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Carbon emission reduction effects of renewable energy technological innovation in China: New insights into the intellectual property rights protection

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ABSTRACT

Renewable energy technological innovation (RETI) is of great significance in reducing carbon emissions. A deeper understanding of the impact of intellectual property rights (IPR) protection on the carbon reduction effect of RETI can provide policymakers with more specific information. Using the dataset from 30 provinces in China during 2007–2018, we provide a detailed analysis of the moderating role of IPR protection in RETI's impact on carbon emissions. The results suggest that RETI has a significant carbon reduction effect, but this effect is not substantial in hydropower technological innovation. Moreover, we find that IPR protection moderates the impact of RETI on carbon emissions; increased levels of IPR protection can enhance RETI's carbon mitigation effect. Specifically, this positive moderating effect is only evidenced in the high energy self-sufficiency ratio and eastern regions, and it diminishes as carbon emissions increase. However, we do not find any evidence that IPR protection moderates the impact of energy storage technological innovation on carbon emissions.

1. Introduction

Human-induced climate change is altering our planet and has become a topic of global concern. Adverse severe impacts have been brought to human societies by global climate change, including decelerating economic growth, threatening human health, and increasing occurrence of extreme climate events and natural disasters such as cold snaps, hurricanes, droughts, and forest fires [1–3]. Worse still, these adverse effects are expanding, and the situation is becoming more and more critical. In response, countries accounting for 70% of the global economy and 65% of carbon dioxide (CO_2) emissions have pledged to achieve net-zero emissions by 2020. However, the national climate governance processes have not stopped the acceleration of global warming. Issues related to carbon reduction pathways to achieve the Sustainable Development Goals (SDGs) have received more attention worldwide [4,5].

In China, renewable energy technological innovation (RETI) is the core pathway to addressing climate change and achieving carbon neutrality. This is mainly attributed to renewable energy being widely accepted as the future energy source due to its carbon-free emissions [6]. RETI lowers renewable energy costs and enables the country to achieve large-scale development, thus changing the current energy mix [7]. Raising RETI's level helps to fundamentally decouple economic growth from environmental pollution and

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resource consumption, leading to sustainable development [8]. To upgrade RETI's level, the Chinese central government released "China's Policies and Actions to Address Climate Change" in October 2021, which proposes prioritizing renewable energy development and comprehensively increasing renewable energy efficiency by upgrading China's RETI levels. Accordingly, it has become the consensus of local governments in China to promote and rely on technological innovation as a common strategic choice for renewable energy development. RETI has been included in the 14th five-year plan of many provinces.

However, the effect of RETI on carbon emissions is still controversial in available studies. Some studies have confirmed that improving RETI helps mitigate carbon emissions and low-carbon transition of the economic structure. Lin and Zhu [9] suggested that RETI upgrades will improve renewable energy capabilities to satisfy energy needs and are considered a cost-effective way to reduce CO_2 emissions. He et al. [6] found that RETI can effectively improve the total factor carbon performance index and thus suggested that RETI should be taken seriously and encouraged by the government. On the contrary, Bai et al. [7] indicated that increased RETI leads to higher CO_2 emissions in an economy with high-income inequality. Since increased income inequality would result in only a few consumers being able to afford new renewable energy technology products. Constrained consumer markets for new products drive companies to reduce their renewable energy technology innovation activities [10]. Moreover, Cheng and Yao [11] stated that the carbon abatement effect of RETI is only evident over a long period. Overall, more empirical evidence is needed on the carbon mitigation effects of RETI.

Regarding the impact of RETI on carbon emissions, the role of intellectual property rights (IPR) protection should be emphasized. Law and finance theory argues that a sound and efficient legal system is a significant element of technological advances [12]. IPR system is part of humanity's innovation systems, and its most direct impact is reflected in technological innovation [13,14]. Renewable energy technology achievements, such as advanced solar power generation and lithium battery energy storage technology, are emerging. The critical role of IPR protection in RETI is gradually emerging. First, compared to conventional technical innovations, RETI requires long-term fixed financial investment and personnel support [15]. The "Measures for the Administration of Priority Examination of Patents" promulgated by the Chinese government has established an expedited examination system for green patents. This has accelerated the commercial exploitation of RETI and improved the incentive for innovation and conversion efficiency of renewable energy technologies. Second, China's overall IPR protection system has been continuously improved in recent years, and a punitive damages system for infringement has been introduced in the patent law revision [16]. These have created a favorable market environment for domestic enterprises to commit to upgrading RETI. With the incorporation of IPR protection performance into local government performance assessment and business environment evaluation systems, IPR protection's role in the impact of RETI on CO_2 emissions at the provincial level deserves further investigation. However, as far as our knowledge goes, little literature analyzes whether IPR protection affects RETI and carbon emissions.

Therefore, taking 30 Chinese provinces from 2007 to 2018 as samples, our purpose is to examine how RETI affects CO_2 emissions and the role of IPR protection in it. Our contribution is as follows. **First,** we incorporate IPR protection, RETI, and CO_2 emissions within

Table 1
Related studies of IPR protection, technological innovation, and CO_2 emissions.

Author(s)	Time	Methodology	Argument(s)
(Lai, 1998) [24]	–	DSGE	The impact of IPRS on TI varies the channel.
(Kanwar and Evenson, 2003) [18]	1981–1995	GLS	Stringent IPRS encourages TI.
(Schneider, 2005) [25]	1970–1990	OLS	IPRS positively affects TI.
(Furukawa, 2010) [28]	–	DSGE	An inverted-U connection exists between IPRS and TI.
(Fan et al., 2013) [20]	2001–2002,2005	OLS	IPR enforcement affects firms' R&D investment.
(Lee and Min, 2015) [30]	2001–2010	FE	GTI negatively affects CE.
(Liu et al., 2018) [29]	2013–2015	OLS	U-shaped relations exist between IPRS and TI.
(Deng et al., 2019) [26]	2003–2014	OLS	A complementary effect between IPRS and TI exists in eastern and western regions.
(Lin and Zhu, 2019) [32]	2000–2015	FMOLS	RETI negatively affects CE.
(Erdoğan et al., 2020) [36]	1991–2017	CCE; AMG	Increased TI in the construction sector increases CE, but this doesn't exist in the energy and transport sectors.
(He et al., 2021) [6]	2002–2015	Tobit	RETI can effectively improve carbon performance.
(Gmeiner and Gmeiner, 2021) [21]	2008–2017	FE	IPRS encourages TI.
(Roh et al., 2021) [22]	2014–2016	PLS-SEM	IPR positively affects GTI of the company.
(Hao et al., 2021) [27]	2003–2016	OLS; SYSGMM	The heterogeneity exists in the impact of IPR and technology spillovers on CE.
(Cheng and Yao, 2021) [11]	2000–2015	PMG; DFE	RETI significantly reduces CE intensity.
(Xu et al., 2021) [31]	2007–2013	FE	Green innovation can promote CE performance.
(Yang et al., 2021) [35]	1997–2018	Panel threshold model	When the IPRS value was below 8.169, technology spillover on CE was positive.
(Razzaq et al., 2021) [37]	1990–2017	Panel quantile model	An asymmetric and murky relationship exists between CE and GTI.
(Dong et al., 2022) [19]	2008–2013	IV	IPR can strengthen R&D input.
(Yang and Zha, 2022) [33]	2000–2017	Decomposition Analysis	Biased technological progress increases renewable energy consumption and reduces energy intensity.
(Hu and Yin, 2022) [23]	2000–2007	DID	IPR can encourage innovative activities.
(Doğan et al., 2023) [34]	1992–2016	D-CCEMG; CCEMG	TI negatively affects CO_2 emissions.
(Ahakwa et al., 2023) [38]	1990–2019	AMG; DCCEMG	The impact of TI on the environment is slope-heterogeneous.

Note: IPRS stands for intellectual property rights protection; TI stands for technological innovation; GTI represents green technology innovation; and CE stands for carbon emissions.

one theoretical structure and identify the moderating effect of IPR protection on RETI's impact on CO_2 emissions. This enriches and expands existing studies on the drivers of CO_2 emissions reduction. Besides, a quantile regression model is employed to portray the full picture of the moderating effect of IPR protection at different levels of CO_2 emissions. **Second,** while studies have examined how RETI affects CO_2 emissions, they have not examined the impact of different types of RETI on CO_2 emissions, such as solar energy, wind power, and hydropower. Our study confirms that RETI reduces CO_2 emissions, but more interestingly, we find hydropower technological innovation does not reduce CO_2 emissions, which is not covered by earlier studies. **Third,** grouped by energy self-sufficiency ratio and geographical location, the heterogeneity of the impact of RETI on CO_2 emissions and the role of IPR protection are analyzed.

The remaining structure of this study is arranged below. Section 2 presents a literature review. Section 3 is methodology. Econometric tests and benchmark regression results are shown in Section 4. Section 5 presents an analysis of different types of RETI, panel quantile regression results, and the analysis of regional heterogeneity. Section 6 is conclusions and policy recommendations.

2. Literature review

Existing research on IPR protection, technological innovation, and CO_2 emissions is characterized by two aspects: IPR protection and technological innovation, technological innovation and carbon emissions. Tracing the research progress in these two areas helps us understand the causal links between IPR protection, RETI, and carbon emissions. Table 1 is a summary of the relevant research in both categories.

2.1. IPR protection and technological innovation

Considerable observations have been conducted in the existing literature on how IPR protection influences technological innovation, and some results have been achieved. New institutional economics states that institutional incentives determine technological innovation [17]. As a fundamental institution for technological innovation protection, the intellectual property system plays an irreplaceable and vital role in encouraging inventions and protecting the fruits of innovation and creativity [18]. Therefore, most theoretical studies mainly supported the argument that IPR protection can promote innovative activities. For example, Kanwar and Evenson [18] stated that IPR protection strongly and positively affects research and development (R&D) investment. Dong et al. [19] claimed that protecting intellectual property rights could strengthen R&D input, facilitating innovation activities. Activities. Evidence for this argument can also be found in Fan et al. [20], Gmeiner and Gmeiner [21], Roh et al. [22], and Hu and Yin [23].

Also, several empirical investigations have demonstrated heterogeneity regarding IPR protection's influence on innovations. For example, Lai [24] stated impacts of IPR protection on innovations vary across channels through which international production is transferred. Schneider [25] found that the influence of IPR protection levels on innovative efficiency is only pronounced among developed countries. Similarly, the existence of regional heterogeneity concerning how IPR protection influences innovative activities is confirmed by Deng et al. [26] and Hao et al. [27].

In addition, there is another opinion that IPR protection on-linearly affects innovation. For example, Furukawa [28] found a reverse U correlation between intelligence protection and technological advances. Moreover, Liu et al. [29] confirmed the U-shaped relationship between protecting intellectual property and innovative technology. Overall, the overwhelming evidence supports the positive effects of IPR protection on technological innovation.

2.2. Technological innovation and carbon emissions

As environmental issues become more prominent, there is concern about whether technological innovation can cut CO_2 emissions. Most of the literature confirmed that technological advances can mitigate climate change and are essential to achieve green development [30,31]. They argued that technological innovations could boost energy performance and cut energy inputs while increasing output. Lin and Zhu [32] discovered that RETI's enhancement can reduce carbon emissions. Cheng and Yao [11] found that long-term progress in renewable energy techniques markedly decreases energy intensity. Yang and Zha [33] found that biased technological progress can increase renewable energy consumption. Doğan et al. [34] demonstrated the carbon mitigation effect of innovative activities through econometric modeling.

Some empirical studies demonstrate that technological innovation affects carbon emissions heterogeneously [6,35]. Besides, Erdoğan et al. [36] stated that innovation's carbon reduction effects are insignificant in the transportation sector, whereas the result is reversed in the construction sector. Razzaq et al. [37] argued that there is an ambiguous relationship between greenhouse gas emissions and green innovations. Ahakwa et al. [38] affirmed the causality of technological innovation to environmental degradation with slope heterogeneity. Overall, the question of how technological innovation affects CO_2 emissions is still being explored.

2.3. Research gaps

The research conducted around IPR protection, technological innovation, and carbon emissions provides insights for this study. There are, however, some research gaps. **Firstly,** by measuring technological innovation using patents number, most previous studies have confirmed the carbon abatement effect of technological innovation. However, patents number do not consider patent depreciation and technology diffusion, which may result in biased measurements. How to scientifically measure technological innovation still needs to be further explored. **Secondly,** although several literatures have analyzed the role of RETI in carbon reduction, the conclusions could be more controversial. Also, the study on RETI needs to discuss the variation in carbon reduction effects of different types of renewable energy, such as biomass energy and energy storage. **Thirdly,** as an institutional factor indispensable to economic and social development, the role of IPR protection in technological innovation has been increasingly emphasized. But few studies have placed IPR protection, RETI, and carbon emissions in the same framework. Even fewer analyzed how IPR protection affects RETI and CO_2 emissions.

3. Methodology

3.1. Model specifications

The IPAT model, put forward in the 1970s, combines anthropogenic drivers with the core factors of environmental issues and forms an analytical framework [39]. It identifies population growth, rising material living standards, and technological resource exploitation and usage advances as fundamental drivers of increased resource and environmental pressures [40]. Since 2000, the IPAT model has been extended to analyze the factors influencing CO_2 emissions [41]. Based on the extended IPAT model, we develop a model to study the factors influencing CO_2 emissions as follows:

$$C = P \times A \times T \times E \tag{1}$$

in Equation (1), C stands for CO_2 emissions; P, A, T, E denote policies for environmental regulation, economic progress, technology innovation, and energy consumption, respectively.

We construct the panel data model based on the expanded IPAT model to examine whether RETI affects CO_2 emissions. The model is set up below:

$$PCO_{2it} = \beta_0 + \beta_1 RETI_{it} + \sum_{k=2}^{n} \beta_k X_{it} + u_i + v_t + \varepsilon_{it} \tag{2}$$

in Equation (2), i and t indicate province and year, respectively; PCO_2 means carbon emissions per unit; $RETI$ denotes renewable energy technological innovation; X represents control variables, including energy consumption, economic development level, environmental regulation, and R&D input intensity. u_i and v_t indicate the province and year fixed effects, respectively; ε_{it} indicates the random error term.

To observe whether IPR protection levels affect the strength or direction of the impact of RETI on carbon emissions, a moderation model is constructed as shown in model (3). The moderation effect is discussed as an interaction between RETI and IPR protection [42]. The model is specified as follows:

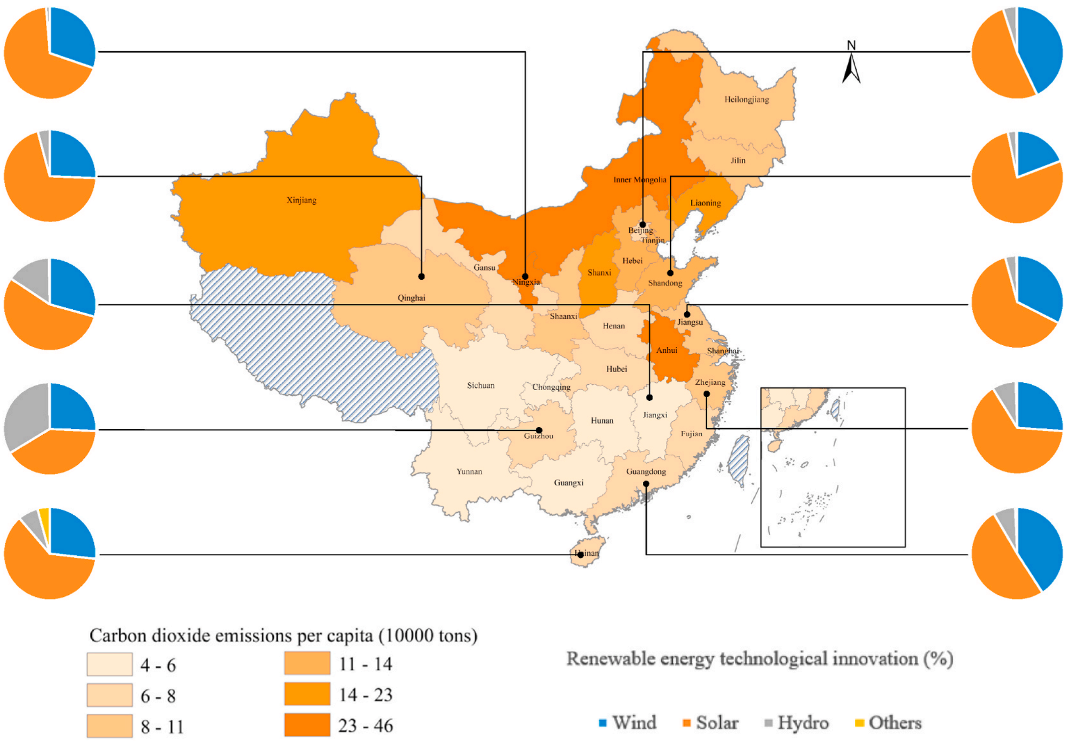

Fig. 1. PCO_2 in 30 Chinese provinces and RETI in the top 5 (the right) and bottom 5 (the left) provinces.

$$PCO_{2it} = \gamma_0 + \gamma_1 RETI_{it} + \gamma_2 IPR_{it} + \gamma_3 RETI_{it} \times IPR_{it} + \sum_{k=4}^{n} \gamma_k X_{it} + u_i + v_t + \varepsilon_{it} \quad (3)$$

in Equation (3), *IPR* means intellectual property rights. In model (3), γ_3 is the coefficient we are most interested in, which captures whether IPR protection influences the carbon mitigation effect of RETI.

3.2. Variables

3.2.1. Dependent variable

CO_2 emissions per capita (PCO_2). In China, the combustion of fossil fuels has been recognized as the primary source of CO_2 emissions. Therefore, CO_2 emissions are obtained by aggregating estimates of CO_2 emissions from different primary energy sources, such as coal, diesel oil, and electricity [43]. In the carbon emissions calculation, we use these nine types of energy consumption with their corresponding carbon emission coefficients. The formula is shown below:

$$PCO_{2it} = \sum_{j}^{9} CO_{2itj} \Big/ P = \sum_{j=1}^{9} EC_{itj} \times ALC_{itj} \times CEF_{itj} \Big/ P \quad (4)$$

in Equation (4), *i*, *t*, and *j* denote province, year, and energy type, respectively; *P* represents the total population of the region; *EC* represents the total energy consumption; *ALC* represents standard coal conversion coefficient; *CEF* represents the carbon emission coefficient of various energy sources. Fig. 1 shows the distribution of CO_2 per capita in 30 Chinese provinces during 2007–2018.

3.2.2. Core independent variables

(1) RETI. RETI aims to realize renewable energy development and focuses on innovation to provide new products, processes, services, and market solutions to enhance renewable energy resource distribution flexibility. Essentially, RETI is a type of green innovation. In previous studies, patent data is broadly applied to measuring technological innovation because it is objective, stable, and readily available [44,45]. However, the approach overlooks the proliferation and depreciation of patents. To remedy this, we regard the renewable energy knowledge stock to measure the RETI level [46]. The formula is the following:

$$RETI_{it} = \sum_{j=0}^{t} RPAT_{ij} \exp[-\beta_1(t-j)]\{1-\exp[-\beta_2(t-j)]\} \quad (5)$$

in Equation (5), *RPAT* indicates patents authorized. β_1 and β_2 indicate the depreciation and diffusion rates with 36% and 3% values, respectively [8]. Following the newest International Patent Classification (IPC) codes for renewable energy, renewable energy contains six categories, such as solar energy, hydropower, and storage. Fig. 1 shows the top 5 and bottom five provinces in RETI from 2007 to 2018 among the 30 Chinese provinces.

(2) IPR protection. In the existing literature, there are two main methods to measure IPR protection: (1) based on the Ginarte-Park (G&P) index [47]; (2) based on the application and protection of patents [48]. However, the G&P index is only calculated at the national level. Compared with the G&P index, the application and protection of patents provide a measure of the variation in IPR protection across provinces. But the laws and regulations on IPR protection promulgated by the Chinese government are applicable to all provinces. Hence, the difference in IPR protection level between provinces lies in laws and regulations implementation. The number of patents does not capture the level of implementation of laws and regulations.

Therefore, we construct an IPR protection index system to reflect the inter-provincial differences in the enforcement intensity of IPR protection in China (see Table 2). This IPR protection index system consists of four dimensions: judicial protection level, administrative protection level, economic development level, and education level [27]. The judicial protection level directly affects IPR legislation

Table 2
The comprehensive evaluation index system for IPR protection.

Dimension	Indicator	Unit	Formula
Judicial protection level	(a) Number of full-time lawyers	Pcs	$\frac{a}{b}$
	(b) Total population	Pcs	
Administrative protection level	(c) Number of cases closed patent infringement cases	Pcs	$\frac{c+d+e}{f}$
	(d) Number of other patent cases	Pcs	
	(e) Number of counterfeit patent cases	Pcs	
	(f) Number of patents granted	Pcs	
Economic development level	(g) Total GDP of each province	10^8 yuan	$\frac{g}{b}$
Education level	(h) Primary school	Year	$\frac{(h\times 6+i\times 9+j\times 12+k\times 16)}{l}$
	(i) Junior high school	Year	
	(j) Senior high school	Year	
	(k) Junior college or above	Year	
	(l) Population aged six years and above	Pcs	

strength in reality. If a province lacks a well-developed judicial system, the operation and implementation of intellectual property laws are constrained [49]. Administrative protection is the key for the government to safeguard IPR law enforcement. The higher the administrative protection level, the stronger the government's supervision and control, and the less ineffective the enforcement of IPR laws [50]. Besides, a province's IPR protection level corresponds to its economic development [51]. It is hard to imagine that someone who has not solved the subsistence problem would attach importance to IPR protection. The public's awareness of IPR protection is the basis for implementing intellectual property law. The higher the education level of the public, the higher the awareness of IPR protection.

Following index system construction, the entropy method is employed in the calculation to determine the weight of each indicator. Details of the steps are listed below.

(1) Standardize original data through Equation (6):

$$< \mathit{listaend} > Z_{\lambda ij} = \frac{X_{\lambda ij} - X_{\min}}{X_{\max} - X_{\min}} \tag{6}$$

in Equation (6), assuming there are r years, n regions, and m indicators, $Z_{\lambda ij}$ is the indicator j of the region i in a year λ. As the logarithm is used in the calculations, the normalized values are shifted as shown in Equation (7):

$$Z'_{\lambda ij} = Z_{\lambda ij} + A \tag{7}$$

(2) Calculate the ratio of the indicator j of the region i:

$$P_{\lambda ij} = \frac{Z'_{\lambda ij}}{\sum_{\lambda=1}^{h} \sum_{i=1}^{m} Z'_{\lambda ij}} \tag{8}$$

in Equation (8), $P_{\lambda ij}$ is the ratio of the indicator j of the region i in a year λ.

(3) Calculate the entropy and redundancy:

$$E_j = -k \sum_{\lambda=1}^{h} \sum_{i=1}^{m} P_{\lambda ij}\, ln\left(P_{\lambda ij}\right), k = \frac{1}{ln(hm)} \tag{9}$$

$$D_j = 1 - E_j \tag{10}$$

in Equation (9), E_j is entropy of the indicator j. In Equation (10), D_j is redundancy of the indicator j.

(4) Standardize coefficients and define weights:

$$W_j = \frac{D_j}{\sum_{j}^{n} D_j} \tag{11}$$

in Equation (11), W_j is weight of the indicator j.

(5) Count the region's IPR protection level.

$$IPR_{\lambda i} = \sum_{j=1}^{m} Z_{\lambda ij} \times W_j \tag{12}$$

in Equation (12), $IPR_{\lambda i}$ is the IPR protection level of the region i in the year λ. Fig. 2 shows the level of IPR protection we calculated for 30 Chinese provinces in 2007, 2013, and 2018.

3.2.3. Control variables

(1) Economic development (ED). The economic development level is a crucial factor that influences CO_2 emissions. When the economy is underdeveloped, the demand for industrialization and infrastructure construction drives energy consumption, exacerbating carbon emissions [52]. When economic development is at a high level, institutional reforms, optimization of industrial structure, and technological advances follow, reducing CO_2 emissions [53]. Therefore, we take ED as a control variable and use GDP per capita to express it.

(2) Energy consumption (EC). Evidence have confirmed that CO_2 emissions correlate with energy consumption, especially coal and oil consumption [5]. For renewable energy consumption, constructing the infrastructure for developing renewable energy requires fossil energy inputs, which generate carbon emissions [54]. Therefore, EC is a control variable denoted as total energy consumption.

(3) Environmental regulation (ER). Effective implementation of environmental regulations is prominent in addressing climate change. Zhao et al. [55] found that ER affects carbon emissions directly and indirectly (through energy consumption structure). Therefore, we take ER as a control variable, measured as the investment in treating industrial pollution.

Fig. 2. The level of IPR protection in 30 Chinese provinces in 2007, 2013, and 2018.

(4) R&D input intensity (RDI). R&D activities can promote new technology creation and strengthen technology acquisition [56]. Consequently, improving R&D intensity is a practical pathway to lower carbon intensity [57]. Therefore, we include RDI as a control variable and use the ratio of R&D expenditures to regional GDP to measure it.

3.3. Estimation strategy

We first perform the cross-sectional dependence (CD) tests to obtain unbiased and valid estimation results because CD is an essential issue in panel data studies. Second, the unit root test is conducted to see if the panel data are stationary. The second-generation unit root test is employed because first-generation unit roots cannot address CD disturbances. After that, a cointegration test is performed to recognize the long-term relations between variables. Fig. 3 shows the pivotal econometric test procedures.

After these tests, the following methods are used to estimate the results: fully modified ordinary least squares (FMOLS), panel-corrected standard error (PCSE), and feasible generalized least squares (FGLS). Compared with ordinary least squares (OLS), FMOLS can address the endogeneity of covariates and the serial correlation of residuals [58]. Compared with FMOLS, PCSE and FGLS can deal with cross-sectional dependence and heteroskedasticity. Compared with PCSE, FGLS can simultaneously address heteroskedasticity, intragroup autocorrelation, and contemporaneous correlation.

3.4. Data

Due to data limitations, our sample is a dataset of 30 Chinese provinces during 2007–2018. We collect the raw data from the Patent Search System of China's State Intellectual Property Office (SIPO) for RETI. SIPO is currently the only database with renewable energy technology patents starting from 1985. We match renewable energy patent application addresses with Chinese provinces to get provincial-level data on renewable energy patents. The data on IPR protection come from the China Lawyer Yearbook, China Education Statistical Yearbook, and China Science and Technology Statistical Yearbook. Data on RDI, ER, EC, ED, and CO_2 emissions come from the China Statistical Yearbook and the China Energy Statistical Yearbook. In our study, all variable data are processed by natural logarithm to minimize the absolute differences between the sample data and avoid the effect of extreme values. Table 3 shows descriptive statistics.

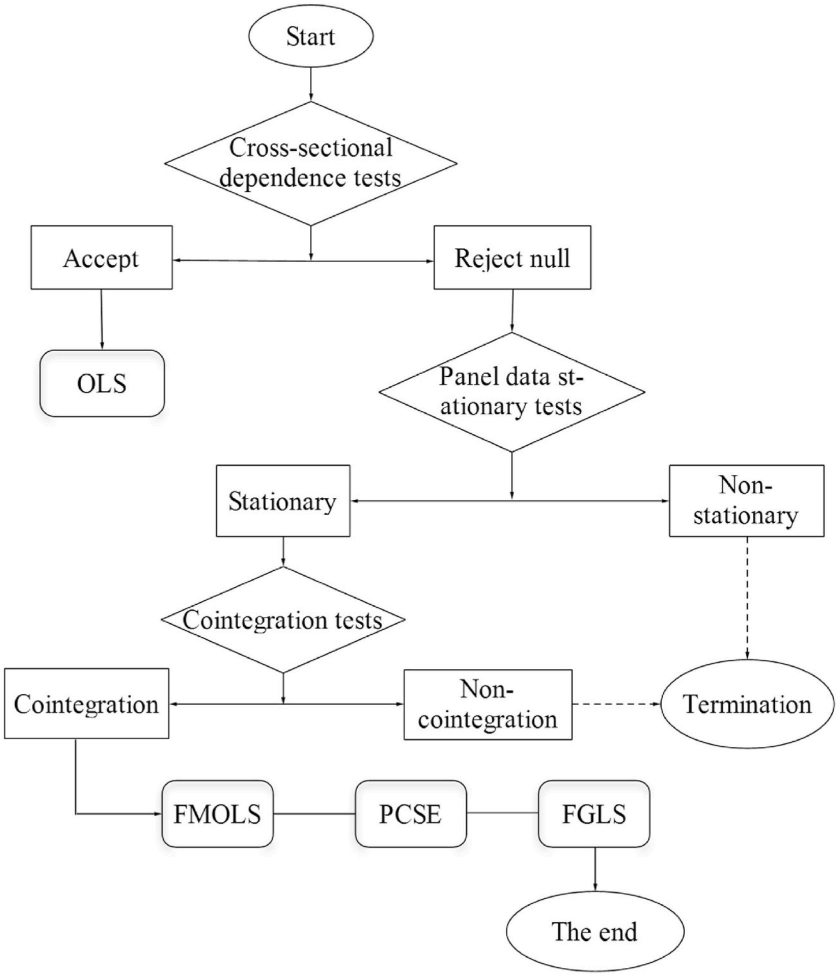

Fig. 3. Pivotal econometric test procedures.

Table 3
Descriptive statistics.

Variables	Unit	Mean	S.D.	Min	Max
PCO_2	10^4 tons	12.483	25.958	3.013	483.946
IPR	–	0.219	0.122	0.024	0.734
RETI	–	143.779	205.258	2.017	1198.818
ED	Yuan	24049.165	12399.680	7878	63951
RDI	%	0.006	0.004	0.001	0.033
ER	10^8 yuan	21.809	20.720	0.352	144.036
EC	10^4 TCE	13671.270	8351.88	1057	38899

Table 4
Results of CD test.

Method	Model (1)		Model (2)	
	Statistic	*P*-value	Statistic	*P*-value
Frees test	4.888***	0.000	4.882***	0.000
Friedman test	48.056**	0.015	42.990**	0.046
Pesaran CD test	16.122***	0.000	14.131***	0.000
Breusch-Pagan LM test	66.918**	0.019	322.464***	0.000

Note: *** indicates $p < 0.01$, ** indicates $p < 0.05$.

4. Empirical results

4.1. Pivotal econometric tests

We first check if the sample data has the CD. Table 4 shows that significant CD exists within the data, referring to intragroup autocorrelation. So we need to test whether the panel data used is stationary. Following Khan et al. [59], we employ the second-generation panel unit root test to assess the stationarity of our data. The results in Table 5 show that all variables belong to the first-order single integer. After that, we conduct the Pedroni test to evaluate cointegration, considering the varying intercepts and trends. According to the results in Table 6, a stable cointegration relation exists between variables in the long term. These tests prove that the model and data are suitable for empirical estimation.

4.2. Benchmark regression results

Based on the panel data test results, we employ FMOLS, PCSE, and FGLS with a two-way fixed effect for regression analysis in Table 7. In columns (1), (3), and (5), the elasticity coefficients of RETI to CO_2 emissions are all significant at the 1% level. Specifically, the coefficients are −0.136, −0.136, and −0.106, respectively. It is evident from the result that RETI has a detrimental effect on carbon emissions. Therefore, increasing RETI's level to attain carbon neutrality is imperative. Our research confirms previous studies' findings that have established RETI's negative impact on carbon emissions [11,32]. This result indicates that raising the RETI level helps fundamentally decouple economic development from environmental pollution and resource consumption.

Based on the data in columns (2), (4), and (6), it can be concluded that the elasticity coefficients of the interaction term between RETI and IPR protection are −0.077, −0.087, and −0.079. These results are significant at the 1% level. The estimated results indicate a moderating effect of IPR protection between RETI and CO_2 emissions. As (IPR) protection increases, the negative impact of RETI on CO_2 emissions becomes more pronounced. The mixed results of previous studies can explain this. First, the IPR system is one of humanity's most important institutional innovations, and its most direct impact is reflected in technological innovation. IPR protection allows innovators to obtain a monopoly of technology for a specific period and corresponding excess innovation revenue, which motivates enterprises to continuously increase their R&D investment [22]. Encouraging technological innovation in renewable energy is a great way to reduce carbon emissions [30]. Second, strong IPR protection tends to choke imitation activities, forcing companies to implement technological innovation in renewable energy to comply with global green and low-carbon development trends [37,60].

4.3. Robustness tests

We use the following methods to test whether the benchmark results are robust. The robustness test results are shown in Table 8.

First, we employ the history of the opening of the commercial port as an instrumental variable of RETI to deal with potential endogeneity. In modern China, the Qing dynasty was isolated from the outside world until the mid-19th century. The invasion of foreign troops forced the Qing government to open up to foreign trade, and advanced technology flowed into China. The earlier a region opens up to the outside world and trade, the longer the history of technology introduction and self-innovation. Moreover, the time of opening foreign ports cannot be altered and is a strictly exogenous variable. Therefore, following Yan et al. [15], the number of years from opening the commercial port of its capital city to December 31, 2018 (denoted by CI) is used as the instrumental variable. In columns (1) and (2), the results of the two-stage least squares (2SLS) method support the benchmark regression results.

Second, we exclude special samples for regression. In October 2015, the State Intellectual Property Office issued the "Work Plan for Accelerating the Construction of Strong Intellectual Property Provinces (for Trial Implementation)", proposing the layout of strong IPR pilot provinces in batches by2020.[1] Those provinces identified as pilots receive government policy attention and financial support, providing a better IPR protection environment for the development of RETI. Therefore, in columns (3) and (4), we exclude the pilot provinces from the samples, and the results remain robust.

Third, we perform robustness tests by using CO_2 emission data from the China Emission Accounts and Datasets (CEADs) (denoted by C_CO_2). The CEADs database provides China's provincial CO_2 inventory, including energy-related emissions (17 fossil fuels in 47 sectors) and process-related emissions (cement production). In existing studies, the data on CO_2 emission provided by CEADs is widely recognized [61,62]. The results in columns (5) and (6) support baseline regression results.

Fourth, we use alternative measures of IPR protection for regression. In column (7), IPR_dum represents the level of IPR protection, and it is a dummy variable for each province's IPR protection index. If the IPR protection index of a province is greater than the median value of all provinces in that year, IPR_dum takes the value of 1. Otherwise, it is 0. In column (8), we chose the share of administrative patent enforcement cases in the number of regional patent grants (IPP) to measure IPR protection [48]. The estimation results of columns (7) and (8) also support the benchmark regression results.

[1] The pilot provinces include Guangdong, Jiangsu, Shanghai, Sichuan, Shandong, Hunan, Fujian, Chongqing, Henan, Shaanxi, Jiangxi, Guangxi, and Gansu.

Table 5
Results of the Pesaran CADF test.

Variables	Levels		First-order difference	
	Constant	Trend and constant	Constant	Trend and constant
PCO_2	−1.348	−1.372	−2.197***	−2.843***
IPR	−2.119**	−2.144	−3.164***	−2.923***
RETI	−1.978	−2.756***	−2.853***	−3.097***
RDI	−1.657	−2.054	−2.776***	−3.335***
ER	−2.239***	−2.764***	−3.485***	−3.539***
EC	−1.481	−1.481	−2.110**	−2.242***
ED	−0.698	−2.149	−2.680***	−2.917***

Note: *** indicates $p < 0.01$, ** indicates $p < 0.05$.

Table 6
Results of Pedroni test.

Method	Model (1)		Model (2)	
	Statistic	*P*-value	Statistic	*P*-value
Modified Phillips-Perron test	7.349***	0.000	9.675***	0.000
Phillips-Perron test	−6.737***	0.000	−12.161***	0.000
Augmented Dickey-Fuller test	−5.705***	0.000	−9.010***	0.000

Note: *** indicates $p < 0.01$.

Table 7
Benchmark regression results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	FMOLS	FMOLS	PCSE	PCSE	FGLS	FGLS
RETI	−0.136***	−0.089***	−0.136***	−0.090*	−0.106***	−0.087***
	(0.000)	(0.000)	(0.006)	(0.075)	(0.000)	(0.001)
IPR		−0.164***		−0.172**		−0.047
		(0.000)		(0.020)		(0.140)
RETI × IPR		−0.077***		−0.087***		−0.079***
		(0.000)		(0.000)		(0.000)
ED	−0.000	−0.010	0.004	−0.012	0.004	−0.001
	(0.990)	(0.318)	(0.878)	(0.663)	(0.689)	(0.945)
EC	0.432***	0.363***	0.421***	0.349***	0.493***	0.391***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
RDI	−0.115**	−0.157***	−0.104	−0.146	−0.013	−0.013
	(0.014)	(0.000)	(0.260)	(0.108)	(0.728)	(0.739)
ER	0.006	0.013	0.009	0.013	0.007	0.010
	(0.608)	(0.166)	(0.779)	(0.674)	(0.429)	(0.283)
Constant	−1.817***	−1.296***	−1.704**	−1.067	−2.087***	−0.955*
	(0.000)	(0.000)	(0.034)	(0.226)	(0.000)	(0.084)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Province fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	359	359	360	360	360	360
R-squared	0.759	0.754	0.820	0.824		

Note: *P*-values in parentheses; *** indicates $p < 0.01$, ** indicates $p < 0.05$, * indicates $p < 0.1$.

5. Further discussion

5.1. Analysis of different types of RETI

Since the FGLS method can address heteroskedasticity, intragroup autocorrelation, and contemporaneous correlation simultaneously, the FGLS regression method is used to ascertain whether the decrease in carbon emissions differs among various categories of renewable energy technologies. The results in Table 9 show that technological innovations in wind power, solar energy, marine energy, biomass energy, and energy storage negatively affect carbon emissions. However, hydropower technological innovation is proven to have a negligible impact on carbon emissions. According to data from China's National Energy Administration, China's installed hydropower capacity reached approximately 391 million kW by 2021, representing 16.5% of the total installed power generation capacity. As an essential component of renewable energy resources, why has hydropower technology failed to reduce carbon emissions significantly? The core reason is that China's hydropower development is long-term and high-level exploitation, and the existing installed capacity is ample. Data from China's National Bureau of Statistics show that installed hydropower capacity has exceeded 90%

Table 8
The results of robustness tests.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	RETI	PCO_2	PCO_2	PCO_2	C_CO_2	C_CO_2	PCO_2	PCO_2
CI	0.203*** (0.000)							
RETI		−0.565* (0.093)	−0.230*** (0.000)	−0.137*** (0.007)	−0.049* (0.065)	−0.038 (0.171)	−0.100*** (0.000)	−0.090*** (0.001)
IPR	−0.670** (0.027)	1.074* (0.101)		−0.104** (0.042)		−0.037 (0.164)		
RETI × IPR	0.007*** (0.002)	−0.549* (0.090)		−0.070*** (0.000)		−0.060*** (0.000)		
IPR_dum							−0.012 (0.512)	
RETI × IPR_dum							−0.001* (0.059)	
IPP								0.001 (0.951)
RETI × IPP								−0.027*** (0.000)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	360	360	204	204	360	360	360	360

Note: *P*-values in parentheses; *** indicates $p < 0.01$, ** indicates $p < 0.05$, * indicates $p < 0.1$; the regression results with province and year fixed effects.

Table 9
Regression results of the effects of different types of RETI on CO_2 emissions.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
Wind	−0.068*** (0.000)					
Solar		−0.089*** (0.000)				
Hydro			0.007 (0.501)			
Marine				−0.081*** (0.001)		
Biomass					−0.143** (0.028)	
Storage						−0.065* (0.091)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes
N	360	360	360	360	360	360

Note: *P*-values in parentheses; *** indicates $p < 0.01$, ** indicates $p < 0.05$, * indicates $p < 0.1$; the regression results with province and year fixed effects.

of economically exploitable capacity.

We further analyze whether IPR protection impacts carbon emission reduction effect of different types of RETI. The results in Fig. 4 show that IPR protection exacerbates the carbon emission reduction effects of technological innovations in wind power (a), solar energy (b), hydropower (c), marine energy (d), biomass energy (e), and energy storage (f). Interestingly, when the value of IPR protection is above 0.08, the previously insignificant negative impact of hydropower technological innovation on CO_2 emissions becomes significant. Therefore, improving IPR protection level is vital to reduce carbon emissions by innovative hydropower technologies.

However, no substantial evidence supports the notion that IPR protection is a determining factor in advancing energy storage technological innovation. This is mainly because of China's rapid development of technological energy storage innovation; enterprises focus their competition on technology and market, and the relevant policy system still needs sound. Related intellectual property litigation cases occur frequently, making it more difficult for enterprises to defend their rights. The promotion of IPR protection to technological innovations in energy storage is limited.

5.2. Analysis of quantile regression results

Research has revealed that the impact of technological innovation in reducing carbon emissions is contingent on the scale of

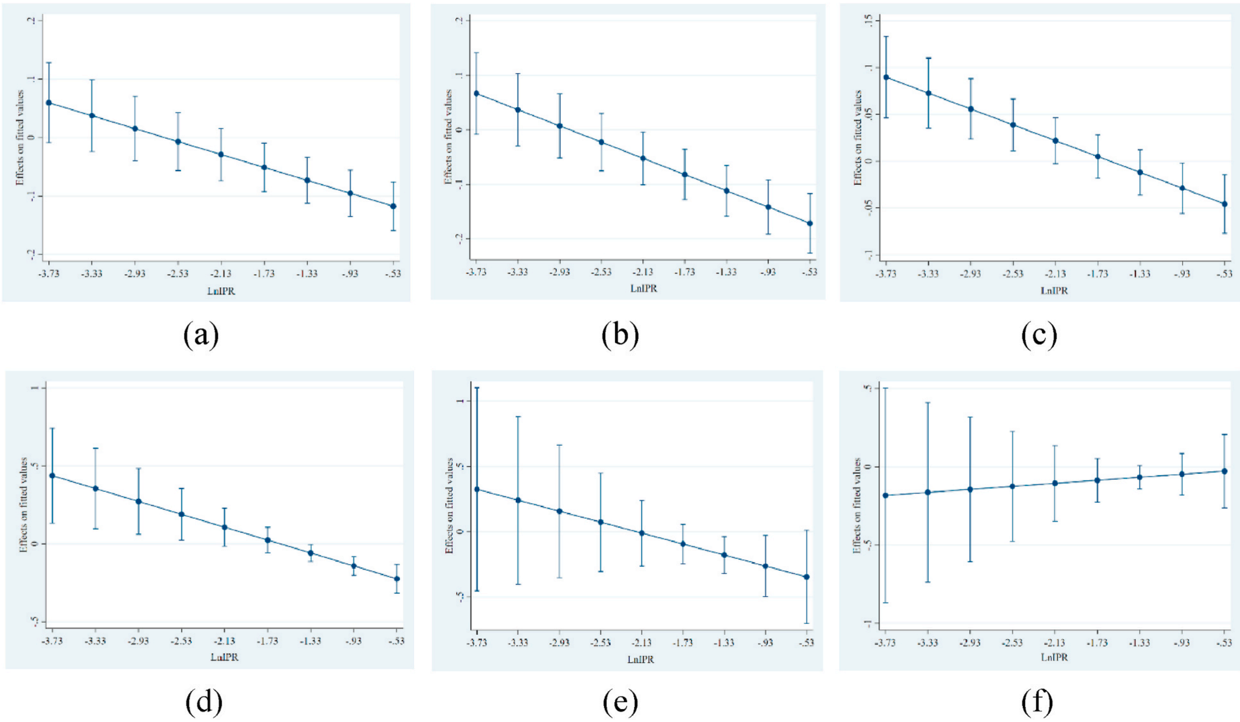

Fig. 4. The effect of IPR protection on the carbon emission reduction effects of technological innovations in wind power (a), solar energy (b), hydropower (c), marine energy (d), biomass energy (e), and energy storage (f).

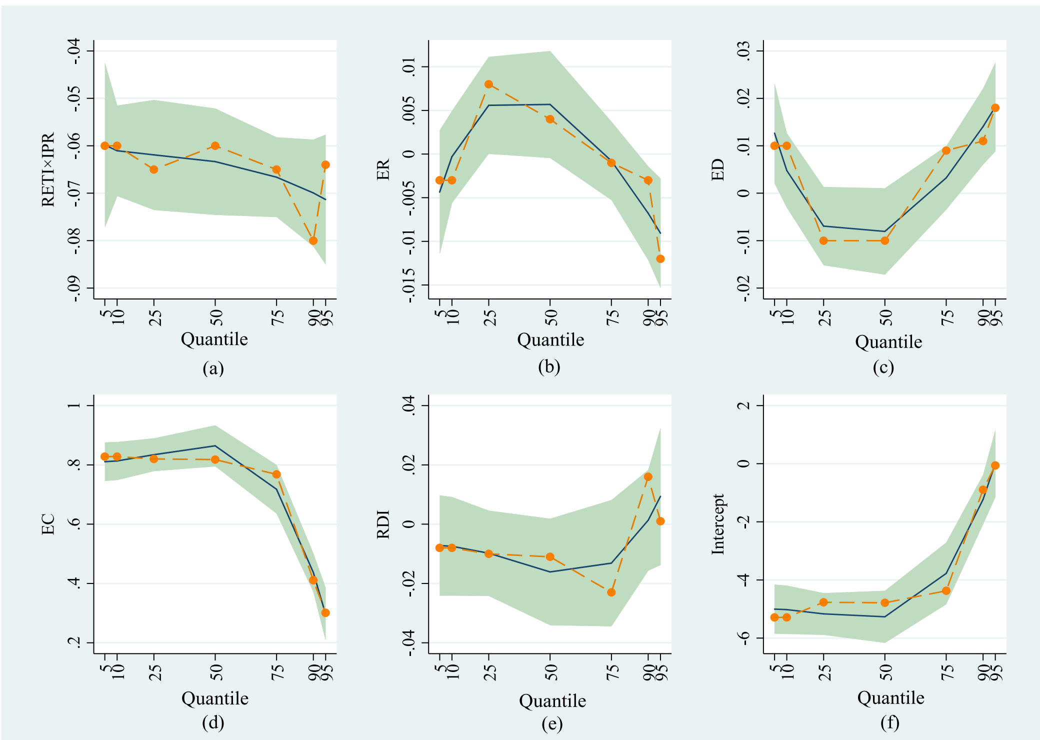

Fig. 5. The quantile regression results of the effect of IPR protection on RETI's carbon emission reduction effect (a), environmental regulation (b), economic development (c), energy consumption (d), R&D input intensity (e), and the intercept term (f).

emissions [63]. There may be differences in the moderating effect of IPR protection at different quartiles. Therefore, to estimate this heterogeneity, we construct the following panel quantile model:

$$\begin{aligned} Q_{PCO_{2it}}(\tau|\cdot) = \lambda_0^\tau + \lambda_1^\tau RETI_{it} + \lambda_2^\tau IPR_{it} + \lambda_3^\tau RETI_{it} \times IPR_{it} + \sum_{k=4}^{n} \lambda_k^\tau X_{it} \\ + u_i^\tau + v_t^\tau + \varepsilon_{it}^\tau \end{aligned} \tag{13}$$

in Equation (13), we set seven quartiles, i.e., Q05, Q10, Q25, Q50, Q75, Q90, and Q95. The 30 Chinese provinces are divided into three classes according to the level of CO_2 emissions, namely low CO_2 emissions area (Q05, Q10, and Q25), medium CO_2 emissions area (Q50), and high CO_2 emissions area (Q75, Q90, and Q95).

Fig. 5 shows the quantile regression results of the effect of IPR protection on RETI's carbon emission reduction effect (a), environmental regulation (b), economic development (c), energy consumption (d), R&D input intensity (e), and the intercept term (f). As shown in the figure, the moderating effect of IPR protection becomes weaker with increased carbon emissions. Specifically, in high carbon emissions regions (Q75, Q90, and Q95), such as Hebei, Shanxi, Inner Mongolia, Jiangsu, Shandong, and Guangdong, the effect of IPR protection on the carbon emission reduction effect of RETI is minimal. This may be due to the following reasons: First, for regions such as Shanxi, Inner Mongolia, and Hebei, regional economic development relies heavily on coal. Coupled with the pursuit of economic growth and the rapid expansion of secondary industries, the incentive for innovation brought about by increased IPR protection is limited, thus failing to create a significant carbon emission reduction effect. Second, for regions such as Jiangsu, Guangdong, and Shandong, the electricity consumption of the steel industry, chip manufacturing, new energy battery, data center, modern service industry, and residents' life in the region has increased rapidly. The energy mix in these regions is coal-based, which leads to increased CO_2 emissions on top of the existing ones. In such a scenario, the effect of IPR protection to promote RETI's carbon reduction may be overshadowed.

5.3. Heterogeneity analysis

5.3.1. Grouped by energy self-sufficiency ratio

The ratio of total primary energy production to total final energy consumption, also known as the energy self-sufficiency ratio, significantly impacts a region's CO_2 emissions [64]. This paper divides the 30 Chinese provinces into two categories: High energy self-sufficiency ratio regions and low energy self-sufficiency ratio regions. The former includes energy-rich areas and old industrial bases, where the energy self-sufficiency ratio is greater than 100%; The latter consists of the Yangtze River Delta, the Pearl River Delta, Beijing-Tianjin-Hebei, and the central region, all of which have energy self-sufficiency ratio below 100%.

The results in Table 10 show that RETI's carbon emission reduction effect is significant in high energy self-sufficiency ratio regions but not significant in low energy self-sufficiency ratio regions. The moderating effect of IPR protection is also only significant in high energy self-sufficiency ratio regions. What explains the above differences? On the one hand, energy prices are often low and readily available due to the relative abundance of energy resources in high energy self-sufficiency ratio regions. Compared with low energy self-sufficiency ratio regions, the lower energy prices in high energy self-sufficiency ratio regions can reduce the cost of technical facilities for renewable energy development and facilitate the development of RETI. Moreover, the lower energy cost makes the innovation incentive effect of IPR protection more significant. On the other hand, inter-provincial energy transmission has caused the phenomenon of "carbon inequity" between provinces. While provinces with a high energy self-sufficiency ratio provide many energy-intensive products to other provinces, their carbon emissions are also increasing significantly. To a certain extent, these regions are responsible for part of the emissions of other provinces. To address this "carbon inequity", provinces with high energy self-sufficiency ratios have focused more on reducing fossil energy consumption and promoting local renewable electricity consumption, contributing to RETI's development. In addition, low energy self-sufficiency ratio regions invest in green projects in high energy self-sufficiency ratio regions to help the latter achieve a low-carbon transition.

Table 10
Regression results grouped by energy self-sufficiency ratio.

Variables	High		Low	
	(1)	(2)	(3)	(4)
RETI	−0.039**	−0.081***	−0.086	−0.068
	(0.016)	(0.007)	(0.234)	(0.399)
IPR		−0.036		0.009
		(0.228)		(0.966)
RETI × IPR		−0.106*		−0.033
		(0.057)		(0.285)
Control	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes
N	216	216	144	144

Note: *P*-values in parentheses; *** indicates $p < 0.01$, * indicates $p < 0.1$; the regression results with province and year fixed effects.

5.3.2. Grouped by geographical location

Following Zha et al. [65], we divide China into the eastern, central, and western regions. The three regions have individual features owing to their different natural constraints and resource status. The regression results of 30 Chinese provinces grouped by geographical location are reported in Table 11. RETI's carbon emission reduction effect is most potent in the eastern region, followed by the western region, but insignificant in the central region. The moderating effect of IPR protection between RETI and carbon emissions is only evidenced in the eastern region. This may be because the eastern region is economically developed and has the leading clean energy technology in the country. Several provinces, such as Anhui and Zhejiang, have proposed clear quantitative targets for non-fossil energy substitution and installed capacity in the 13th Five-Year Plan. Besides, the eastern region has a higher level of IPR protection and generally more vital awareness of IPR protection, which supports RETI.

6. Conclusions and policy implications

We provide evidence for RETI's carbon emission reduction effect and the moderating effect of IPR protection, using panel data covering 30 Chinese provinces from 2007 to 2018. Based on the econometric test results, FMOLS, PCSE, and FGLS are used for the baseline regression, and a series of robustness tests are provided. We then analyze the carbon reduction effects of different types of RETI and the moderating effect of IPR protection. Moreover, we analyze the differences in moderating effects across quartiles. Finally, regional heterogeneity is examined and grouped by energy self-sufficiency ratio and geographical location.

Our findings are as follows: (1) An increase in the level of RETI can reduce CO_2 emissions. (2) As IPR protection increases, the impact of RETI on reducing CO_2 emissions becomes more significant. This indicates that a robust IPR system is necessary for China's efforts to decrease carbon emissions. (3) Technological innovations in wind power, solar energy, marine energy, biomass energy, and energy storage are proven to negatively affect CO_2 emissions, while hydropower technological innovation does not affect CO_2 emissions significantly. In addition, IPR protection exacerbates the carbon emission reduction effects of technological innovations in wind power, solar energy, hydropower, marine energy, and biomass energy. But there is no evidence that IPR protection can moderate energy storage technological innovation and CO_2 emissions. (4) Panel quantile results show that the moderating effect of IPR protection on RETI's carbon emission reduction effect decreases as the quantile rises. (5) The results grouped by energy self-sufficiency ratio and geographical location show that RETI's carbon emission reduction effect is evidenced in the high energy self-sufficiency ratio in the eastern and western regions but insignificant in the low energy self-sufficiency and central regions. Moreover, the moderating effect of IPR protection on the impact of RETI on CO_2 emissions is only significant in high-energy self-sufficiency and eastern regions.

These findings have led to the identification of several policy implications. First, the government should focus on a large-scale high proportion of renewable energy development and utilization to promote CO_2 emission reduction and actively develop more efficient, economical, and reliable comprehensive utilization technologies, including wind, solar, biomass, marine energy, and energy storage technologies. Enterprises of all types of ownership should be encouraged to carry out solid alliances and deep collaboration among industries, universities, and research institutes around the energy industry chain and innovation chain, focus on breaking through crucial core technologies, and actively participate in practical cooperation with multilateral mechanisms and international organizations in energy science and technology. Second, the IPR system is an essential institutional innovation for humanity; therefore, IPR protection should be actively stimulated in achieving carbon reduction. The government needs to enhance IPR protection and encourage the development of IPR in creation, management, protection, and application. This will create a favorable institutional environment for green and low-carbon technology innovation. Especially in high carbon emission areas, IPR protection should be strengthened to obtain more excellent carbon emission reduction benefits. Third, the green industry in China has experienced rapid growth, which has led to increased intellectual property disputes between enterprises. Most of these disagreements are related to patent technology within the green technology sector. Enhancing IPR protection for green technologies in China is essential, focusing on the central and western regions. The government's efforts to strengthen IPR protection must consider four crucial areas: judicial protection, administrative protection, economic development, and education. The interplay between these factors highlights the potential for adequate IPR protection. Fourth, China's energy resources are unevenly distributed, and the resource advantages of energy-rich regions should be fully utilized to provide a better development platform for the development of RETI. The government advocates energy-importing regions to help energy-exporting provinces and actively promote inter-provincial "carbon equity".

Our study preliminarily explores the impact of IPR protection on RETI's carbon reduction effect. Along with the urgency of achieving China's dual-carbon goals, policymakers need more detailed and micro-level policy recommendations. However, limited by data availability, our study uses data from provincial administrative units. Subsequent studies will provide more empirical evidence on the correlation across the prefecture-level IPR protection, RETI, and CO_2 emissions. In addition, the potential mechanism by which IPR protection influences RETI's carbon emission reduction effect can be emphasized in the subsequent research.

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Author contribution statement

Dongqin Cao:Conceived and designed the experiments; performed the experiments; analyzed and interpreted the data and wrote

Table 11
Regression results grouped by geographical location.

Variables	Eastern		Central		Western	
	(1)	(2)	(3)	(4)	(5)	(6)
RETI	−0.141***	−0.074***	0.011	0.204	−0.097***	−0.087**
	(0.000)	(0.003)	(0.940)	(0.243)	(0.006)	(0.016)
IPR		0.189***		−0.426**		−0.065*
		(0.003)		(0.291)		(0.058)
RETI × IPR		−0.077***		0.268		−0.054
		(0.000)		(0.589)		(0.503)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes
N	132	132	96	96	132	132

Note: *P*-values in parentheses; *** indicates p < 0.01, ** indicates p < 0.05, * indicates p < 0.1; the regression results with province and year fixed effects.

the paper.
Lijuan Si:Conceived and designed the experiments; performed the experiments; analyzed and interpreted the data.
Guanglei Yang: Conceived and designed the experiments; performed the experiments; wrote the paper.
Hongying Zhang: Conceived and designed the experiments; analyzed and interpreted the data..

Data availability statement

Data will be made available on request.

Additional information

Supplementary content related to this article has been published online at [URL].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

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