benchmarking competition" under the incentive of economic performance assessment and promotion mechanism (Zhang et al. 2021; Yang et al. 2022c). The effect of local government competition on the economic low-carbon transition can be subject to shocks at different levels of economic development and geographic locations. (Wu et al. 2020a). Economic development level in eastern China is relatively high, and local governments have a stronger preference for economic development, and its competition intensity is also particularly strong. Under high competition intensity, pursuing economic development speed and actively carrying out productive investment has become the primary goal of local governments. The "promotion tournament" centered on economic growth will lead to local governments reducing environmental regulation intensity for economic development, tolerating and even supporting highly polluting enterprises development, and creating a situation of predatory development of resources, which is not conducive to the low-carbon transformation of local economies (Liu et al. 2022a; Ju and Ke 2022). However, the central and western areas of China are rich in resources, and the ecological environment is often fragile, and its competition intensity is also relatively weak (Gan et al., 2021). The central government has higher requirements for the local ecological environment. According to the foot voting theory, when regions have a higher preference for the environment, the government will set stricter environmental standards to reduce carbon emissions in the production process (Li 2022). At this time, the inhibition of local government competition on low-carbon transformation is not as obvious as that in the eastern region.

H2: Affected by competition intensity, and the impact of local government competition on economic low-carbon transition are characterized by heterogeneity.

As further economic development and environmental pressure accumulate, economic and social low-carbon transition is inevitable. The central government also requires localities to take the path of ecological priority and green development, and support green technology innovation to achieve the dual carbon goal (Feng et al.

2022). However, green technology innovation can be profoundly influenced by local government competition. Under the way of economic growth as the primary assessment, GDP index is the core basis for officials' assessment and promotion (Wu et al. 2020a). Pursuing the speed of economic growth, favoring short-term achievements in regional development, and accelerating the catching up and surpassing of neighboring and even national benchmark regions have become the rational choice of regional government officials (Liu et al. 2022b). As a result, once local governments invest more financial resources in the development of stimulating economic growth in their jurisdictions through fiscal and tax incentives, they will compress their investment in green technology and technological innovation (Deng et al. 2022). In addition, there may be a race among governments to lower environmental regulation standards to attract investment in high energy-consuming industries (Jia et al., 2022). They may even conspire with highly polluting local enterprises to sacrifice ecological quality in exchange for high economic growth. For the increasingly tightened central environmental policies, they are implemented through tokenism, which ultimately inhibits the contribution of green technological innovation toward economic low-carbon transition. Based on the above analysis, the following hypothesis is proposed. The specific mechanistic analysis can be seen in Fig. 1.

H3: Local government competition will inhibit the contribution of green technology innovation to economic low-carbon transition.

Material and methods

Economics strategies

Generalized method of moments (GMM) has its advantage in tackling individual effects, autocorrelation, heteroskedasticity, and endogeneity problems of panel data, which can enable more sophisticated estimation of parameters (Arellano and Bond 1991). And the system GMM model has been more extensively used as compared to the differential GMM model which can solve the weak instrumental variables. This paper bridges local government competition, green technology innovation, and economic low-carbon transition to investigate the impact of green technology innovation on economic low-carbon transition with local government competition. In addition, the dependent variable in the current period may be confounded by the dependent variable in the previous period. Referring to Wu et al. (2021), this paper opts to introduce the lag term of the economic low-carbon

transition and conducts the analysis using SYS-GMM. The specific model settings are as follows:

$$LTC_{it} = a_0 + a_1 LTC_{it-1} + a_2 lnGTECH_{it} + \beta_i X_{it} + \varepsilon_{it} \tag{1}$$

Next, in order to identify the impact of the interaction between local government competition and green technology innovation on economic low-carbon transition, the interaction term of the two is added to Eq. (1). The specific model is set as follows.

$$LTC_{it} = a_0 + a_1 LTC_{it-1} + a_2 GTECH_{it} + a_3 Comp_{it} + a_4 Inter_{it} + \beta_i X_{it} + \varepsilon_{it} \tag{2}$$

where i and t are province and time, respectively. LTC is the dependent variable, i.e., economic low-carbon transition. LTC_{it-1} represents the lagged term of economic low-carbon transition. $GTECH$ is green technology innovation, and $Comp$ is local government competition. $Inter$ is the interaction term of green technology innovation and local government competition with decentralization, and X is the control variable.

Considering that green technology innovation at various levels will exert a heterogeneous impact on economic low-carbon transition, thus green technology innovation is taken as a threshold variable to investigate the specific impact of green technology innovation at various levels on economic low-carbon transition. Taking the single-threshold model as an example, the specific setting form is as follows.

$$\begin{aligned} LTC_{it} = {} & a_0 + a_1 LTC_{it-1} \\ & + a_2 lnGTECH_{it} \cdot I\left(lnGTECH_{it} \leq \gamma\right) \\ & + a_3 lnGTECH_{it} \cdot I\left(lnGTECH_{it} > \gamma\right) \\ & + \beta_i X_{it} + \lambda_i + \varepsilon_{it} \end{aligned} \tag{3}$$

Moreover, green technology innovation may likewise influence economic low-carbon transition in a nonlinear manner under the changing role of local government competition. To verify the above effects, the model is constructed by using local government competition as a threshold variable as follows.

$$\begin{aligned} LTC_{it} = {} & a_0 + a_1 LTC_{it-1} + a_2 lnGTECH_{it} \cdot I(Comp \leq \gamma) \\ & + a_3 lnGTECH_{it} \cdot I(Comp > \gamma) + \beta_i X_{it} + \lambda_i + \varepsilon_{it} \end{aligned} \tag{4}$$

where $I(\cdot)$ is the indicator function. In parentheses, $GTECH$ and $comp$ are the threshold variables. γ is the unknown threshold value. The model is actually equivalent to a segmented function model. When the $thresholdvariable \leq \gamma$, the coefficient of the explanatory variable is a_2, while when the $thresholdvariable > \gamma$, the coefficient of the explanatory variable is a_3.

Besides, the classical econometric model only averages or globally estimates the regression coefficients, which is difficult to reflect the heterogeneity of each coefficient in different spatial areas, thus making it difficult to explore the useful local characteristics among variables (Su et al. 2021; Liu et al. 2021; Cao et al. 2022). To further explore the impact of green technology innovation and local government competition on economic low-carbon transition, this paper takes spatial factors into account to analyze the spatial heterogeneity of the object to be studied. Since the traditional geographically weighted regression model may yield insufficient estimation power of the model parameters, referring to Yang et al. (2022b), a temporal dimension is introduced to construct a geographically and temporally weighted regression (GTWR) to make the estimation results more effective. The GTWR takes into account the heterogeneity of explanatory variables across spatial geographic locations. The model is set up as follows.

$$\begin{aligned} LTC_i = {} & \beta_0(u_i, v_i, t_i) \\ & + \sum_{k=1}^{p} \beta_k(u_i, v_i, t_i) lnGTECH_{ik} \\ & + \sum_{k=1}^{p} \beta_k(u_i, v_i, t_i) COMP_{ik} \\ & + \sum_{k=1}^{p} \beta_k(u_i, v_i, t_i) inter_{ik} \\ & + \sum_{k=1}^{p} \beta_k(u_i, v_i, t_i) x_{ik} + \varepsilon_i \end{aligned} \tag{5}$$

The temporal distance d_{ij}^{ST} is

$$d_{ij}^{ST} = \sqrt{a[(u_i - u_j)^2 + (v_i - v_j)2] + \beta(t_i - t_j)^2} \tag{6}$$

The temporal weighting function takes the following form.

$$w_{ij}^{ST} = exp\left\{ -\left(\frac{a[(u_i - u_j)^2 + (v_i - v_j)2] + \beta(t_i - t_j)^2}{b_{ST}^2} \right) \right\} \tag{7}$$

where (u_i, v_i, t_i) is the latitude, longitude, and time of 30 provincial administrative regions in China, b_{ST} is the bandwidth of the spatio-temporal function, and the optimal bandwidth is verified by crossover.

Variable descriptions

Dependent variable

Economic low-carbon transition (LTC). The economic low-carbon transition is a comprehensive system involving many aspects of economic and social development (Yang et al. 2022b; Liu et al. 2022c). Based on the study of the characteristics of low-carbon economic development, with reference to the 2009 CO_2 report of the International Energy Agency and the current research on economic low-carbon transition,

Table 1 Economic low-carbon transition indicator system

	Indicator type	Definition	Name	Direction
Economic low-carbon transition indicator system	Energy consumption and emission subsystem	Energy consumption per unit of GDP (tons of standard coal/yuan)	×1	-
		The proportion of coal in energy consumption (%)	×2	-
		Carbon emissions per unit of GDP (tons/100 million yuan)	×3	-
	Ecological environment subsystem	SO_2 emissions per unit of GDP (tons/100 million yuan)	×4	-
		Forest coverage rate (%)	×5	+
		Greening coverage rate of built-up areas (%)	×6	+
		Per capita park green space (m^2/person)	×7	+
		Number of national-level nature reserves (pcs)	×8	+
	Economic construction subsystem	GDP per capita (yuan)	×9	+
		Domestic GDP growth rate (%)	×10	+
		Tertiary industry share (%)	×11	+
		Per capita disposable income of urban residents (yuan)	×12	+
	Technology support subsystem	R&D personnel full time equivalent (10,000 person-years)	×13	+
		R&D expenditure investment intensity (%)	×14	+
		Harmless disposal rate of domestic waste (%)	×15	+
		Energy processing conversion efficiency (%)	×16	+
	Social development subsystem	Urbanization rate (%)	×17	+
		Engel coefficient (%)	×18	+
		Bus vehicles per 10,000 people (standard units)	×19	+
		Urban registered unemployment rate (%)	×20	+

this paper constructs the index system of low-carbon transition from five dimensions: energy consumption and emission subsystem, ecological environment subsystem, economic construction subsystem, technology support subsystem, and social development subsystem, respectively (see Table 1).

According to the index system of economic low-carbon transition, this paper adopts the entropy value method to determine the degree of China's economic low-carbon transition from 2006 to 2019 in each area. The entropy value method is an objective weighting method, which can effectively avoid the bias caused by manual factors. The entropy value method is an objective weighting method, which can effectively avoid the bias caused by manual factors. Firstly, the indicators are standardized, and then the weights are obtained for each indicator, and finally the economic low-carbon transition index

of each area is summed up. The specific calculation method is as follows:

First, the indicators were divided into positive and negative indicators based on attributes and standardized separately.

$$a_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad a_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{8}$$

where, a_{ij} is the standardized data of indicator j in area i. xij is the true value of the indicator. The maximum $max(xij)$ and the minimum $min(xij)$ of the indicator are then calculated. The calculated values are also panned by 1 unit to ensure that the results are greater than 0.

Second, the weights (P_{ij}) and entropy values (E_{ij}) associated with indicator j in area i are calculated in the following form.

$$P_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} x_{ij}} E_{ij} = -K \sum_{i=1}^{n} \left(P_{ij} \times lnP_{ij} \right) \tag{9}$$

Third, the redundancy (D_{ij}) and indicator weights (W_{ij}) of indicator j are calculated. The form is as follows.

$$D_{ij} = 1 - E_{ij} \quad W_{ij} = \frac{D_{ij}}{\sum_{j=1}^{m} D_{ij}} \tag{10}$$

Finally, the economic low-carbon transition index is calculated for each area for all years.

$$LTC_{EI} = \sum_{p=1}^{n} a_{ij} \times w_{ij} \tag{11}$$

Core explanatory variables

Green technology innovation (*GTECH*). How to measure green technology innovation (*GTECH*) is the key point. At present, scholars mainly use the number of green patents to measure green technology innovation, including the number of patent applications and the number of patents granted. Compared with the number of patents granted, the number of patent applications focuses more on the importance of green technology at the local level, which can hardly reflect the level of green technology development at the local. Thus, this paper filters the number of green patents granted in the period from 2006 to 2019 by sub-area based on the International Patent Classification (IPC) codes for green patents issued by the World Intellectual Property Office (WIPO) and based on the patent application information provided by the State Intellectual Property Office as a proxy variable for green technology innovation.

Moderate variables

Local government competition (*COMP*). Local government competition is a multi-dimensional and comprehensive competition, covering economic competition, ecological competition, and service competition, etc. This paper mainly considers the competition among local governments in the economic aspect. The economic competition among local governments is mainly reflected in the competition and catching up among areas' economic development, and thus local government competition is influenced by the economic development of neighboring areas. Meanwhile, the areas with the highest economic development level in the nation also bring a strong demonstration effect on the economic development of the area. Therefore, this paper defines local government competition measured under two dimensions of economic levels considering both adjacent and national dimensions. The specific measurement is shown in Eq. (12).

$$COMP = \frac{MGDP}{PGDP} \times \frac{NGDP}{PGDP} \tag{12}$$

where *MGDP* is the highest *GDP* per capita in adjacent areas other than the area. PGDP is the *GDP* per capita of the area. *NGDP* is the highest *GDP* per capita of any area in the nation.

Control variables

For robustness considerations, following Ren et al. (2021), Irfan et al. (2022), and Li et al. (2021), this paper incorporates other factors that influence economic low-carbon transition, including fixed assets per capita (*Fa*), human capital (*Hum*), urban population density (*Ur*), openness (*Op*), and environmental regulation (*Er*). Fixed assets per capita (*Fa*). Fixed assets per capita (*Fa*) are estimated using the perpetual inventory method. The specific calculation method is as follows:

$$Fa_{it} = I_{it}/P_{it} + (1 - \delta)Fa_{it-1} \tag{13}$$

Among them, Fa_{it} refers to the capital stock of region i in year t, I_{it} refers to the nominal fixed asset investment amount of the region in the current year, Fa_{it-1} is the fixed asset investment price index. Fa_{it-1} refers to the capital stock of the previous year; δ is the capital depreciation rate. With reference to Ren et al. (2022), the capital depreciation rate is set at 9.6%.

Human capital (*Hum*). Per capita years of schooling serves as an indicator of human capital (*Hum*). It is specifically calculated as.

$$\begin{aligned} Hum = (primary \times 6 + junior \times 9 \\ + senior \times 12 + college \times 16)/Population\ aged\ over\ 6\ year \end{aligned} \tag{14}$$

Among them, *Hum* is the level of human capital, *primary* is the number of primary school graduates, *junior* is the number of junior high school graduates, *senior* is the number of senior high school graduates, and *college* is the number of college graduates.

In addition, the number of college students per 10,000 population to represent the stock of human capital is used as a proxy variable to perform robustness analysis of the model. (3) Urban population density (*Ur*) is characterized by the ratio of urban population to total population. (4) Openness (*Op*). Openness (*Op*) is measured as the share of total external trade in GDP of each area. (5) Environmental regulation (*Er*). The existing literature on government environmental regulation has a large number of indicators, referring to the currently more accepted methods; the final measure of environmental regulation (*Er*) is the amount of investment in industrial pollution control as a share of GDP.

Table 2 Variable definitions

Variables	Variable	Obs	Mean	Std. dev	Min	Max
Dependent variable	LCT	420	0.376	0.096	0.170	0.667
Core explanatory variables	GTECH	420	2187	3634	4.000	28,490
Moderate variables	COMP	420	4.487	3.340	0.550	21.558
Control variables	Fa	420	3.101	1.783	0.320	8.250
	Ed	420	0.119	0.072	0.030	0.500
	Ur	420	0.046	0.067	0.001	0.385
	Op	420	0.300	0.359	0.010	1.740
	Er	420	0.143	0.129	0.002	0.986

Fig. 2 Economic low-carbon transition levels by area
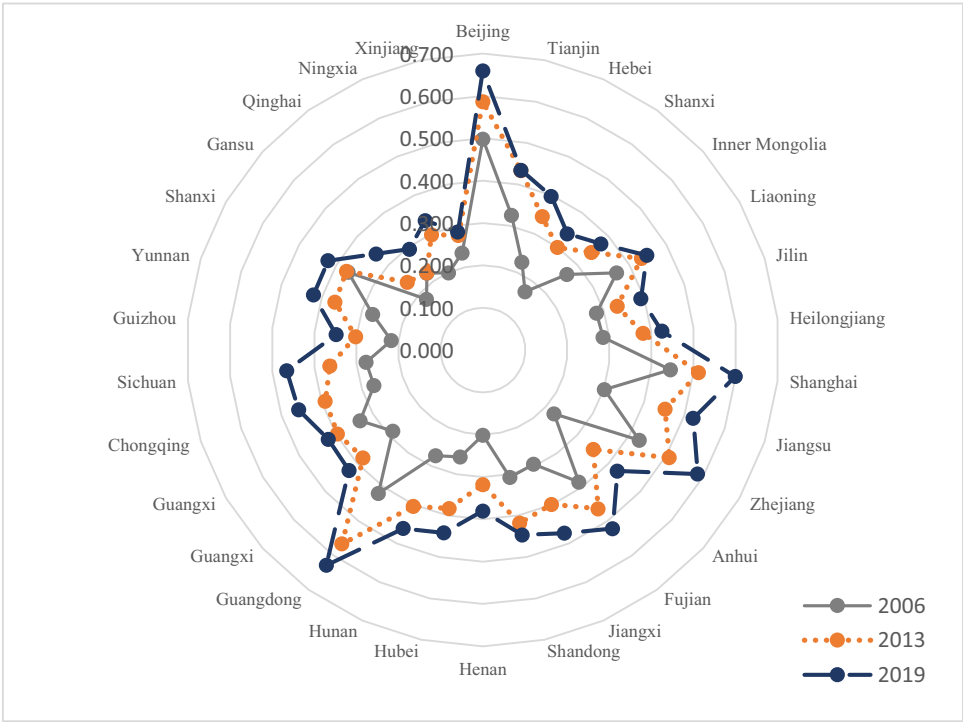
Data sources

This paper explores the impact of local government competition and green technology innovation on economic low-carbon transition in 30 provincial administrative areas across China during the period from 2006 to 2019. The various data were primarily derived from the China Statistical Yearbook, China Environmental Statistical Yearbook, China Environmental Yearbook, and EPS database.[3] Some of the missing data were filled in by interpolation method. Moreover, in order to eliminate the interference of heteroskedasticity and the problem of dimensionality, some data were logarithmized. The main variables are defined as shown in Table 2.

Results

Green technology innovation and economic low-carbon transition

Using the dataset of 30 provincial-level administrative areas in China from 2006 to 2019, the green technology innovation level and low-carbon economic transition status of each area were measured, and the years 2006, 2013, and 2019 are selected for visualization and presentation (see Figs. 2 and 3). Figure 2 reflects the level of economic low-carbon transition for each region in 2006, 2013, and 2019. This paper reveals that the average value of the economic low-carbon transition level of each area increased from 0.294 in 2006 to 0.439 in 2019, which indicates that the overall economic low-carbon transition

Fig. 3 Green technology innovation levels by area
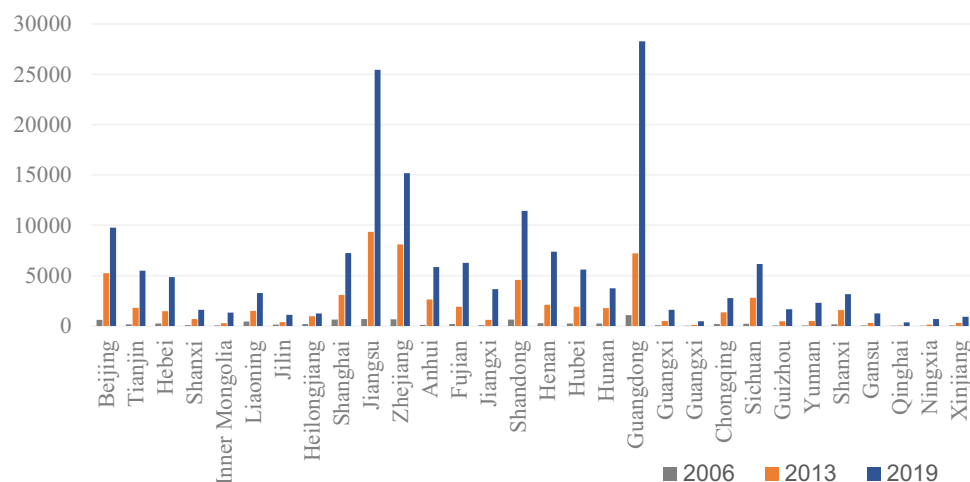
Table 3 Values of variance inflation factors for the major variables

	GTECH	COMP	Fa	Ed	Ur	Op	Er
VIF	2.34	1.78	1.96	2.75	2.19	3.91	1.29
1/VIF	0.43	0.561	0.510	0.364	0.457	0.255	0.776

level of Chinese society is increasing. In addition, the change trend of economic low-carbon transition is more consistent across regions, but the gap in the level of economic low-carbon transition between areas is widening. In 2006, the standard deviation and extreme deviation of the level of economic low-carbon transition among Chinese regions were 0.082 and 0.328, respectively, and in 2019, they expanded to 0.092 and 0.374, respectively. By areas, the level of economic low-carbon transition in eastern regions is higher, such as Beijing, Guangdong Province, Shanghai, and Zhejiang Province, while the central and western regions have lower levels of economic low-carbon transition, such as Gansu, Ningxia, and Qinghai and Xinjiang provinces, and fail to achieve coordinated development of economic low-carbon transition among areas.

Figure 3 reflects the green technology innovation level of each area in 2006, 2013, and 2019. This paper confirms that, as a whole, the green technology innovation level is improving, and the green technology innovation capacity of each area is increasing. Moreover, it is observed by areas that the green technology innovation level varies widely among areas, and the gap is rapidly increasing. More meticulously, the green technology innovation level in the eastern area is higher than that in the central and western areas, among which the green technology innovation level in the northwest and northeast is lower and the green technology innovation level is improved at a slower pace.

Overall, from 2006 to 2019, economic low-carbon transition and green technology innovation in all areas of China showed an upward trend. However, the differences in the level of economic low-carbon transition and green technology innovation between areas are obvious, and the high level areas of low-carbon economy and green innovation are concentrated in the eastern coast. Secondly, the speed of economic low-carbon transition and technological innovation level improvement varies greatly among different areas, with the improvement in the eastern area much higher than that in the central and western areas, and the gap between regions has a tendency to keep expanding. Based on the visual observations in Figs. 2 and 3, this paper will further analyze the impact of green technology innovation on economic low-carbon transition in Chinese provinces through an empirical model that incorporates the consideration of local government competition factors.

Correlation analysis result

Because of the limitations of the economic data and empirical design, the problem of cointegration is easily produced by the existence of certain correlations among the explanatory variables in the model. Thus, before conducting the model regression, the correlation test is first performed for each of the primary variables. Table 3 confirms that the variance inflation factor values for all variables lie in the range of 1.29 to 3.91, which is considerably less than 10, indicating that the multicollinearity issue among the variables is within a manageable range.

Table 4 Baseline regression results

Variable	OLS			SYS-GMM		
	(1)	(2)	(3)	(4)	(5)	(6)
L.LTC				0.961***	0.989***	0.953***
				(0.018)	(0.017)	(0.021)
GTECH	0.028***		0.026***	0.003***		0.003***
	(0.002)		(0.002)	(0.001)		(0.001)
COMP		−0.004***	−0.007***		0.001	−0.001
		(0.001)	(0.001)		(0.001)	(0.001)
INTER			−0.002***			−0.001**
			(0.000)			(0.001)
Fa	0.008***	0.016***	0.005***	−0.001	0.001	−0.001
	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)
Ed	−0.015	−0.283***	−0.079	0.003	−0.015	0.003
	(0.051)	(0.057)	(0.050)	(0.021)	(0.023)	(0.019)
Ur	−0.015	0.109*	−0.011	0.010	0.017*	0.005
	(0.050)	(0.058)	(0.048)	(0.013)	(0.009)	(0.013)
Op	0.115***	0.161***	0.091***	−0.001	0.003	−0.000
	(0.012)	(0.014)	(0.012)	(0.006)	(0.006)	(0.006)
Er	−0.143***	−0.207***	−0.148***	−0.005	−0.008*	−0.008
	(0.020)	(0.022)	(0.019)	(0.005)	(0.004)	(0.006)
_Cons	0.155***	0.355***	0.220***	−0.004	0.004	0.002
	(0.015)	(0.013)	(0.018)	(0.007)	(0.010)	(0.010)
N	420	420	420	390	390	390
R-squared	0.768	0.688	0.790			
AR(2)-P				0.335	0.341	0.333
Sargan-P				0.315	0.285	0.312

Discussion on baseline regression results

To investigate the impact of green technology innovation on the low-carbon transition of the economy under local government competition, this paper validates the three associations in both static and dynamic terms (see Table 4). Therefore, the lagged one-period term of economic low-carbon transition is incorporated into the model, and Eq. (1) is estimated using SYS-GMM model (see columns (4)-(6) in Table 4). Among them, column (4) contains the results of the effect of green technology innovation on the economic low-carbon transition, column (5) contains the results of the effect of local government competition on the economic low-carbon transition, and column (6) contains the results of the effect of considering the interaction of government competition and green technology innovation on the economic low-carbon transition. Columns (1)–(3) show the results of the static OLS model estimation and are included together as a reference. The results from columns (4)–(6) reveal that the coefficients of the first-order lagged terms of the dependent variables are all positive and significant ($p < 0.01$), which indicates a strong inertial dependence of China's economic low-carbon transition,

with a strong correlation between the development of low-carbon transition in the previous year. This is due to the fact that economic low-carbon transition is not a leap overnight, but a gradual accumulation. Economic low-carbon transition is a complex system that integrates economy, ecology, and society. Factors such as market barriers, industrial technological innovation, and enterprise equipment renewal have led to the need for long-term planning and gradual transition by local governments for the development of a decarbonized economy (Liu et al. 2017).

Second, all the p values of $AR(2)$ fail the significance test, i.e., the differences of the disturbance terms will not be autocorrelated of second or higher order. The Sargan test also accepts the original hypothesis that the instrumental variables are valid, thus justifying the model setting. Both columns (4) and (6) of Table 4 indicate that green technology innovation has a significant facilitating effect on economic low-carbon transition, and hypothesis (1) is verified. The improvement in green technology innovation level can effectively diminish the energy consumption per unit of output, which, especially after China's stricter environmental red lines and emission standards are set, strongly motivates localities to develop

Table 5 Threshold effect test results

Threshold variables	Thresholds	F value	p value	Critical value			Threshold estimates
				0.1	0.05	0.01	
GTECH	Single threshold	49.35[***]	0.000	22.31	24.71	34.77	3.040
	Double threshold	33.74[***]	0.000	18.20	23.49	27.66	7.480
COMP	Single threshold	11.52	0.720	30.90	37.32	48.41	3.984

corresponding green technology innovation incentives, accelerates the development and utilization of low-carbon and carbon-free energy, and promotes the low carbonization of regional energy structures (Liu et al. 2016). Secondly, green technology innovation can strongly strengthen the research and development and promotion of low-carbon materials, products and technologies, and promote the greening of the entire product life cycle as well as the low carbonization of residents' lives, which further positively supports economic low-carbon transition (Owen et al. 2018). Column (5) of Table 4 suggests that the increase in local government competition had an insignificant effect on the economic low-carbon transition. Column (5) of Table 4 suggests that the increase in local government competition had an insignificant effect on the economic low-carbon transition of the regional economy. Columns (3) and (6) of Table 4 confirm that the interaction term (*INTER*) between local government competition and green technology innovation negatively affects economic low-carbon transition ($p < 0.05$). Although the inclusion of binding ecological indicators in the assessment system of officials and the establishment of the "one vote veto" system for environmental assessment have driven local governments to emphasize green development and environmental protection, when faced with the choice between economic development and green technology innovation, local government officials still prefer to maintain economic development in order to achieve their own promotion due to career considerations. However, given the choice between economic development and green technology innovation, local government officials prefer to maintain economic development in order to achieve their promotion requirements. As a result, local governments may choose biased policies and invest resources in industries that are conducive to economic development, neglecting the improvement of ecological protection and social services (Wu et al. 2020b). Moreover, there may be competition among local governments to lower environmental regulation standards to attract investment in energy-intensive industries, which will further inhibit the promotion of green technology innovation to economic low-carbon transition. Therefore, local government competition plays a negative moderating role in the impact of green

technology innovation on economic low-carbon transition. Hypothesis (3) is verified.

Discussion on nonlinear effect results

Table 4 confirms that green technology innovation and local government competition positively contribute to economic low-carbon transition; however, whether this specific effect is linear or not needs to be tested. To further test the impact of green technology innovation and local government competition on economic low-carbon transition, the threshold regression model proposed by Hansen (1999) is utilized to further analyze green technology innovation and local government competition as threshold variables (Aye and Edoja 2017). Table 5 reports the threshold effect test results, confirming that there is a significant double threshold effect of green technology innovation on economic low-carbon transition when green technology innovation is the threshold variable, while the threshold effect test results of local government competition are not significant, which implies that there is not significant nonlinear relationship between green technology innovation on economic low-carbon transition under the influence of local government competition in China at this stage.

Tables 5 and 6 verify the threshold values of 3.040 and 7.480 when green technological innovation is the threshold variable, which divided the green technological innovation development level into three stages. Green technology innovation level in the first stage is lower than 3.040, and its impact coefficient on low-carbon transition is 0.437; green technology innovation level in the second stage is greater than 3.040 but less than 7.480, at which time the impact coefficient of

Table 6 Panel threshold model estimation results

Threshold variables	Thresholds	Coef	p value
GTECH	GTECH < 3.040	0.0437[***]	0.000
	7.480 > GTECH ≥ 3.040	0.0280[***]	0.000
	GTECH ≥ 7.480	0.0300[***]	0.000
Other variables	Yes		
R^2	0.899		
N	420		

green technology innovation on low-carbon transition is 0.028; and with the further improvement of green technology innovation level, it breaks through 7.480 and reaches the third stage, at which time the impact coefficient of green technology innovation on low-carbon economic transition is 0.030. From the above, it can be noted that the contribution of green technology innovation to the economic low-carbon transition has "N" characteristics.

Green technology innovation will have different degrees of impact on economic low-carbon transition at different stages of development. When reaching a certain development stage, its contribution to economic low-carbon transition slows down, and when crossing such stage, the impact of green technology innovation on economic low-carbon transition starts to increase again. This result may be due to the fact that in the initial stage of economic green transition, in order to acquire an edge in market competition, localities must increase technological transition efforts, eliminate backward production capacity, and implement policies of clean production, energy conservation, and emission reduction, which can rapidly promote the economic low-carbon transition (Yang et al. 2022a). Once the green technology innovation reaches a certain level, the backward production capacity has been gradually eliminated. Constrained by capital, talent, and other factors, coupled with the existence of the "resource curse," local governments to break away from the original development path to achieve industrial and technological upgrading will increase the cost and difficulty, thus leading to a lack of incentive for enterprise innovation, development into a bottleneck. The role of green technology innovation in promoting economic low-carbon transition has begun to diminish, and the speed of economic decarbonization has slowed down. However, with the further increase in green technology innovation, once the path dependence of development is broken, the new innovation level can trigger a "recombination of production factors" and a new change in production conditions, which can enable regional industries and economies to enter a new stage of low-carbon transition (Tavoni et al. 2012). Consequently, the ability to break through the second stage of green technology innovation level is the key to further economic low-carbon transition. It can be observed through the data available in each area that the green technology innovation level of 11 provinces in China, including Qinghai, Guangxi, Ningxia, Xinjiang, Jilin, Gansu, Heilongjiang, Inner Mongolia, Shanxi, Hainan, and Guizhou, has not yet broken through the second

stage of development, at which time the promotion of green technology innovation to the economic low-carbon transition is relatively small, and the green technology innovation level needs to be further improved.

Discussion on heterogeneity results

The threshold model reveals that the impact of various stages of green technology innovation on economic low-carbon transition has significant differences. However, there is no threshold effect of local government competition; thus, the impact of green technology innovation on economic low-carbon transition under different government competition intensity cannot be further analyzed. In addition, Table 4 confirms that local government competition inhibits the contribution of green technology innovation to economic low-carbon transition. Do the above effects work the same for all areas? If not, how does it work within different areas? To further clarify the above issues, this paper divides the studied sample into low local government competition areas and high local government competition areas based on the intensity of government competition using combining the natural interruptions. In particular, the low government competition areas are 12 provinces and cities including Inner Mongolia, Liaoning, Beijing, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Hebei, and Chongqing, and the high local government competition areas include 18 provinces and autonomous regions including Heilongjiang, Jilin, Hebei, Shanxi, Anhui, etc. The specific categories are shown in Fig. 4.

This section continually follows the SYS-GMM model to estimate the results (see Table 7). In Table 7, columns (1)–(3) show the empirical results for low local government competition intensity areas, and columns (4)–(6) show the empirical results for high government competition intensity areas. This paper reveals that green technology innovation contributes significantly to economic low-carbon transition in both low and high government competition areas. Local government competition inhibits the low-carbon transition, but only in low government competition intensity areas. The interaction term between local government competition and green technology innovation is significant and negative in low government competition intensity areas, but not in high government competition intensity areas. Considering that low government competition intensity areas are mainly coastal or economically developed areas, it implies that changes in local government competition intensity
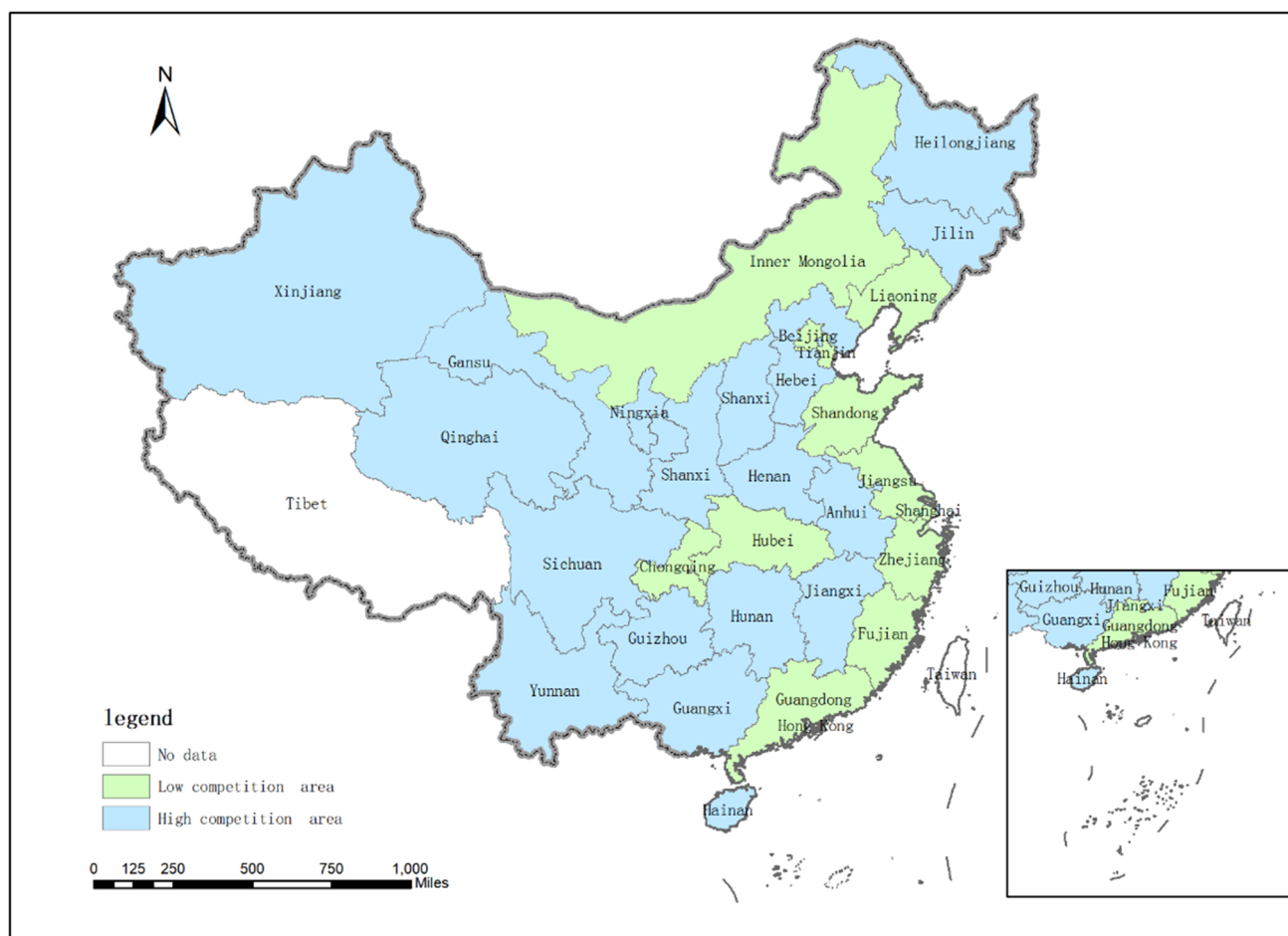
Fig. 4 Spatial partitioning of local government competition

Table 7 Heterogeneity results

Variable	SYS-GMM					
	(1)	(2)	(3)	(4)	(5)	(6)
L.LTC	0.972***	0.989***	0.906***	0.926***	0.950***	0.923***
	(0.014)	(0.016)	(0.026)	(0.035)	(0.027)	(0.038)
GTECH	0.003***		0.004***	0.005***		0.004**
	(0.000)		(0.001)	(0.001)		(0.002)
COMP		−0.003*	−0.003*		−0.001	−0.001
		(0.002)	(0.002)		(0.001)	(0.001)
GTECH×COMP			−0.004***			−0.001
			(0.001)			(0.001)
_Cons	0.022***	0.016	0.035***	0.006	0.033**	0.029**
	(0.007)	(0.011)	(0.009)	(0.010)	(0.013)	(0.011)
Other variables	Yes	Yes	Yes	Yes	Yes	Yes
AR(2)-P	0.919	0.861	0.972	0.340	0.358	0.342
Sargan-P	0.436	0.354	0.614	0.959	0.934	0.945
N	169	169	169	221	221	221

Table 8 Robustness test results

Variable	Two-step Sys-GMM					
	(1)	(2)	(3)	(4)	(5)	(6)
L.LTC	0.946***	0.945***	0.942***	0.956***	0.930***	0.942***
	(0.019)	(0.022)	(0.015)	(0.023)	(0.019)	(0.025)
GTECH	0.003***	0.003***	0.003**	0.003**	0.005***	0.004***
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
COMP		−0.001*		−0.001		−0.001
		(0.001)		(0.001)		(0.001)
GTECH×COMP		−0.001**		−0.001**		−0.001*
		(0.001)		(0.001)		(0.001)
_Cons	0.010	0.026***	−0.001	0.006	0.007	−0.001
	(0.006)	(0.009)	(0.009)	(0.010)	(0.006)	(0.011)
Control	Yes	Yes	Yes	Yes	Yes	Yes
AR(2)-P	0.272	0.206	0.497	0.330	0.544	0.340
Sargan-P	0.119	0.114	0.175	0.327	0.186	0.283
N	390	390	360	360	377	377

have a greater impact on the economic low-carbon transition in developed economic areas, while the impact on economically more backward areas is not obvious. It is evident from Fig. 3 that the low government competition areas are concentrated in the three major urban clusters along the Chinese coast (Beijing-Tianjin-Hebei, Yangtze River Delta, and Pearl River Delta) and the Chengdu-Chongqing metropolitan area, which are economically developed, densely populated, and have frequent exchanges of various factors. At the same time, the economic and social integration development among the above regions tends to be integrated, which makes green technologies often have strong spillover effects, and the benefits from cooperation between regions are much greater than those from competition (Guo et al. 2019). Thus, in these areas, the increase of local government competition intensity will inhibit the promotion of green technology innovation for economic low-carbon transition. The areas with high local government competition intensity are the central and western areas with relatively backward economies, where local government officials are mainly faced with promotion incentives brought by economic development. In addition, these areas have prominent local fragmentation problems, so the government must strengthen the competitiveness of the region in order to continuously achieve regional economic development, which in turn may form a stronger contribution to the low-carbon economic transition. Thus, the intensity of local government competition does not have a significant inhibitory effect on the economic low-carbon transition of their economies. This finding further validates hypothesis 2.

Discussion on robustness test results

In order to verify the reliability of the results, three strategies are used to test the robustness of the sample. First, the time span of the study is changed. The paper chooses to re-estimate the remaining data by excluding 2019, and the results are presented in columns (1) and (2) in Table 8. Second, the model is re-estimated by using the number of college students per 10,000 population to represent the stock of human capital as a proxy variable, and the results are presented in columns (3) and (4) in Table 8. Considering that Hainan is an island, it is different from other areas in terms of development environment and development pattern, so it is deleted and re-estimated for the remaining 29 provincial administrative areas, and the results are shown in columns (5) and (6) in Table 8.

Table 8 reveals that the significance and directionality of the key variables are generally consistent with the baseline regression results, demonstrating the robustness of the previous empirical test results.

Discussion on further analysis results

The relationships between green technology innovation and economic low-carbon transition can be informed from the overall and area levels through the SYS-GMM model and the threshold model. However, the influence of green technology innovation and local government competition on economic low-carbon transition cannot be analyzed from the perspective of each area. In order to further discuss the relationship between these three, the analysis is conducted through the GTWR model.
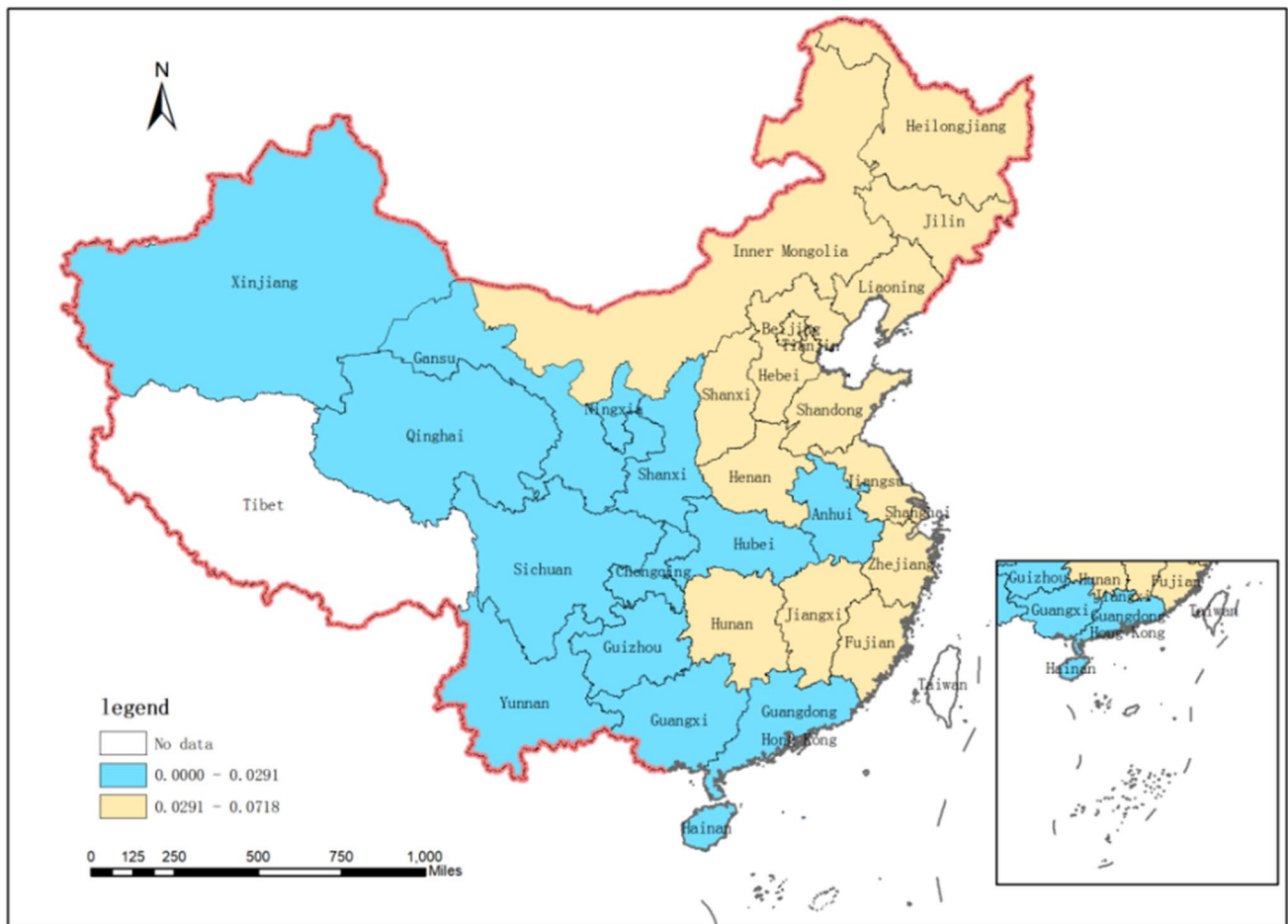
Fig. 5 Spatial impact of green technology innovation on the economic low-carbon transition

Figures 5, 6, and 7 reflect the spatial effects of green technology innovation, local government competition, and the interaction term of the two on the economic low-carbon transition, respectively. Figure 5 depicts that green technology innovation in the eastern coastal and economically developed areas, such as Beijing, Shanghai, and Zhejiang, has contributed more significantly to economic low-carbon transition. Figure 6 illustrates that the increase in the intensity of government competition does not inhibit economic low-carbon transition in the more economically backward central and western areas, which is also reflected in Fig. 7. The combined results suggest that the spatial characteristics of local government competition and green technology innovation on economic low-carbon transition are relatively consistent, with a stronger contribution of green technology innovation towards economic low-carbon transition in the eastern as well as developed areas, and a more pronounced inhibitory effect of government competition on economic low-carbon transition,

while the opposite results are found in the central and western areas.

Conclusion and policy implications

This paper utilizes a dataset of 30 provincial-level administrative areas in China from 2006 to 2019 to examine green technology innovation levels and economic low-carbon transition, as well as the impact of local government competition and green technology innovation on economic low-carbon transition as explored via SYS-GMM model, panel threshold model, and GWTR model. The conclusions indicate that China's overall green technology innovation level and low-carbon economic transition level are rising year by year; however, the differences among provinces have enlarged. Moreover, green technology innovation significantly stimulates the economic low-carbon transition, and its stimulating effect varies at different
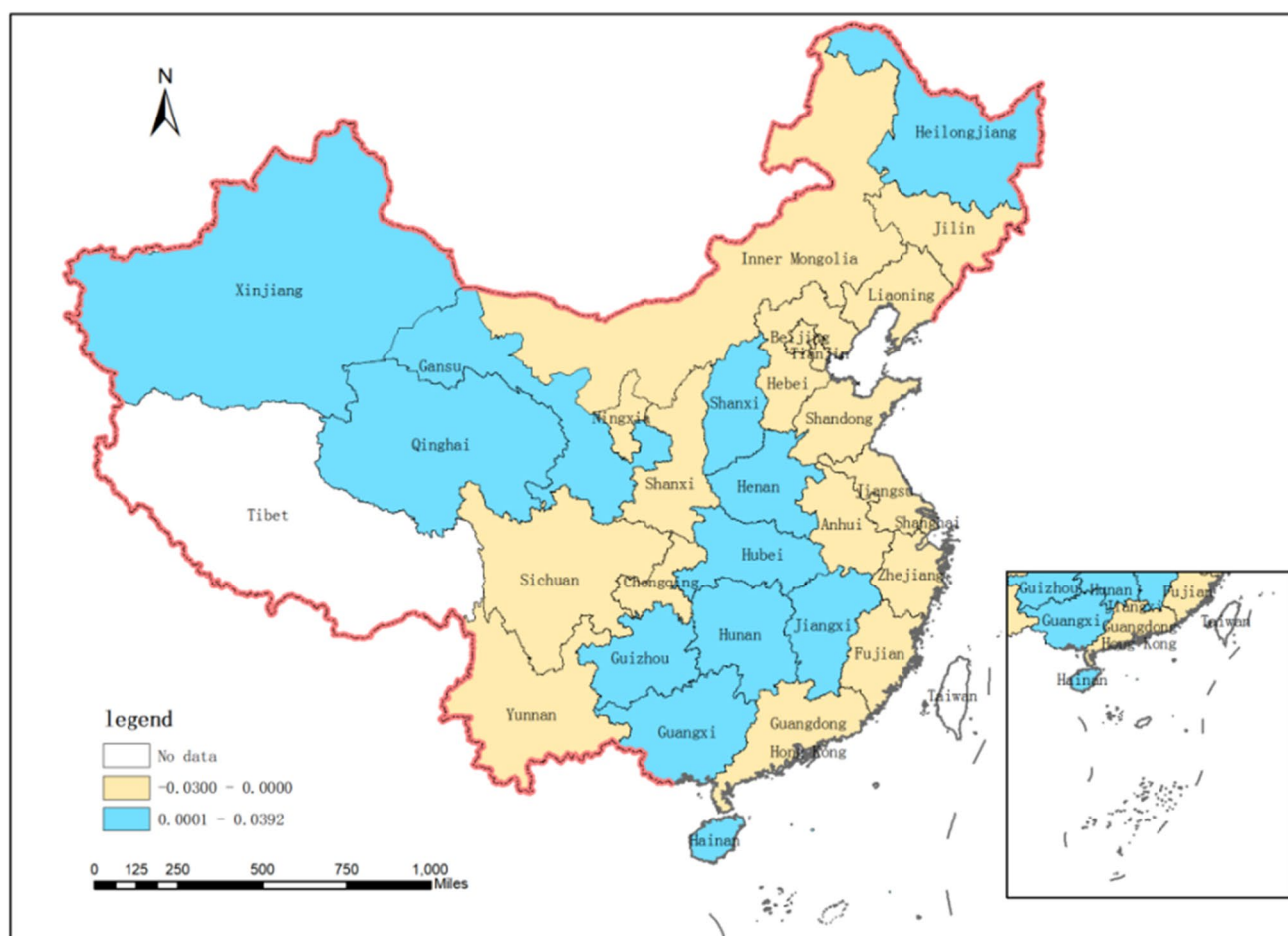
Fig. 6 Spatial impact of local government competition on economic low-carbon transition

development levels, with an overall "*N*" trend of rising, then falling and subsequently rising. Finally, local government competition not only significantly dampens the economic low-carbon transition in low-competition intensity areas, but also negatively moderates green technology innovation, which is not evident in high-competition areas.

(1) Green technology innovation is a vital way to improve the low-carbon transformation of regional economy. Policymakers shall vigorously increase R&D investment, actively promote green technology and innovate production methods. Moreover, policymakers shall hasten to construct a green technology innovation system, thereby exerting the role of the engine of green technology to economic low-carbon transition.

(2) Policymakers should also further develop the assessment system for local government officials and actively implement an effective reward and punishment mechanism to maximize the initiative of local

governments and enterprises to avoid free-riding and vicious competition. Policy makers shall incorporate green technology-related contents into the political promotion system, so as to stimulate local governments to compete for the incentive to increase green technology innovation and realize economic low-carbon transition.

(3) Differentiated policies should be implemented. Low government competition areas should continuously strengthen technological exchanges and environmental cooperation among areas and establish a joint low-carbon emission reduction system in the area. The high government competition area should reasonably guide the behavior of local governments, promote the change of competition direction among local governments, and form a benign competition for low carbon and green development. Meanwhile, high government competition areas should change the previous concept of "GDP growth only" and establish a certain consultation mechanism with neighbor-

Fig. 7 Spatial impact of local government competition on economic low-carbon transition

ing governments to guide resource sharing and technical cooperation, so as to avoid excessive internal consumption caused by local government competition and reduce the negative impact on economic low-carbon transition of neighboring areas.

Although this paper explores the issues to be pre-studied as comprehensively as possible, there are still some unavoidable limitations. First, this paper is still deficient in the construction of the index system for measuring green technology innovation and economic low-carbon transition, and the comprehensiveness of the evaluation index system can be reinforced in the subsequent research. Secondly, because of data barriers, this paper has only been able to examine the situation at the provincial level, but not at the county and city levels. Thirdly, local government competition includes economic, social, and environmental aspects, which are quantitatively represented in this paper only at the economic level and inevitably omit

other aspects, which can be further discussed in future studies.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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