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The inferiors imitate the superiors: the government's low-carbon concerns and the renewable energy technology of firms

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Existing research has focused mainly on the technological effects of rigid constraints such as low-carbon policies, but there has been little exploration of flexible constraints such as the government's low-carbon concerns. To explore the role of flexible low-carbon constraints and effective paths for achieving low-carbon development, this paper theoretically and empirically investigates the influence of the government's low-carbon concerns on local firms' innovation in renewable energy technology and the underlying mechanism. Benchmark analysis shows that the government's low-carbon concerns can improve renewable energy technology among firms in an area. Mechanism analysis reveals that low-carbon concerns promote firms' renewable energy technology adoption by increasing the amount of research and development (R&D) investment and government subsidies and energy use costs of firms in the area. Heterogeneity analysis reveals that heterogeneity exists across technologies, firms, industries and locations in terms of the incentive impact of the government's low-carbon concerns on the level of renewable energy technology innovation. Extensive analysis indicates that the government's low-carbon concerns have a long-term incentive impact on the renewable energy technology of local firms and a positive demonstration impact on the renewable energy technology of neighboring firms. This study is helpful in that it explores the major driving factors behind the creation of a low-carbon economy and the achievement of climate targets.

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Introduction

Under the dual pressures of the gradual depletion of traditional energy sources, such as fossil fuels, and its obvious negative effects on the environment, industrialized economies, such as the US and the European Union, are promoting renewable energy development in a comprehensive way. Low-carbon energy, represented by renewable energy, is gradually replacing coal and oil, and the energy transformation of countries worldwide has entered a critical stage. China's capacity to fulfill its carbon peak and carbon neutrality objectives, as the world's greatest energy consumer and carbon dioxide emitter, mainly influences the chances of global sustainable development. Among the feasible solutions to this problem, the innovation and application of renewable energy technology is one worthwhile measure that can be taken. However, due to market failure and the country's stage of economic development, China's renewable energy technology reform faces many problems. It is difficult to commercialize immature renewable energy technology, and a great deal of R&D support is needed before such technology can become competitive in the market. Given the importance of renewable energy technologies for reducing carbon emissions, the Chinese government has implemented numerous low-carbon policies in recent years to correct market failure and make technological progress biased toward low-emission and sustainable low-carbon energy to encourage the development of renewable energy technologies.

The majority of the related research has focused on the link between government environmental policy and renewable energy technology from three perspectives (Blundell et al. 2020, Shapiro and Walker/, 2018, Wang et al. 2023a, 2023b, 2023c, 2023d, 2023e, 2023f, 2023g). First, based on Porter's hypothesis, some studies propose that positive and appropriate environmental policies can improve firms' level of environmental awareness, stimulate firms' technological innovation behavior, and ultimately mitigate or reimburse firms for the environmental costs they incurred as a result environmental regulations (Alvarez-González et al. 2023, Hasan and Du 2023, Wang et al. 2023a, 2023b, 2023c, 2023d, 2023e, 2023f, 2023g). Second, from the perspective of energy demand, some studies posit that climate change has put pressure on governments and firms to reduce carbon emissions (Du et al. 2022a, Du et al. 2022b, Li et al. 2023a, 2023b, Wang et al. 2023a, 2023b, 2023c, 2023d, 2023e, 2023f, 2023g). Strict environmental policies and preferential renewable energy policies reduce the level of demand for traditional energy and lead to fewer emissions and more sustainable alternative energy, which are conducive for the emergence and use of renewable energy technology (Li et al. 2023a, 2023b, Li et al. 2022, Wang et al. 2020). Additionally, some studies state that market failure is caused by the information asymmetry between environmental quality and uncertainty in the innovation process, which prevents renewable energy technology innovation from reaching an optimal state (Greenstone and Hanna 2014, Wang et al. 2023a, 2023b, 2023c, 2023d, 2023e, 2023f, 2023g, Xie et al. 2017). The government's environmental policy can compensate for the lack of market mechanisms, and a reasonable environmental policy is conducive to strengthening the expectation of high returns on R&D and investment, easing the pressure placed on firms in terms of R&D costs, reducing the degree of uncertainty of innovation activities, and thus promoting the innovation of renewable energy technologies (Dechezlepretre and Sato 2017, Jia et al. 2022).

The literature provides a basis on which to understand the link between environmental policy and renewable energy technology. Regarding the research perspective, research framework, and indicator measurement, the literature still needs to be enhanced and developed. The potential contributions of this work are as follows. First, this study introduces government low-carbon concerns under heterogeneous firm theory and discusses the link between low-carbon policies and firms' renewable energy technology, which broadens the academic view of macro policy governance and micro firm decision-making. Second, this study examines the internal mechanism of the effects of the government's low-carbon concerns on the influence of local firms' renewable energy technology from three perspectives—the amount of R&D investment of firms, the amount of government subsidies obtained by firms, and energy use costs of firms—and further discusses the long-term motivating impact of the government's low-carbon concerns on local firms' renewable energy technology and the impact of government low-carbon concerns on neighboring firms' level of renewable energy technology innovation, which broadens the study framework in the literature on this subject. Third, this study obtains 2,874 government work reports from 287 cities in China through web crawlers and establishes a low-carbon word frequency database to establish indicators of government low-carbon concerns. Based on the Chinese patent database and in combination with the World Intellectual Property Organization's "Green List of International Patent Classification", firm renewable energy technology indicators are established through multiple rounds of data matching and cleaning. The indicators are established considering the representativeness of the data selection and the accuracy of the measurements.

The remainder of this work is structured as follows. Part 2 presents the theoretical model, which incorporates the government's low-carbon concerns into the theoretical framework of heterogeneous firms, analyzes the problems associated with firms' renewable energy technology, and puts forward theoretical propositions. Part 3 describes the research design, which includes the model setting and data introduction. Section 4 presents the empirical findings and investigates the influence and mechanism of the government's low-carbon concerns regarding renewable energy technology. Part 5 is an extensive analysis that examines the heterogeneous impacts of the government's low-carbon concerns on the renewable energy technology innovation of firms and expands the benchmark analysis from the long-term effects to the demonstration effects. The last section presents the conclusions and policy implications.

Theoretical model

Under the framework of heterogeneous firm theory (Melitz 2003), the concept of low-carbon concerns is introduced to investigate the link between the government's low-carbon governance and firm's low-carbon technology. Based on the monopoly competition product market hypothesis, there are L consumers in the product market, and firms' products have certain characteristics that differentiate them from those of other firms. According to Dixit and Stiglitz (1977), the consumer utility function in *CES* form is as follows:

$$U = (Q_p^c)^{-\alpha}\left[\int_{\omega\in\Omega} q(\omega)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}} \tag{1}$$

where $Q_p{}^c$ measures the output of items with significant amounts of energy consumption and emissions, which has a negative influence on consumer utility; α is used to measure consumers' aversion to firms' high energy consumption and high-polluting production, and $\alpha > 0$; Ω represents a collection of product categories; and σ is used to measure the degree of substitution elasticity of various products, and $\sigma > 1$. The disposable income constraints of consumers are as follows:

$$\int_{\omega\in\Omega} p(\omega)q(\omega)d\omega = I \tag{2}$$

where I is used to measure consumers' income. Using Formulas (1) and (2), the demand function form of product ω is obtained under the condition of maximizing consumer utility:

$$q(\omega) = \frac{I}{P}\left[\frac{p(\omega)}{P}\right]^{-\sigma} \tag{3}$$

where P represents the price level, and the specific form is shown in Formula (4):

$$P = \left[\int_{\omega\in\Omega} p(\omega)^{1-\sigma}d\omega\right]^{1/(1-\sigma)} \tag{4}$$

Assuming that labor is the only factor input, the cost of entering the market is f_e units of labor. The productivity level of firms φ is a random variable with an independent identical distribution, and the probability density function is $g(\varphi)$. Incumbent firms may face exogenous shocks. If the productivity of a firm is at too low of a level, then the firm exits the market. The probability of an exogenous shock is δ, which is not influenced by productivity. Assume that the fixed cost input of the firm in each production process is f units of labor force and that the input of low-carbon technological innovation is F units of labor force. In addition, the supply of the labor force is endogenously determined by the clearing conditions of the labor market. Backward and advanced firms are the two types of firms considered here. The difference between them lies in their willingness and ability to adopt low-carbon technology for production. It is assumed that firms can invest cost c to seek rents without low-carbon technological innovation and prevent closure. Since backward firms do not carry out the production of low-carbon technology, it is assumed that the additional emission tax rate that they need to bear is θ and that θ is in direct proportion to the government's low-carbon concerns. According to the above analysis, the cost function forms of backward and advanced firms are as follows:

$$TC_{p0}(\varphi) = \begin{cases} TC^c(\varphi) = w\left[\frac{1}{1-\theta}\frac{q^c}{\varphi} + f + c\right], & \text{if } \varphi^* \le \varphi \le \varphi^+ \\ TC^F(\varphi) = w\left[\frac{q^F}{\varphi} + f + F\right], & \text{if } \varphi \ge \varphi^+ \end{cases} \tag{5}$$

where w represents the wage rate. Without loss of generality, labor is regarded as the valuated object; that is, w is taken as 1. C and F represent backward and advanced firms, respectively. φ^* measures the survival productivity of firms; φ^+ represents the undifferentiated technological productivity of the firm, that is, the productivity level at which there is no difference in profits between rent-seeking and low-carbon-technology behaviors. Using the basic assumption of firm profit maximization, the price function of the firm is calculated as follows:

$$p(\varphi) = \begin{cases} p^c(\varphi) = \frac{1}{p\varphi(1-\theta)}, & \text{if } \varphi^* \le \varphi \le \varphi^+ \\ p^F(\varphi) = \frac{1}{p\varphi}, & \text{if } \varphi \ge \varphi^+ \end{cases} \tag{6}$$

In equilibrium, if the distribution of firm productivity is $\mu_{P0}(\varphi)$, then the price index P of market equilibrium is as follows:

$$P = \left[\int_0^{\infty} p(\varphi)^{1-\sigma}M\mu(\varphi)\right]^{1/(1-\sigma)} = M^{1/(1-\sigma)}p(\overline{\overline{\varphi}}) \tag{7}$$

where the number of continuing firms in the market under equilibrium is M and the weighted average productivity of firms is $\overline{\overline{\varphi}}$. The survival productivity of firms φ^* needs to meet $\pi^c(\varphi^*) = 0$ when rent-seeking occurs. Only firms whose productivity level is higher than φ^* can provide products to the market, and other firms thus withdraw from the market. The relative income of firms with productivity $\varphi(\varphi^* \le \varphi \le \varphi^+)$ and firms with survival productivity level φ^* is as follows:

$$\frac{r^c(\varphi)}{r^c(\varphi^*)} = \left[\frac{\varphi}{\varphi^*}\right]^{\sigma-1} \tag{8}$$

In addition, because firms with productivity φ^* have zero profit in each period,

$$\pi^c(\varphi^*) = 0 \Rightarrow r^c(\varphi^*) = \sigma(f + c) \tag{9}$$

Based on Formulas (8) and (9), the following is calculated:

$$r^c(\varphi^+) = \sigma\left(\frac{\varphi^+}{\varphi^*}\right)^{\sigma-1}(f + c) \tag{10}$$

The relative income of firms with productivity φ^+ in terms of rent-seeking and low-carbon technological innovation is as follows:

$$\frac{r^F(\varphi^+)}{r^c(\varphi^+)} = \left[\frac{1}{1-\theta}\right]^{\sigma-1} \tag{11}$$

Because firms with productivity $\varphi_{p0}{}^+$ should make the same profits as those with low-carbon-technological-innovation and rent-seeking behaviors, we have the following:

$$\pi^F(\varphi^+) = \pi^F \Rightarrow r^F(\varphi^+) - r^c(\varphi^+) = \sigma(F - c) \tag{12}$$

Based on Formulas (10), (11) and (12), the following is calculated:

$$\varphi^+ = \{(F-c)/[((1-\theta)^{1-\sigma} - 1)(f + c)]\}^{1/(\sigma-1)}\varphi^* = \lambda\varphi^* \tag{13}$$

where $\lambda = \{(F-c)/[((1-\theta)^{1-\sigma} - 1)(f + c)]\}^{1/(\sigma-1)}$. Furthermore, the average profit of the surviving firms in the market and the conditions for their free entry and exit are as follows:

$$\begin{aligned} \overline{\pi} &= \int_{\varphi^F}^{\varphi^*}\pi^c(\varphi)\frac{g(\varphi)}{1-G(\varphi^*)}d\varphi + \int_{\varphi^*}^{+\infty}\pi^F(\varphi)\frac{g(\varphi)}{1-G(\varphi^*)}d\varphi \\ &= \kappa(\varphi^*)(f + c) + \frac{1-G(\varphi^+)}{1-G(\varphi^*)}\kappa(\varphi^+)(F - c) \end{aligned} \tag{14}$$

$$\overline{\pi} = \frac{\delta f_e}{1 - G(\varphi^*)} \tag{15}$$

where $\kappa(\varphi^*) = [\overline{\overline{\varphi}}(\varphi^*)/\varphi^*]^{\sigma-1} - 1>0$ and $\kappa(\varphi^+) = [\overline{\overline{\varphi}}(\varphi^+)/\varphi^+]^{\sigma-1} - 1>0$. Combining Formulas (13), (14) and (15), the implicit function equation of firm survival productivity under market equilibrium is obtained as follows:

$$[1 - G(\varphi^*)]\kappa(\varphi^*)(f + c) + [1 - G(\lambda\varphi^*)]\kappa(\lambda\varphi^*)(F - c) - \delta f_e = 0 \tag{16}$$

By solving the differential of Formula (16), the relationship between technical indifference productivity φ^+ and the government's low-carbon concerns θ can be obtained as follows:

$$\frac{\partial\varphi^+}{\partial\theta} = -\frac{\lambda\varphi^*(1-\theta)^{-\sigma}}{[(1-\theta)^{1-\sigma} - 1]} \frac{[1 - G(\varphi^*)][\kappa(\varphi^*) + 1](f + c)}{[1 - G(\varphi^*)][\kappa(\varphi^*) + 1](f + c) + [1 - G(\lambda\varphi^*)][\kappa(\lambda\varphi^*) + 1](F - c)} < 0 \tag{17}$$

Combining the above factors with Formula (17), the following proposition is obtained:

Proposition: An improvement in the amount of the local government's low-carbon concerns can reduce the level of technological indifference productivity and decrease the opportunity costs of firms' low-carbon technology compared with rent-seeking, thus improving the probability of firms' renewable energy technology.

Research design

Model setting. The micro-econometric model is concerned primarily with micro-individual behavior. Typically, the sample data are panel or cross-sectional data with a high number of observations and significant degree of variability (Adamopoulos et al. 2022, Heckman and Serletis 2014). In this study, the data are characterized by micro firms, panel data, and large-sample observations. In addition, considering the binary dummy variable characteristics of the dependent variable, the panel *logit* micro-econometric model is used to investigate the link between the government's low-carbon concerns and renewable energy technology and to verify the theoretical proposition. The panel *logit* micro-econometric model can eliminate unobservable factor interference by introducing individual fixed effects to control for the interference of factors that do not change over time and time fixed effects to control for the interference of factors that do not change with changing individual characteristics. According to existing research (Du and Li 2020, Li and Du 2021, Wang et al. 2023a, 2023b, 2023c, 2023d, 2023e, 2023f, 2023g), the following micro-econometric equation is constructed:

$$RET_{it} = \alpha + \beta GCC_{it} + \gamma X_{it} + \eta_i + \eta_t + \varepsilon_{it} \quad (18)$$

where i represents the firm and t represents the year. RET_{it} indicates the firm's renewable energy technology. With reference to existing research (Lin and Chen 2019, Noailly and Shestalova 2017, Popp et al. 2011), this variable is measured by whether firms apply for renewable energy patents. Table 1 reports the international patent classification number of renewable energy technology, which is compiled in accordance with the World Intellectual Property Organization's Green List of International Patent Classification.

GCC_{it} represents the government's low-carbon concerns. This paper uses the frequency of low-carbon words to account for the overall word count in the report as a proxy variable for the local government's low-carbon concerns. Given that local government work reports in China do not strictly distinguish between pollution emissions and carbon emissions, they are often considered part of environmental governance. Thus, a low-carbon vocabulary is established based on the abstract vocabulary of low carbon and the environment, energy efficiency, ecology, pollution prevention, greening, and reducing emissions and the specific vocabulary of low carbon and the environment, such as haze, carbon dioxide, sulfur dioxide, chemical oxygen demand, PM2.5, and PM10. Additionally, to further validate the research findings, the robustness section attempts to narrow the definition scope of low-carbon vocabulary, retaining only low carbon, carbon emission reduction, carbon dioxide, greenhouse gas, energy consumption, energy efficiency, energy conservation, and other words directly related to carbon emissions and energy use, and to establish a low-carbon vocabulary thesaurus[1].

η_i and η_t represent firm and year fixed effects, respectively. ε_{it} denotes the random error term. X_{it} is the control variable. Additional control variables are as follows:

$$X_{it} = \delta_1 Scale_{it} + \delta_2 CK_{it} + \delta_3 Export_{it} + \delta_4 Age_{it} + \delta_5 SOE_{it} + \delta_6 FE_{it} \quad (19)$$

where $Scale_{it}$ represents the firm's production scale, which is measured by the number of workers. CK_{it} is the firm's capital intensity level, which is calculated by dividing the average fixed asset balance by the number of workers. $Export_{it}$ indicates the export status of the firm. If the firm has an export transaction record for the current fiscal year, then the value is 1, and otherwise, the value is 0. Age_{it} is the firm's duration, which is measured by the difference between the current year and the establishment year. SOE_{it} and FE_{it} represent state-owned and foreign enterprises, respectively. The dummy variables for state-owned and foreign enterprises are constructed based on firm affiliation.

Data introduction. Based on the usual practices in the literature (Liu et al. 2023, Tian et al. 2022), the low-carbon concerns of local governments is determined based mainly on 2874 government work reports issued by 287 cities in China from 2003 to 2013. The frequency of low-carbon words is extracted from the reports, and its proportion to the total number of words in the report is calculated. Data on renewable energy technology patent applications come mainly from the patent database, which covers the patent applications of all Chinese firms and individuals, including the patent application number, patent application date, applicant, patent classification number and other information. The data on firm characteristic are mainly from the databases of Chinese industrial firms, Chinese firms' pollution emissions and Chinese customs. The industrial firm database includes yearly data from China's National Bureau of Statistics', which are acquired by summarizing the quarterly and annual reports supplied by sample firms. The pollution emission database is based on annual data gathered from quarterly questionnaires completed by key polluting firms and includes information on firms in each district and county whose pollution emissions account for the top 85% of total emissions. The customs database covers all monthly transaction records, including mainly import and export firm and commodity information. The macrolevel city data and microlevel firm data are matched according to the year and city code. The matching criterion is one to many, which means that one city matches several firms. The sample interval covers the period 2003–2014. Table 2 reports the descriptive statistics of the core variables in this paper.

Empirical estimation results and analysis

Benchmark analysis. In view of the dual characteristics of firms' renewable energy technology innovation variables, this paper uses panel *logit* regression to examine the influence of local governments' low-carbon concerns on firms' level of renewable energy technology innovation. The regression process controls for individuals and year fixed effects. The findings are shown in Fig. 1. The findings show that the *GCC* variable is positive and

Table 1 Patent number of renewable energy technology.

Renewable energy technology	Patent classification number
Wind energy	F03D
Solar energy	F03G6; F24J2; F26B3/28; H0127/142; H02N6; H01L31/04-058
Biomass and waste energy	C10L5/42-44; F02B43/08; C10L5/46-48; F23G5/46; F23G7/10; [C10L1 or C10L3 or C10L5] and [B09B1 or B09B3 or F23G5 or F23G7]; [F01K27 or F02G5 or F25B27/02] and [F23G5 or F23G7]
Geothermal energy	F03G4; F24J3/08
Ocean energy	E02B9/08; F03B13/10-26; F03G7/05

Table 2 Descriptive statistics.

Variable	Observation	Mean	Std. Dev.	Min.	Max.
RET	2,995,607	0.0017	0.0413	0	1
GCC	2,995,607	0.4378	0.2079	0	22872
Scale	2,943,883	255.21	354.85	6	2368
CK	2,936,435	407.54	765.71	13.12	5638.50
Export	2,995,607	0.2178	0.4128	0	1
Age	2,992,474	9.8952	8.2526	1	50
SOE	2,995,607	0.1032	0.3043	0	1
FE	2,995,607	0.1587	0.3654	0	1

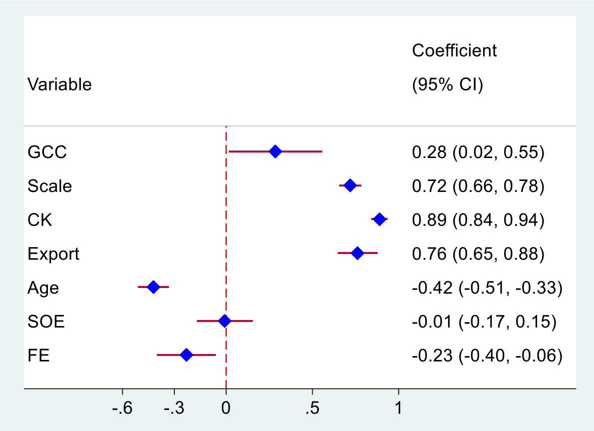

Fig. 1 Benchmark analysis. A vertical line with an abscissa scale of 0 is considered invalid. The graphic depicts the effect size and 95% confidence interval (CI) of the linked variable with diamonds and two-sided lines, respectively. When the CI horizontal line intersects the invalid vertical line at the 5% level, the variable coefficient is not significant.

significant, indicating that the government's low-carbon concerns can improve firms' renewable energy technology in the region.

The results of the firm-level control variable analysis are consistent with the predictions. The firm scale variable *Scale* is positive and significant, indicating that as firm scale increases, the probability of firm renewable energy technology innovation increases; that is, large firms are more capable of innovation in terms of renewable energy technologies. The capital-intensive variable *CK* is positive, indicating that as the amount of per capita capital investment increases, the probability of renewable energy technology innovation increases; that is, the probability of capital-intensive firms carrying out technology becomes greater. The variable *Export* is positive, indicating that compared with domestic firms, export firms are more likely to carry out technological innovation. The variable *Age* is negative, indicating that with increasing age, the market share becomes more stable and the business mode becomes more mature, which weakens the motivation for innovation to a certain extent. Furthermore, the variable *FE* for foreign firms is negative, while the variable *SOE* for state-owned firms is not significant. This finding suggests that compared to private and state-owned firms, foreign firms are less likely to innovate in renewable energy technologies, which supports the pollution haven hypothesis to some extent.

Robustness analysis. The benchmark analysis indicates that improvements in the government's low-carbon concerns can, to a certain extent, increase innovation in renewable energy technologies among local firms. This section describes the robustness analysis performed by replacing the measurement method and scope of the core indicators as well as the core variables. The benchmark analysis uses whether the firm has applied for renewable energy technology patents as the dependent variable. To verify the robustness of the benchmark analysis[2], column (1) of Table 3 uses the number of enterprise renewable energy technology patent applications as the dependent variable and a *Poisson* count model to examine the impact of the government's low-carbon concerns on firm renewable energy technology. In columns (2) and (3) of Table 3, whether the firm has obtained renewable energy technology patent authorizations and the number of authorizations are used as the dependent variables. The *logit* and *Poisson* counting models are used to examine the robustness of the benchmark analysis. The results show that the coefficients of the *GCC* variables are all significantly positive, indicating that as the number of the government's low-carbon concerns increases, the probability and number of applications and authorizations for renewable energy technology patents by firm increase, verifying the conclusions of the benchmark regression.

Table 3 Robustness analysis I: Replacing the dependent variable.

	Patent application	Patent grant	
	(1) Number	(2) Whether	(3) Number
GCC	0.4114***	0.2118***	0.2439***
	(0.0534)	(0.0220)	(0.0651)
Constant	−16.3511***	−20.5203***	−21.2715***
	(0.8446)	(1.0650)	(1.3128)
Control variable	YES	YES	YES
Individual fixed effects	Controlled	Controlled	Controlled
Time fixed effects	Controlled	Controlled	Controlled
Pseudo R2		0.2213	
Observations	2,930,219	2,930,228	2,930,228

The numbers in parentheses represent standard errors, while symbols *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

In addition, the benchmark regression measures the government's low-carbon concerns according to the proportion of low-carbon words reported by local governments, and column (1) of Table 4 measures the government's low-carbon concerns according to the number of low-carbon words reported by governments. Columns (2) and (3) further narrow the definition of the term "low carbon". The regression results show that after altering the primary explanatory variables' measurement and measurement window, the coefficient of the local government's low-carbon concerns is still significantly positive, indicating that the number of such concerns increases the probability of firms' renewable technology innovation, which once again supports the conclusions of the benchmark analysis.

Since 2010, China has been piloting low-carbon city initiatives. The government departments of low-carbon pilot cities may pay more attention to low carbon emissions in the process of urban development. Therefore, in column (4) of Table 4, low-carbon pilot cities are used as an alternative indicator of government low-carbon concerns, and the influence of such concerns on local firms' renewable energy technology innovation is investigated via the difference-in-differences (DID) method. The findings show that the variable for the government's low-carbon concerns, measured by low-carbon pilot cities, is still significantly positive, indicating that such concerns have an incentivizing effect on local firms' renewable energy technology innovation, which supports the robustness of the benchmark conclusion.

Internal mechanism. Benchmark regression and robustness analysis reveal that the government's low-carbon concerns can

Table 4 Robustness analysis II: Replacing the core independent variables.

	Narrow GCC index			
	(1) Frequency	(2) Proportion	(3) Frequency	(4) Low-Carbon City
GCC	0.1826***	1.0317***	0.2068***	0.2867***
	(0.0600)	(0.3831)	(0.0519)	(0.0688)
Constant	−16.8281***	−16.4188***	−16.4188***	−16.1704***
	(0.3857)	(0.3629)	(0.3626)	(0.2915)
Control variable	YES	YES	YES	YES
Individual fixed effects	Controlled	Controlled	Controlled	Controlled
Time fixed effects	Controlled	Controlled	Controlled	Controlled
Pseudo R2	0.1816	0.1815	0.1818	0.1871
Observations	2,930,219	2,930,219	2,930,219	2,930,219

The numbers in parentheses represent standard errors, while symbols *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 5 Internal mechanism.

	(1) R&D	(2) Government Subsidy	(3) Coal Consumption
GCC	0.4372***	0.9069***	−0.7303***
	(0.0318)	(0.0169)	(0.0890)
Constant	−8.6653***	−6.8412***	0.6325***
	(0.0419)	(0.0264)	(0.0995)
Control variable	YES	YES	YES
Individual fixed effects	Controlled	Controlled	Controlled
Time fixed effects	Controlled	Controlled	Controlled
R2/Pseudo R2	0.1160	0.0956	0.1509
Observations	751,806	1,715,917	196,140

The numbers in parentheses represent standard errors, while symbols *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

increase the probability of the firms in the region carrying out renewable energy technology innovation. However, the above research does not involve a discussion of the underlying mechanism involved. This section seeks to further investigate the internal mechanism through which the local government's low-carbon concerns influence firms' renewable energy technology innovation.

First, as the number of the government's low-carbon concerns increases, additional low-carbon policies are introduced and implemented in succession, thus increasing the carbon emission constraints faced by firms in the region. According to Porter's hypothesis, when faced with environmental constraints, firms may choose to increase their R&D investment, thereby improving their innovation in renewable energy technology (Porter and Linde 1995, Yang et al. 2012). Column (1) of Table 5 takes firm R&D as the explained variable and government low-carbon concerns as the explanatory variable. The findings show that the government's low-carbon concerns are positive, which indicates that such concerns promote firms' innovation in renewable energy technology by increasing the R&D of firms; that is, increasing R&D investment is one effective mechanism by which the government's low-carbon concerns lead to firms' innovation in renewable energy technology.

Second, as the number of the local government's low-carbon concerns increases, the government's support and subsidy policies may be more inclined toward low-carbon manufacturing, thus reducing the opportunity costs of low-carbon technology and encouraging a larger number of firms to carry out renewable energy technology innovation (Hu et al. 2020, Li and Gao 2022). Column (2) of Table 5 takes the subsidies received by firms from the government as the dependent variable and the government's low-carbon concerns as the independent variable. The findings show that the government's low-carbon concerns are positive, which indicates that such concerns promote the innovation of firms' renewable energy technologies by increasing the amount of the government subsidies received by firms in the region; that is, obtaining more government subsidies is an effective mechanism by which the government's low-carbon concerns lead to firms' renewable energy technology innovation.

Finally, with the increase in the amount of local governments' attention being paid to low levels of carbon emissions, firms' consumption of primary energy, especially coal, decreases, and the energy cost increases, thus prompting some firms to carry out renewable energy technology innovation (Hafezi and Zolfagharinia 2018). Column (3) of Table 5 takes the coal consumption of firms as the dependent variable and the government's low-carbon concern as the independent variable. The findings show that government's low-carbon concerns are negative, indicating that such concerns inhibit the coal consumption of firms and promotes firms' innovation in renewable energy technology by increasing the energy costs of firms in the region. That is, an increase in firms' energy costs is an effective mechanism through which the government's low-carbon concerns lead to firms' renewable energy technology innovation.

Extensive analysis

Heterogeneity analysis. Regarding technical characteristics, differences in innovation types may affect the relationship between the government's low-carbon concerns and firms' renewable energy technology innovation. According to the technology types in the sample, the different impacts of regional governments' low-carbon concerns on the amounts of firms' biomass and waste energy, wind energy, solar energy and other types of renewable energy technology innovation is investigated. The analysis results are shown in the upper-left part of Fig. 2[3]. A comparison of the coefficients of the effects of government low-carbon concerns on different types of renewable energy technologies clearly reveals that the government's low-carbon concerns have a significant positive influence on biomass and waste energy technology innovation but not on wind and solar energy technology innovation. The reason for this may be that the utilization and innovation of wind energy and solar energy may depend more on the natural conditions of the region in which the firm is located. Therefore, these types of renewable energy technologies are less affected by the low-carbon constraints of local governments. In contrast, biomass and waste energy technology innovation is more dependent on firms' willingness and ability to carry out innovation, and thus, these types of innovation are more inclined to be influenced by the low-carbon concerns of local governments.

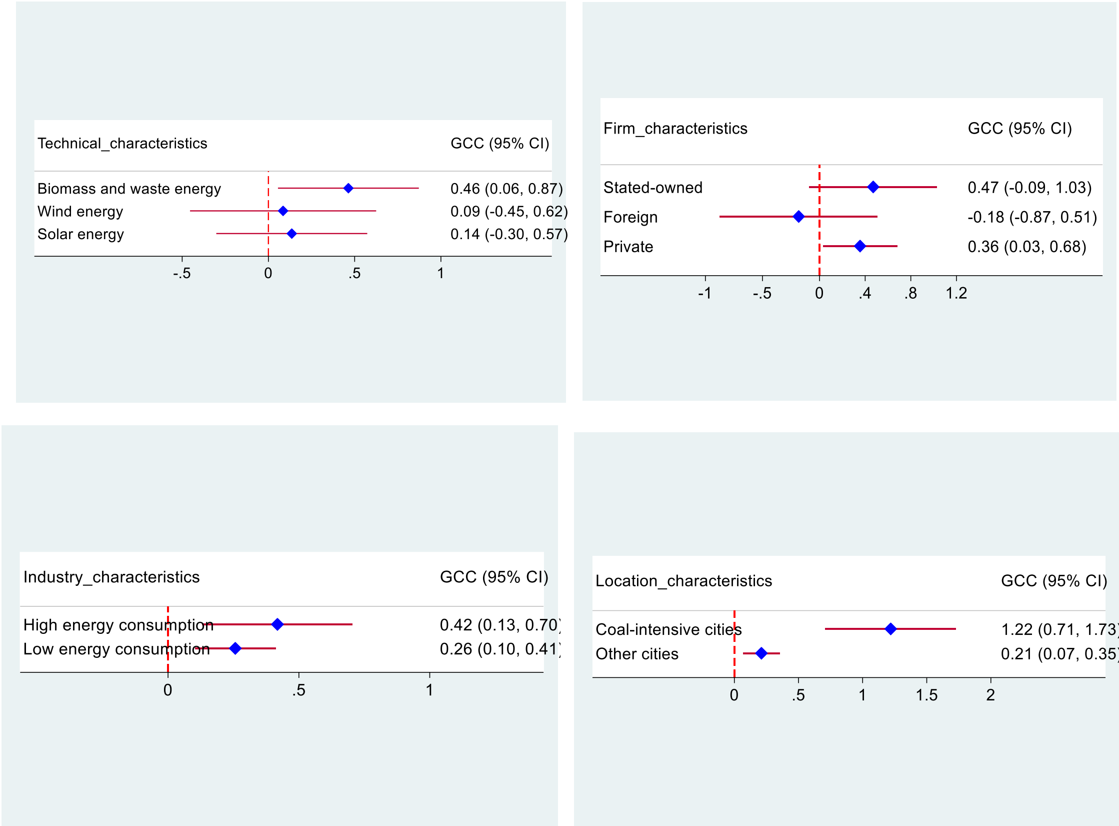

Fig. 2 Heterogeneity analysis. A vertical line with an abscissa scale of 0 is considered invalid. The graphic depicts the effect size and 95% confidence interval (CI) of the linked variable with diamonds and two-sided lines, respectively. When the CI horizontal line intersects the invalid vertical line at the 5% level, the variable coefficient is not significant.

Regarding firm characteristics, differences in the types of firm ownership may affect the relationship between the government's low-carbon concerns and firms' renewable energy technology innovation. Based on the differences in firm ownership, this paper investigates the different influences of regional governments' low-carbon concerns on the renewable energy technology innovation of firms with different ownership structures, the findings of which are presented in the upper-right part of Fig. 2. A comparison of the coefficients of government low-carbon concerns among the sample firms with varied ownership structures reveals that compared to other firms, private firms have the strongest stimulating influence on renewable energy technology, owing to the local government's low-carbon concerns. One possible explanation for this is that state-owned firms can often obtain a larger amount of policy support, while foreign firms may be better able to carry out pollution transfer. Therefore, with the increasing attention paid by local governments to low carbon emissions, the market reactions of state-owned firms and foreign firms are not as sensitive as are those of private firms.

For industry characteristics, the differences between different energy consumption industries may affect the relationship between the government's low-carbon concerns and firms' renewable energy technology. Based on the disparity in energy consumption across industries, the differential impact of the government's low-carbon concerns on the renewable energy technology innovation of firms with different energy consumption levels is investigated. The analysis results are shown at the lower-left part of Fig. 2. A comparison of the coefficients of the government's low-carbon concerns in the sample shows that such concerns have a significant promoting influence on the renewable energy technology of firms with different levels of energy consumption and have a stronger promoting influence on high-energy-consuming firms. The reason for this may be that the proportion of emission reduction costs in the production costs of high energy-consuming firms is greater than that of other firms, which makes high energy-consuming firms more willing to carry out renewable energy technology innovation.

Regarding location characteristics, the difference in resource endowments across regions may affect the relationship between the government's low-carbon concerns and firms' renewable energy technology innovation. Based on the differences in regional coal output, this paper examines the differential influence of regional governments' low-carbon concerns on the renewable energy technology of firms in coal cities and those in other cities. The analysis results are shown in the lower-right part of Fig. 2. A comparison of the coefficients of the government's low-carbon concerns in the sample of firms in coal cities and those in other cities reveals that the low-carbon concerns of the local government play a stronger role in supporting the renewable energy technology of firms in coal cities. The reason for this may be that coal cities have long used large amounts of carbon-emitting coal as their main energy source. When local governments pay more attention to low-carbon transformation, the firms in coal cities become increasingly constrained. Therefore, firms in coal cities also have a stronger motivation to carry out renewable energy technology innovation to achieve energy transformation than do firms in other cities.

Long-term and adjacent impacts. According to the findings of the preceding investigation, an increase in the number of the local government's low-carbon concerns can improve the probability of

Table 6 Long-term and adjacent impact.

	Long-Term Impact		Adjacent Impact
	(1) Lag one phase	(2) Lag two phase	(3)
GCC	0.5712***	0.5559***	0.4713*
	(0.1634)	(0.1835)	(0.2755)
Constant	−17.3695***	−17.5459***	−16.5108***
	(0.5653)	(0.5446)	(0.3653)
Control variable	YES	YES	YES
Individual fixed effects	Controlled	Controlled	Controlled
Time fixed effects	Controlled	Controlled	Controlled
Pseudo R2	0.1370	0.1311	0.1814
Observations	1,940,105	1,438,074	2,930,219

The numbers in parentheses represent standard errors, while symbols *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

renewable energy technology among local firms and allow for the further exploration of the underlying mechanism involved. Since firms' renewable energy technology innovation is a long-term process, this section further examines the long-term impact of the government's low-carbon concerns on firms' renewable energy technology innovation. Columns (1) and (2) of Table 6 investigate the influence of the government's low-carbon concerns on firms' renewable energy technology innovation in the following one and two years, respectively. The findings show that the variable for the government's low-carbon concerns *GCC* is positive, which indicates that in the long run, the government's low-carbon concerns have a long-term motivational influence on the renewable energy technology of local firms.

In addition, the current research focuses on the influence of environmental governance on firms' technological progress. Studies of the neighborhood effect of environmental governance focus on the problem of pollution transfer but generally ignore the impact of environmental policies on neighboring regions' technological progress. Therefore, we cannot help but ask whether the local government's growing concerns regarding low carbon emissions has a demonstration effect on neighboring firms. To answer this question, this paper establishes the low-carbon concerns of local governments in other cities in the same province to measure the demonstration effect of the government's low-carbon concerns. For the low-carbon concern indicator in other cities, we refer to Li and Du (2021), and the specific calculations are as follows. First, we calculate the total word frequency of government work reports in those cities in the province other than the city in which the firm is located within the sample interval. Second, we calculate the frequency of low-carbon words in government work reports in those cities other than the city in which the firm is located within the sample interval. Finally, the proportion of low-carbon words in other cities in the same province is calculated as a proxy variable for the adjacent government's low-carbon concerns. The results are reported in Column (3) of Table 6 and reveal that the government's low-carbon concerns in other regions are positive, which indicates that such concerns in other regions can increase the probability of local firms' innovation in renewable energy technology. The results support that the low-carbon concerns of local governments have a demonstration effect on the renewable energy technology innovation of firms in other regions.

Further discussion. The greatest problems faced in the large-scale development of renewable energy are its high costs and problematic consumption effects. Renewable energy technology may minimize utilization costs and address grid connection and consumption issues for some renewable energy sources, and it is the primary driving factor behind large-scale renewable energy development (Kreier 2022, Murray et al. 2014, Wang et al. 2023a, 2023b, 2023c, 2023d, 2023e, 2023f, 2023g). Against this background, this study investigates the influence of local governments' low-carbon concerns on firms' renewable energy technology innovation. The results show that the such concerns can improve renewable energy technology, which supports Porter's hypothesis (Ambec et al. 2013, Cohen and Tubb, 2018, Dagestani et al. 2023). The mechanisms indicate that R&D investment (Shi et al. 2023, Uche et al. 2023), government subsidies (Lee et al. 2022, Yang et al. 2021a, 2021b) and energy use costs (Klemun et al. 2023, Zhao et al. 2016) can lead to renewable energy technology innovation. Additionally, this study further explores the long-term and adjacent effects of government low-carbon concerns on firms' renewable energy technology. These results are consistent with those of existing research (Antelo et al. 2023, Emodi et al. 2019, Yang et al. 2021a, 2021b), which verifies the long-term incentive impact and positive demonstration impact of environmental policies.

Conclusions and policy implications

Conclusions. Renewable energy technology is a major driving factor in the creation of a low-carbon economy and the accomplishment of climate targets. Under the framework of heterogeneous firm theory, based on multivariate heterogeneous data from local government work reports, microfirm production and operation, and firm patent innovation, this paper discusses how local governments' low-carbon concerns affect local firms' renewable energy technology innovation and its internal mechanism at the theoretical and empirical levels, exploring the role of flexible low-carbon constraints and effective paths through which to achieve low-carbon development. The key research findings are as follows. First, the government's low-carbon concerns can improve the probability of firms adopting renewable energy technology. Second, firms' increasing R&D investment, subsidies received by firms from the government, and increasing energy use costs are important mechanisms through which the government's low-carbon concerns can lead to innovation in renewable energy technology. Third, in terms of technical characteristics, the government's low-carbon concerns have a greater promoting influence on firms' technology in terms of biomass and waste energy. In terms of firm characteristics, government low-carbon concerns have a stronger incentive influence on private firms' renewable energy technology. In terms of industry characteristics, the government's low-carbon concerns have a greater influence on renewable energy technology innovation in high energy-consuming industries than in other industries. Regarding location characteristics, the government's low-carbon concerns have a stronger incentive effect on renewable energy technology innovation in coal cities than in other cities. Finally, the government's low-carbon concerns have a long-term incentive effect, promoting the renewable energy technology innovation of local firms, and a positive demonstration effect, supporting the renewable energy technology innovation of neighboring firms.

Policy implications. The findings of this study have the following policy implications. First, we focus on the top-level design and strengthen the supervision of carbon emissions. The Chinese central government and various departments should strengthen the incentive and restraint roles of low-carbon and energy-saving indicators in the assessment of local officials, realize the internalization of firm carbon emission costs, further deepen China's carbon tax system reform and improve the unified national carbon market. Second, various policies should be comprehensively implemented, and the synergy between policies should be emphasized. Policies such as R&D subsidies and energy cost regulation policies can encourage firms to innovate in renewable energy and accelerate the optimization of the energy structure. Chinese firms that use coal as their primary source of energy should focus on investing in R&D for renewable energy technologies, accelerate the supply-side reform of the energy industry, and gradually increase the proportion of renewable energy consumption in overall energy usage. Third, we consider the heterogeneity characteristics and implement different carbon emission reduction objectives and regulatory policies. For firms with natural resource endowments supporting renewable energy technology innovation or regional advantages, greater R&D support policies should be implemented to encourage them to take the lead in achieving low-carbon transformation. For state-owned firms lacking the power of renewable energy technology and high-energy-consuming industries with high-level carbon emissions, hard constraints that strictly limit carbon emissions should be implemented. Fourth, the policy support system should be strengthened, and the long-term and demonstration effects of technological innovation should be leveraged. Local governments at all levels can increase their support for firms' renewable energy technology innovation by setting up related support funds, transforming traditional production equipment and processes, and promoting firms' adoption of a low energy-consuming production mode and green manufacturing mode.

Limitations and future recommendations. There are also other limitations to this research that need to be addressed in more detail in future studies. The government's low-carbon concerns involve complicated and wide-ranging internal mechanisms that influence local enterprises' innovation in renewable energy technologies. The underlying mechanisms are examined in this study from the viewpoints of energy consumption, government subsidies, and R&D. However, there could be mechanism recognition bias because of the lack of particular R&D expenditures and government subsidies connected to renewable energy, as well as data restrictions. Thus, the focus of future studies should be how to adopt more precise mechanism identification techniques and test more plausible mechanisms. Additionally, additional research is needed to determine whether the findings apply to other nations, particularly industrialized nations, as the Chinese government's low-carbon actions clearly exhibit Chinese features. Furthermore, broad generalizations would be possible if global firms were included in the sample and if horizontal comparisons were carried out.

Data availability
Data will be made available on request.

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Notes
1 We thank the reviewer for the suggestions on the cleaning and screening process of the indicator for the government's low-carbon concerns.
2 We thank the reviewer for the suggestions on supplementing the number of applications, whether they are authorized, and the amount of authorization for firm renewable energy technology patents as a robustness test.
3 Within the sample interval, the renewable energy technology patents of firms include three main categories: biomass and waste energy, wind energy, and solar energy. The sample size of other renewable energy technology patents is very small and cannot be used for subsample regression.

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