



# Renewable energy technology innovation and inclusive low-carbon development from the perspective of spatiotemporal consistency

Long Xin<sup>1,2</sup> · Hui Sun<sup>1,2</sup> · Xuechao Xia<sup>1,2</sup>

Received: 30 June 2022 / Accepted: 6 October 2022 / Published online: 18 October 2022  
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## Abstract

As an emerging driving factor, the positive impact of renewable energy technology innovation (RETI) on inclusive low-carbon development (ILCD) may be undervalued or even neglected. This paper develops an evaluation system to measure China's ILCD by using provincial panel data from 2006 to 2020. Based on the combined perspective of spatial spillover effect and threshold effect, this paper examines the spatial spillover effects and the regional boundary of RETI on ILCD in different periods and further analyzes five heterogeneities. The results show that (1) RETI and ILCD are increasing steadily, presenting a spatial pattern of “high in the east and low in the west.” (2) Overall, RETI significantly promotes ILCD in local and neighboring areas. RETI in the growth period inhibits local ILCD, which in the mature period promotes local and neighboring ILCD. (3) The spatial spillover boundary of the whole RETI is 1400 km, that of RETI in the growth period is 1000 km, and that of RETI in the mature period is 1600 km. (4) The promotion effect of RETI on ILCD enhances over time and shows a spatial pattern of “eastern > central > south > north > western.” It is further found that RETI strongly promotes ILCD in non-resource-based, high marketization, and strong environmental regulation areas. Therefore, it is necessary to break down administrative and market barriers, strengthen inter-regional cooperation and interconnection of resource elements, and establish a dynamic management mechanism of “one province, one policy” according to the regional heterogeneity for providing decision-making reference in promoting global energy transition and climate governance.

**Keywords** Renewable energy technology innovation · Inclusive low-carbon development · Spatial spillover effect · Spatial threshold effect · Regional boundary

## Introduction

Climate warming is one of the most urgent global problems in the world (Lin and Li 2022). To deal with the increasingly severe climate crisis, more than 120 countries worldwide have announced carbon neutrality targets. They are actively exploring effective pathways for the synergistic development of economic development and climate governance (Grainger and Smith 2021). Low-carbon development was proposed in 2003, aiming to encourage countries

to adopt green industrial transformation, sustainable economic growth and collaborative social development (Lyu et al. 2019). However, there are significant differences in economic development among countries in the world, and traditional low-carbon development models may aggravate social inequality, weaken economic growth drivers, and hinder the global low-carbon transition and climate governance (Wu et al. 2018). Therefore, it is of great significance for global climate governance to promote the change of the traditional low-carbon development model and actively explore a differentiated and inclusive low-carbon development model.

As the largest developing country and a carbon emitter in the world, China has set the goals of “carbon peak and carbon neutrality,” announced that it would not build any new overseas coal power projects, and promoted the Carbon Peaking Action Program by 2030, which fully demonstrates China's determination to deal with climate change and promote green and low-carbon development

Responsible Editor: Roula Inglesi-Lotz

✉ Hui Sun  
shui@xju.edu.cn

<sup>1</sup> School of Economics and Management, Xinjiang University, Urumqi 830046, China

<sup>2</sup> Centre for Innovation Management Research, Xinjiang University, Urumqi 830046, China

(Xin et al. 2022a). However, in proactively taking international responsibility for addressing climate issues and promoting low-carbon development, China has ignored the imbalance and inadequacy of economic and social development, which poses a significant challenge to promoting inclusive low-carbon development (ILCD) (Tol and Verheyen 2004). On the one hand, China's 70-year industrialization has long relied on coal resource consumption and achieved rapid economic growth at a lower cost. But with the increasing constraints on emission reduction, China's energy structure system will undergo a comprehensive low-carbon transition from coal to clean energy; at that time, the withdrawal of a large amount of fossil energy infrastructure could generate economic impacts (He et al. 2022; Sun et al. 2019). At the same time, the traditional energy industry is labor-intensive, and the gradual withdrawal of enterprises may lead to problems such as unemployment, health care and social security, which further aggravates social inequality and hinders the inclusive development of society (Marí-Dell'Olmo et al., 2022). On the other hand, some local governments have relaxed backward production capacity and poor energy management, leading to the categorical use of "one-size-fits-all" policy measures such as pulling the plug on electricity, halting production and limiting production, and cutting off loans in high-energy-consuming industries to carry out campaign-style carbon reduction near the environmental assessment, which has a severe impact on the sustainable development of economy and society (Pan and Hong 2022). Therefore, it is necessary to fully consider the differentiation and inclusiveness of regional low-carbon development levels to promote the high-quality completion of low-carbon transition goals and tasks according to local conditions.

Renewable energy technology innovation (RETI) is a crucial way to reduce carbon emissions and promote green development (Lin and Zhu 2019). The government of China actively adopts policy tools such as electricity price subsidies for renewable energy, government renewable energy technology funds and tax breaks and exemptions for renewable energy investment to encourage renewable energy technology development (Ren et al. 2022). Accordingly, the RETI in China has rapidly increased, with the number of RETI patents in China reaching 410,000 in 2020, 3.1 times that of the USA and 4.2 times that of Japan, respectively. The leapfrog development of China's RETI has become a guarantee of core capability for China to fulfill its commitment as a major country to global climate change (Lin and Zhu 2019). However, the outbreak of COVID-19 in early 2020 had a profound impact on the energy sector and the macro economy, affecting global renewable energy development and low-carbon transition. In 2020, the global economy

shrank by 4.3%, and the impact of the COVID-19 pandemic exceeded the effect of the global financial crisis in 2008 (Chen and Yeh 2021). A prolonged economic downturn will exacerbate poverty and social inequality and hamper countries' efforts to achieve sustainable development and address climate change. Therefore, a clear understanding of the impact mechanism of RETI on ILCD in China not only contributes to achieving carbon neutrality but also provides experience and valuable reference for promoting global economic "green recovery."

To promote ILCD, this paper explores the following issues: (1) how to define the connotation of ILCD scientifically, and further to build a complete and reasonable index system to measure regional ILCD effectively? (2) Does RETI have a spatial spillover effect and spatial threshold effect on ILCD? (3) What are the differences between the spatial spillover effect and regional boundaries of RETI on ILCD in different periods? The study of the above issues is not only beneficial to observe and grasp the reality of low-carbon and inclusive economic growth in the process of China's economic transformation, but also can provide a new perspective for understanding and guiding ILCD and promotion of global climate governance.

Therefore, based on inclusive growth and sustainable development theories, this paper organically combines inclusive growth and low-carbon development to further define the theoretical connotation of ILCD and construct the economic growth, social inclusion and low-carbon development (ESC) analytical framework from three dimensions of economic growth, social inclusion and low-carbon development. Secondly, the improved entropy weight method is used to estimate the ILCD level of 30 provinces in China from 2006 to 2020. Kernel density estimation and Moran's I index are used to describe the spatial and temporal patterns of ILCD. Finally, based on the spatiotemporal consistency perspective, this paper examines the spatial spillover effects and the regional boundary of RETI on ILCD in different periods, and further explores the differential spatial effects under the constraints of time, region, resource endowment, marketization level, and environmental regulation. The proposed policy recommendations may help break through regional constraints and provide a reference for decision-making on renewable energy development and ILCD in China and other countries.

The rest of the study includes the following sections: the "Literature review" section combs the relevant literature on inclusive growth, inclusive green growth, low-carbon development, RETI and low-carbon development and the main marginal contribution of the paper; the "Methodology and data" section clarifies methodology and data; the "Empirical results" section analyzes empirical results; the "Conclusions and discussions" section puts forward conclusions and recommendations.

## Literature review

### Inclusive growth

To narrow the gap between the rich and the poor and promote social equity, the Asian Development Bank (2008) first proposed inclusive growth, believing that it is an equal opportunity growth in which everyone participates in economic development opportunities equally and shares economic development achievements fairly. The existing research on inclusive growth focuses on the definition of theoretical connotation, measurement and influencing factors of inclusive growth. Regarding theoretical connotation, Chatterjee (2005) argued that inclusive growth is the process of reducing poverty and social exclusion. Ali and Zhuang (2007) claimed that inclusive growth is an equal opportunity growth, in which everyone has equal opportunities to participate in and share economic development achievements. World Bank (2012) considered inclusive growth as part of the sustainable development theory, which focused on social equity and income distribution in the development process. Some scholars equate inclusive growth with “pro-poor growth” or “shared growth,” which focuses on whether growth benefits the poor and the results of growth (Besley and Cord 2007; Rauniyar and Kanbur 2010; Birdsall 2007; Besley and Persson 2009). Ianchovichina and Lundström (2009) defined inclusive growth as a growth model that has long-term sustainability and creates employment opportunities and reduces poverty. They believed that inclusive growth emphasized the growth and transformation of the economic growth model. Sugden (2012) and George (2011) thought that inclusive growth is economic growth in which all social members can participate and share, focusing on equal growth opportunities.

Existing studies also differ in the measurement of inclusive growth. Some scholars have measured the inclusive growth level in different countries through the social opportunity function, welfare function or the poverty equivalent growth rate methodology (Ali and Son 2007; Domonkos and Ostrihon 2015). Liu et al. (2017) presented a novel hesitant fuzzy multiple attribute decision-making (HFMAADM) approach based on the nondimensionalization of decision-making attributes to evaluate inclusive growth in China. Alekhina and Ganelli (2021) combined per capita income growth and stock index to measure inclusive growth in ASEAN countries. Sun et al. (2018) and Jiang et al. (2021) measured the inclusive growth level in coastal and rural areas of China by constructing a system of indicators.

In addition, scholars have further focused on the influencing factors of inclusive growth. Many scholars have found that it can promote inclusive growth by taking some measures such as expanding fiscal redistribution, improving

female access to education, enhancing trade openness and frugal entrepreneurship, expanding government size and promoting infrastructure development and ICT-trade nexus (Aoyagi and Ganelli 2015; Hong et al. 2019; Whajah et al. 2019; Mutiiria et al. 2020; Adeleye et al. 2021; Hossain and Sarkar 2021; Kang and Martinez-Vazquez 2021). And human capital, taxes and transfer payments indirectly affect inclusive growth (Oyinlola et al. 2021; Parolin and Gornick 2021). However, a few studies have found that deviations in environmental regulation intensity, industrial robot use, and tourism growth inhibit inclusive growth (Hampton et al. 2018; Ge and Li 2020; Fu et al. 2021).

### Inclusive green growth

With the depletion of natural resources and the gradual deterioration of the ecological environment, countries worldwide have begun to realize that they should take a sustainable development pathway that balances inclusive and green. The concept of inclusive green growth was first proposed at the Rio + 20 Summit in 2012, aiming to closely link green development and inclusive growth with the world's interests (Jha et al., 2018). In March 2016, with the announcement of the new Sustainable Development Goals (SDGs) by the United Nations, many countries began to take inclusive green growth as the core content and implemented this new development strategy (Albagoury, 2016).

The research on inclusive green growth is increasing, mainly focusing on theoretical connotation, inclusive green growth measurement, and impact factor analysis. Existing studies on the definition of inclusive green growth have primarily developed from development economics and welfare economics, and the concept has not been uniformly defined. From the development economics standpoint, World Bank (2012) argued that inclusive green development is an effective way to address the survival and development needs of the world's poor people because it has the sustainable development characteristics of green growth and social equity. Berkhout et al. (2018) argued that inclusive green growth needs to focus on the welfare growth and intergenerational inheritance of current and future generations based on welfare economics when weighing the relationship between economic growth, inclusion and greenness. Slingerland and Kessler (2015) pointed out that inclusive green growth balances social equity and environmental sustainability and works to improve social welfare.

The measurement of inclusive green growth is mainly conducted on scale and efficiency. Most scholars construct an index system to measure inclusive green growth levels. For example, Kumar (2015) built an inclusive green growth evaluation system for low-carbon livable cities based on five dimensions such as energy consumption, green buildings,

greenhouse gas emissions, land utilization and sustainable transportation. Albagoury (2016) employed the subjective weighting method to calculate inclusive and green growth separately to measure inclusive green growth in Ethiopia. Sun et al. (2020a, b) constructed China's inclusive green growth analysis framework from four dimensions, including economic development, fair social opportunities, green production and consumption and ecological environment protection. Li et al. (2021a, b) constructed an index system to measure inclusive green growth in the Asia–Pacific region from four dimensions, including economic prosperity, social inclusion, resource utilization and environmental sustainability. Liu et al. (2021a, b, c) constructed an index system from the economic, social and ecological dimensions to examine the inclusive green growth level and its spatial differences in the Yangtze River Basin. Cao (2022) constructed an index system from the three dimensions of inclusion, green and growth to measure the inclusive green growth level in Anhui Province. Besides, based on the perspective of efficiency, a few scholars have used the SBM-DDF model, EBM model and Malmquist-Luenberger index to calculate the inclusive green growth efficiency in different regions and analyze their regional heterogeneity (Sun et al., 2020a; Chen et al. 2020a, b; Wang et al. 2021a, b; He and Du 2022).

In addition, some scholars have further analyzed the influencing factors of inclusive green growth. For example, Berkhout et al. (2018) used SYS-GMM to verify the U-shaped relationship between digital finance and inclusive green growth. Zhang et al. (2022) found that promoting the tourism industry towards high-quality contributes to inclusive green growth. Ojha et al. (2020) constructed the CGE model and found that carbon tax has a positive effect on inclusive green growth in India. Gu et al. (2021) examined that economic policy uncertainty has a nonlinear impact on inclusive green growth. Wu and Zhou (2021) found that fiscal expenditure structure efficiency has an essential effect on inclusive green growth. Ren et al. (2022) verified that digital economy agglomeration is conducive to inclusive green growth.

## Low-carbon development

As the climate problem becomes more intensified, low-carbon development has become a crucial strategy for countries worldwide. Low-carbon development is a vital way of reducing carbon emissions while achieving economic growth goals (Mulugetta and Urban 2010; Sun et al. 2020a, b). The existing study on low-carbon development is mainly in evaluating and influencing factor analysis. In the assessment of low-carbon development, some scholars use carbon intensity or per capita carbon emissions to measure regional low-carbon development levels based on the scale perspective (Shan and Bi 2012; Sheng and Lu 2016; Mondal

et al. 2018; Liu et al. 2019; Cheng et al. 2020; Ouyang et al. 2020). From an efficiency perspective, some scholars use the Super-slack model, SBM-Undesirable model, and improved DEA model to measure low-carbon development performance at the national, provincial, and city levels, and further explore their regional heterogeneity (Zhang et al. 2019a, b; Zha et al. 2019; Chen et al. 2020a, b).

Other scholars have comprehensively evaluated low-carbon development levels by constructing an index system. For example, Hu et al. (2011) constructed an Economy–Energy–Electricity–Environment (E4) analysis framework to characterize the low-carbon development level in China. Su et al. (2012) evaluated city-level low-carbon development level from five dimensions, including economic development, social progress, energy structure, living consumption, and environmental development. Qu and Liu (2017) used the DPSIR model to construct a low-carbon development index system based on city-level data. Tan et al. (2017) established the evaluation index framework for low-carbon development from five aspects, including economy, society, energy, transportation and environment. Wang et al. (2019) constructed an evaluation index system of low-carbon development for coal enterprises based on economy, energy and emission reduction. Wang et al. (2021a, b) established the evaluation index system of city-level low-carbon development from five dimensions in economy, society, urban planning, energy utilization and environment. Ye et al. (2022) constructed the low-carbon development index system from six aspects of economic development, social progress, energy consumption, low-carbon emissions, carbon sequestration capacity, and environmental carrying capacity.

Furthermore, scholars pay more attention to the influencing factors and realization paths in low-carbon development. Some studies have examined that the measures such as Internet Plus, national policies, clean energy use, carbon tax policies, industrial transformation, digital economy and the promotion of global value chains directly promote low-carbon development in different regions (Zhang et al. 2019a, b; Wang et al. 2020; Zhang et al. 2021; Liu et al. 2021a, b, c; Wang et al. 2022; Lin and Li 2022; Shi and Xu 2022). Zeqiraj et al. (2020) found that the development of the stock market indirectly improves the low-carbon development in EU countries by promoting technological innovation. In recent years, many scholars have used the DID test to verify that the carbon emissions trading system, urban forest construction, and government transfer payments to resource-exhausted cities (TPREC) have positive effects on low-carbon development (Zhang and Zhang 2019; Liao et al. 2021; Li and Wang 2022). But Liu et al. (2020) found that potential energy intensity aggravates carbon emission inequality and hinders low-carbon development. Meanwhile, a few studies have also found that the manufacturing development model transition and renewable energy consumption



have a nonlinear effect on low-carbon development (Tang et al. 2020; Li et al. 2021a, b).

## RETI and low-carbon development

With climate problems and the global energy crisis increasingly severe, research on how to develop RETI to accelerate low-carbon development is emerging (Khan et al. 2021). There are mainly three points on the relationship between RETI and low-carbon development:

**Promotional effect.** Sun et al. (2021a, b) verified that RETI promotes low-carbon development using data from Turkey. Liguó et al. (2022) found that RETI is beneficial to low-carbon development in the USA, where green international cooperation technology development plays a positive moderating role. Liu et al. (2021a, b, c) found that RETI reduces carbon emissions in oil-importing countries, but has no significant effect on oil-exporting countries. Godil et al. (2021) verified that RETI effectively promotes carbon reduction in the transportation sector in China. Khattak and Ahmad (2022) confirmed that there is a long-term negative effect of RETI on carbon emissions using data from OECD economies. Altıntaş and Kassouri (2020) examined that RETI has negatively impacts on the carbon footprint of European countries. Lin and Zhu (2019) verified that RETI could slow down climate warming and increase R&D investment in science and technology to promote low-carbon development effectively. You et al. (2022) found that green technology promotes renewable energy consumption and reduces carbon emissions in the USA. Wang and Zhu (2020) found that RETI not only reduces carbon emissions but also has a positive spatial spillover effect. Zeqiraj et al. (2020) empirically found that the stock market further promotes low-carbon development by enhancing RETI using data of EU member states.

**Nonlinear influence.** Cheng and Yao (2021) found that RETI has no effect on carbon intensity in the short term but significantly reduces carbon intensity in the long term. Bai et al. (2020) empirically examined that RETI has a threshold effect on low-carbon development. When income inequality exceeds the threshold value, RETI significantly promotes low-carbon development. Shao et al. (2021) used data from N-11 countries to verify that there is a long-term negative impact between RETI and carbon emission, but has no significant effect in the short term. He et al. (2021) confirmed that in promoting low-carbon development, marketization level and market potential play an important regulatory role. Zhao et al. (2022a, b) found that RETI promotes low-carbon development in China, but regional inequality has a negative regulatory effect.

No effect. Chen and Lei (2018) found that RETI has no significant impact on the low-carbon development of countries in the world, which may be because the energy consumption structure is still dominated by non-renewable energy, and the development of renewable energy is in the initial stage and plays a limited role. In addition, some scholars believe that there is an energy rebound effect in RETI, which offsets the promotion effect of technological progress on low-carbon development (Du et al. 2021a, b; Miao and Chen 2022; Zheng et al. 2022; Yan et al. 2019).

In general, the existing research focuses on inclusive growth, inclusive green growth, low-carbon development and carbon emission reduction effects of RETI, but there are still the following lacks: (1) although existing studies have revealed the significance of inclusive green growth for climate governance, in the face of increasingly prominent climate injustice in the process of achieving “carbon neutrality,” few studies have focused on the inclusiveness of low-carbon development. (2) The ILCD focus on the theoretical research, lacking the study on the measurement, spatial and temporal variation, and impact mechanism of ILCD in China. (3) Although the spatial spillover effect or threshold effect of RETI for carbon emission reduction have been analyzed separately (Wang and Zhu 2020), the possible co-existence of spatial spillover and threshold effects of RETI and ILCD are not considered, which may lead to biased research results. (4) The effect of RETI may be restrained by geographical distance and administrative boundaries, and the spatial spillover effect does not always exist (Jang et al. 2017). However, the existing literature lacks research on the spatial spillover attenuation characteristics and regional boundaries of RETI on ILCD.

Therefore, different from previous studies, the marginal contributions of this paper are as follows: (1) this paper organically combines inclusive growth and low-carbon development, systematically composes the theoretical logic of ILCD from three aspects of economic growth, social inclusion and low-carbon development, further constructs a comprehensive evaluation index system of ILCD scientifically and reasonably, and provides a research paradigm for effective measurement of ILCD. (2) This paper combines the spatial Durbin model and the panel threshold model to comprehensively investigate the spatial spillover effect and spatial threshold effect of RETI on ILCD in different periods, which effectively avoids the possible result bias caused by the separation of spatial and temporal effects. (3) The spatial spillover regional boundaries of RETI on ILCD in different periods are examined using the threshold distance spatial weight matrix, which is conducive to an empirical understanding of strengthening regional exchanges and cooperation of RETI to reduce emissions and promote carbon neutrality.

## Methodology and data

### Methods

#### The construction and evaluation of the ILCD index system

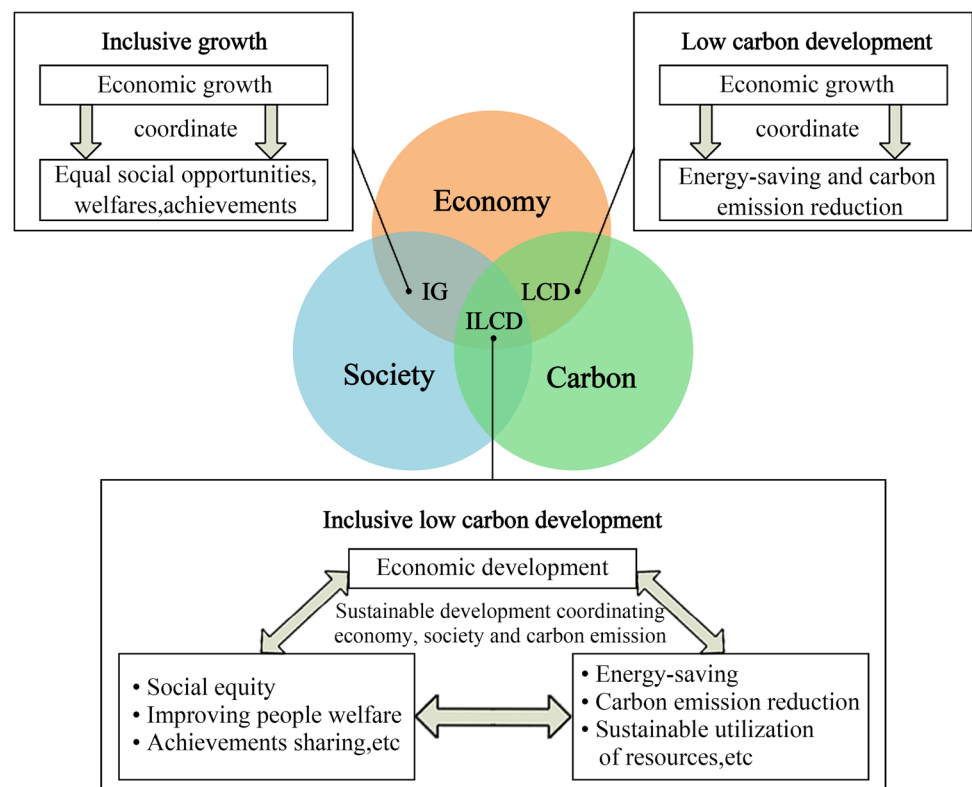
The scientific and objective evaluation of ILCD contributes to accelerating the realization of “carbon peak and carbon neutrality” goals, which is also significant for promoting the reform and construction of the global climate governance system (Xin et al. 2022b). The existing research has not formed a unified academic definition of ILCD. Based on the expansion and extension of the concept of inclusive green development, this paper regards ILCD as an organic combination of inclusive growth and low-carbon development. On the other hand, the realization of the “carbon peak and carbon neutrality” target should pay attention to regional differences, which aims to avoid the “one-size-fits-all” policy and campaign-style carbon reduction. The fairness and sharing of regional economic and social development should be taken into account while promoting carbon emission reduction targets, and the whole ILCD should be realized through diversified and flexible low-carbon development policies.

Therefore, ILCD should contain the following characteristics: (1) enhance income growth and poverty reduction. Steady economic growth is the basic element

to raise the income level of residents, and also the material guarantee to reduce poverty rate and income gap. (2) Promote social equality. The development model should be “people-oriented” to ensure that ordinary people have equal rights to participate in economic development, while the fruits of social development should be shared by all. (3) Improve the quality of low-carbon environment. It requires that economic and social development be accompanied by high efficient utilization of resources and synergistic governance of pollution and carbon reduction, which includes intensifying energy conservation and carbon reduction, enhancing low-carbon technological innovation capacity, creating a green and low-carbon environment and promoting low-carbon lifestyles. (4) Coordinated and sustainable development of all systems. It is necessary to strike a balance between economic growth, social inclusion and low-carbon development, rather than focusing on one at the expense of the other, which aims to pursue comprehensive coordinated and sustainable development.

Based on the theory of inclusive growth and sustainable development, this paper constructs an economic growth–social inclusion–low carbon development (ESC) analytical framework (Fig. 1). Meanwhile, considering scientificity, comprehensiveness, representativeness, and availability of the index system construction, 32 indicators are finally selected to characterize ILCD comprehensively (Table 1).

**Fig. 1** Connotation framework of ILCD



**Table 1** Indicator system of ILCD in China

First-level indicators	Second-level indicators	Third-level indicators	Unit	Attribute
Economic growth	Economic output	Per capita GDP	Yuan	+
		GDP growth rate	%	+
		The proportion of secondary industry	%	-
		The proportion of tertiary industry	%	+
	Income level	Per capita disposable income of urban residents	Yuan	+
		Per capita disposable income of rural residents	Yuan	+
		Per capita income ratio between urban and rural areas	/	-
Social inclusion	Medical opportunity equity	Number of health technicians per 10,000 people	/10,000 persons	+
		Number of beds in medical and health institutions per 10,000 people	/10,000 persons	+
	Education opportunity equity	Education funds investment intensity	%	+
		Educational resources per 10,000 people	/10,000 persons	+
	Employment opportunity equity	Employment rate	%	+
		Unemployment insurance coverage rate	%	+
	Social security opportunity equity	The proportion of expenditures for primary pension insurance fund	%	+
		The proportion of primary medical insurance fund expenditures	%	+
	Infrastructure condition equity	Per capita urban road area	m <sup>2</sup>	+
		Number of public buses and trams per 10,000 people	/10,000 persons	+
	Information services opportunity equity	Number of mobile phones per capita	/10,000 persons	+
		Internet coverage rate	%	+
Low-carbon development	Energy saving and carbon reduction	Total energy consumption	Tons of standard coal	-
		Per capita water consumption	m <sup>3</sup>	-
		Carbon emission intensity	Tons / million yuan	-
		The proportion of clean industry	%	+
		Number of green patents granted	case	+
	Low-carbon environment	Per capita park green space	m <sup>2</sup>	+
		The green coverage rate of urban built-up area	%	+
		Forest coverage rate	%	+
	Low-carbon life	Harmless treatment rate of domestic waste	%	+
		Centralized treatment rate of sewage treatment plants	%	+
		The comprehensive utilization rate of industrial solid waste	%	+
		City gas penetration rate	%	+
		Investment intensity of environmental pollution control	%	+

### The improved entropy weight method

As an objective weighting method, the entropy weight method determines the weights according to the attributes of each index, which can avoid the bias caused by human factors. The traditional entropy method ignores the influence of the time

factor, but ILCD is a dynamic development pattern over time. Therefore, this paper refers to the study of Dong et al. (2020), the improved entropy method is used to calculate the ILCD index. If there are  $\theta$  years,  $m$  provinces, and  $n$  indexes, then  $X_{tij}$  denotes index  $j$  of province  $i$  in year  $t$ . The calculation formulas are as follows:

Firstly, the indicators are standardized (Eq. 1 and Eq. 2):

$$X'_{ij} = \frac{X_{ij} - \min(X_{ij})}{\max(X_{ij}) - \min(X_{ij})} \quad (1)$$

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

Secondly, the indicators are homogenized and the weights are calculated (Eq. 3):

$$p_{ij} = X'_{ij} / \sum_{i=1}^{\theta} \sum_{j=1}^m X'_{ij} \quad (3)$$

Thirdly, calculate the information entropy (Eq. 4):

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^m p_{ij} \ln(p_{ij}) \quad (4)$$

Fourthly, calculate the coefficient of variation (Eq. 5):

$$a_j = 1 - e_j \quad (5)$$

Fifthly, calculate the weights of each indicator (Eq. 6):

$$W_j = a_j / \sum_{j=1}^n a_j \quad (6)$$

Finally, calculate the composite score (Eq. 7):

$$S_{it} = \sum_{j=1}^n W_j \times X'_{ij} \quad (7)$$

### Kernel density estimation

Kernel density estimation is a nonparametric method to estimate the probability density of a random variable, which examines the characteristics of the variable such as distribution, morphology, ductility and polarization phenomena. The calculations are shown in Eqs. 8 and 9.

$$f(x) = \frac{1}{Nh} \sum_{i=1}^N K\left(\frac{X_i - x}{h}\right) \quad (8)$$

$$K(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \quad (9)$$

where  $K(\cdot)$  is the kernel function,  $X_i$  is an independent and identically distributed variable,  $x$  is the mean,  $N$  is the number of variables, and  $h$  is the smoothing parameter called bandwidth. The larger the bandwidth is, the smoother the estimated density curve is, and the larger the deviation is, the lower the estimation accuracy is.

### Spatial correlation test

Before the spatial econometric analysis, the study first adopts Moran's  $I$  index to test spatial correlation. The calculation formula is as follows:

$$I_G = \frac{\sum_{i=1}^n \sum_{j \neq i}^n W_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (10)$$

$$I_L = x_i \sum_{j \neq i}^n W_{ij} x_j \quad (11)$$

where  $I_G$  and  $I_L$  are global spatial autocorrelation and local spatial autocorrelation indexes, respectively;  $n$  is the number of provinces,  $x_i$  and  $x_j$  are observed values, respectively; and  $W_{ij}$  is the spatial weight matrix. According to the study of Liu et al. (2022), the matrices, including the adjacency matrix ( $W_1$ ), geographical distance matrix ( $W_2$ ), economic distance matrix ( $W_3$ ), and economic-geographical distance matrix ( $W_4$ ), are constructed for the empirical test.

**PTM** In this paper, the panel threshold model (PTM) model proposed by Hansen (1999) is used to examine the threshold characteristics of RETI on ILCD, which can effectively test the significance of the endogenous nonlinear constraint effect (Feng et al. 2022). The calculation formula is as follows:

$$ILCD_{it} = \beta_0 + \beta_1 RETI_{it} I(RET_{it} \leq \lambda) + \beta_2 RETI_{it} I(RET_{it} > \lambda) + \beta X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (12)$$

$$ILCD_{it} = \beta_0 + \beta_1 RETI_{it} I(RET_{it} \leq \lambda_1) + \beta_2 RETI_{it} I(\lambda_1 < RETI_{it} \leq \lambda_2) + \beta_3 RETI_{it} I(RET_{it} > \lambda_2) + \beta X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (13)$$

where  $\beta$  is the estimated coefficient,  $\lambda$  is the threshold value, and  $I(\bullet)$  is an index function.  $X_{it}$  is a set of control variables,  $\mu_i$  denotes the individual fixed effect;  $\nu_t$  is the time-fixed effect;  $\varepsilon_{it}$  means the random error term.

### SPDM

ILCD and RETI in different provinces may affect each other spatially, and it is needed to consider spatial factors for spatial effects testing. The spatial panel Durbin model (SPDM) considers the spatial effects of both explanatory and explanatory variables (Sun et al. 2021a, b). Therefore, this paper adopts the SPDM to investigate the spatial effect of RETI on ILCD. The calculation formula is as follows:

$$ILCD_{it} = \alpha_0 + \rho \sum_{i=1}^n W_{ij} ILCD_{it} + \alpha_1 RETI_{it} + \alpha_2 \sum_{i=1}^n W_{ij} RETI_{it} + \alpha_3 X_{it} + \alpha_4 \sum_{i=1}^n W_{ij} X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (14)$$



where  $\rho$  represents the effect of local ILCD on ILCD in the surrounding area,  $\alpha_2$  is the spatial lag term coefficient of RETI,  $X_{it}$  denotes a series of control variables, and  $W_{ij}$  is the spatial weight matrix.

Furthermore, referring to the study of LeSage and Pace (2009), the direct and indirect effects are decomposed using partial differentiation. The formulas for the converted model are as follows:

$$Y_{it} = (I_{NT} - \rho W_{ij})^{-1} X_{it} (I_{NT} \beta + W_{ij} \delta) + [I_{NT} - \rho W_{ij}]^{-1} \varepsilon_{it} \quad (15)$$

According to formula (15), the derivative of the  $k$ th explanatory variable is derived as an independent variable, and the partial differential equations are as follows:

$$MEM = \frac{\partial Y_{it}}{\partial X_{it}} = (I_{NT} - \rho W_{ij})^{-1} (I_{NT} \beta + W_{ij} \delta) \quad (16)$$

$$\begin{aligned} ME_{Total} &= \frac{1}{NT} i(MEM), i = ones(NT, 1) \\ ME_{Direct} &= \frac{1}{NT} Trace(MEM) \\ ME_{Indirect} &= ME_{Total} - ME_{Direct} \end{aligned} \quad (17)$$

### Spatial threshold model

Because the threshold effect of RETI on ILCD in time and the spatial spillover effect in space are inseparable, it is necessary to consider both spillover effects and threshold effects. Therefore, to test the spatial threshold effect of RETI on ILCD, a model including threshold effect and spatial spillover effect is creatively constructed. According to the construction principles of PTM and SPDM and the reference to the study of Yuan et al. (2020), the calculation formula is defined in this paper as follows:

$$\begin{aligned} ILCD_{it} &= \sigma_0 + \rho \sum_{i=1}^n W_{ij} ILCD_{it} + \sigma_1 RETI_{it} (RETI_{it} \leq \lambda_1) \\ &+ \sigma_2 \sum_{i=1}^n W_{ij} RETI_{it} (RETI_{it} \leq \lambda_1) + \sigma_3 RETI_{it} (\lambda_1 < RETI_{it} \leq \lambda_2) \\ &+ \sigma_4 \sum_{i=1}^n W_{ij} RETI_{it} (\lambda_1 < RETI_{it} \leq \lambda_2) + \sigma_5 RETI_{it} (RETI_{it} > \lambda_2) \\ &+ \sigma_6 \sum_{i=1}^n W_{ij} RETI_{it} (RETI_{it} > \lambda_2) + \sigma_7 X_{it} + \sigma_8 \sum_{i=1}^n W_{ij} X_{it} \\ &+ \mu_i + \nu_i + \varepsilon_{it} \end{aligned} \quad (18)$$

where  $\sigma_1$ ,  $\sigma_3$ , and  $\sigma_5$  denote the direct effect coefficients of RETI on ILCD;  $\sigma_2$ ,  $\sigma_4$ , and  $\sigma_6$  denote the spatial lag term coefficients of RETI on ILCD; other variables are the same as above.

## Data

### Explained variable: ILCD

The improved entropy weighting method is used to measure the ILCD index, as shown in the “The construction and evaluation of the ILCD index system” section.

### Explanatory variable: RETI

Existing studies mainly adopt the number of renewable energy patents and R&D investment in renewable energy technology to analyze RETI (Nesta et al. 2014; Irandoust 2016; Lin and Chen 2019; Pitelis et al. 2020; Hille and Lambernd 2020). However, considering the technological depreciation and diffusion of RETI, this paper refers to the knowledge stock method of Lin and Zhu (2019) to construct the RETI index to measure RETI reasonably. The specific calculation formula is as follows:

$$RETI_{it} = \sum_{s=0}^t RPAT_{it} \exp[-\beta_1(t-s)] \{1 - \exp[-\beta_2(t-s)]\} \quad (19)$$

where  $RPAT_{it}$  is the number of renewable energy patents. According to the study of Popp (2002), the depreciation rate  $\beta_1$  is 0.36 and the diffusion rate  $\beta_2$  is 0.3.

### Control variables

Referring to the existing studies (Yang et al. 2021; Sun et al. 2022; Liu et al. 2021a, b, c; Zhao et al. 2022a, b; Su et al. 2021a, b; Sun et al. 2021a, b; Fang et al. 2020), the following control variables are selected. Population size (POP) is defined by the total population. Industrial structure (IS) is represented by the ratio of the added value of tertiary industries to that of secondary industries. Energy structure (ES) is described by the proportion of coal consumption in total energy consumption. Human capital (HC) is expressed by the proportion of college students in the total population.

### Data source

This paper takes panel data of 30 Chinese provinces from 2006 to 2020. Given the data availability, the samples of Tibet, Hong Kong, Taiwan, and Macau are not included. The number of renewable energy patents is obtained from the Patent Search and Analysis System (<http://www.pss-system.gov.cn>). Social and economic data are from the China Statistical Yearbook, and environmental and meteorological data are from the China Environmental Statistical Yearbook. Descriptive statistics of variables are shown in Table 2.

Empirical results

Temporal and spatial evolution analysis

Temporal evolution

To clarify the dynamic change of RETI and ILCD, this paper draws the kernel density curve of ILCD and RETI in China from 2006 to 2020 (Fig. 2). The kernel density curve of RETI showed a multi-peak distribution and the center of the curve shifted rapidly to the right, demonstrating that RETI in China rapidly increased and the degree of multipolar differentiation gradually intensified. The peak height of the curve first increased and then decreased, the width gradually widened and the trailing phenomenon was insignificant, indicating that the number of regions with higher RETI levels increased and the internal gap gradually expanded. This may be because of the differences in economic development, resource endowments and the pressure of energy conservation and emission reduction among provinces. Local governments adopt differentiated strategies to formulate strategic planning for renewable energy development and implement policy choices with varying intensity, resulting in large differences in RETI among regions.

The kernel density curve of ILCD showed a single-peak distribution and the center of the curve gradually moved to the right, demonstrating that ILCD in China steadily increased. The peak height gradually increased and the

width gradually decreased, indicating that the gap in ILCD among provinces in China steadily narrowed. The left tail of the curve slowly moved to the center, the right tailing of the curve was evident, and the ductility of the curve showed a widening trend, indicating that the ILCD level in some regions was significantly higher than that in the other areas and the gap between areas kept widening. This may be because carbon emission reduction policies such as carbon emission trading market, carbon finance, and low-carbon pilot cities are still in the pilot stage, which only play a limited role in regional low-carbon development and are difficult to integrate ILCD in different regions, resulting in significant regional heterogeneity in ILCD.

Spatial evolution

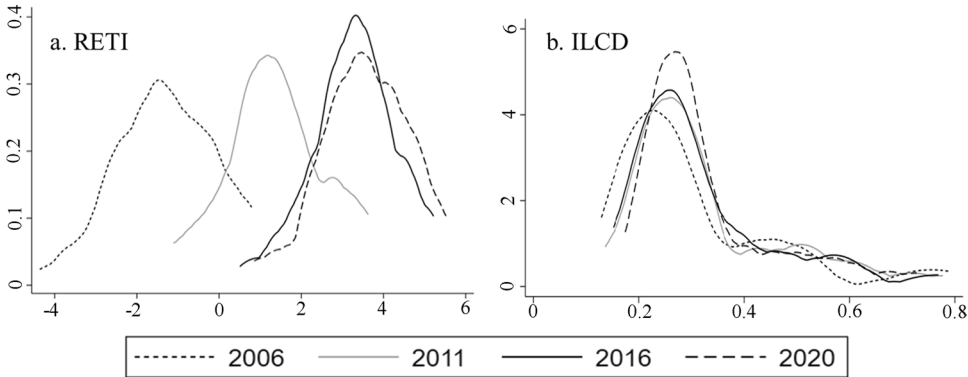
To further clarify the spatial distribution characteristics of RETI and ILCD, this paper uses ArcGIS10.3 to conduct a spatial visualization analysis of RETI and ILCD in China from 2006 to 2020. It can be seen in Fig. 3 that RETI forms a pattern of “low in the northwest and high in the southeast.” The results are similar to the conclusions of Xin et al. (2022a). Specifically, the high RETI area mainly concentrates on the southeast coastal region and has an expanding trend in the surrounding areas. The low RETI area is primarily distributed in the northwest and southwest regions, and its spatial extent has been reduced with the continuous advancement of the energy transition process. The southeast coast has abundant resources such as hydropower and tidal energy, which provide supports for technological innovation and help local renewable development (Ouyang et al. 2021). However, although the northwest regions have abundant resources of solar and wind energy, it is difficult to support the development of RETI with relatively poor infrastructure, resulting in a development gap in RETI between the southeast and the northwest (Apergis and Payne 2010; Wang et al. 2011).

ILCD has an overall spatial pattern of “high in the east and low in the west”, with a decreasing stepwise way

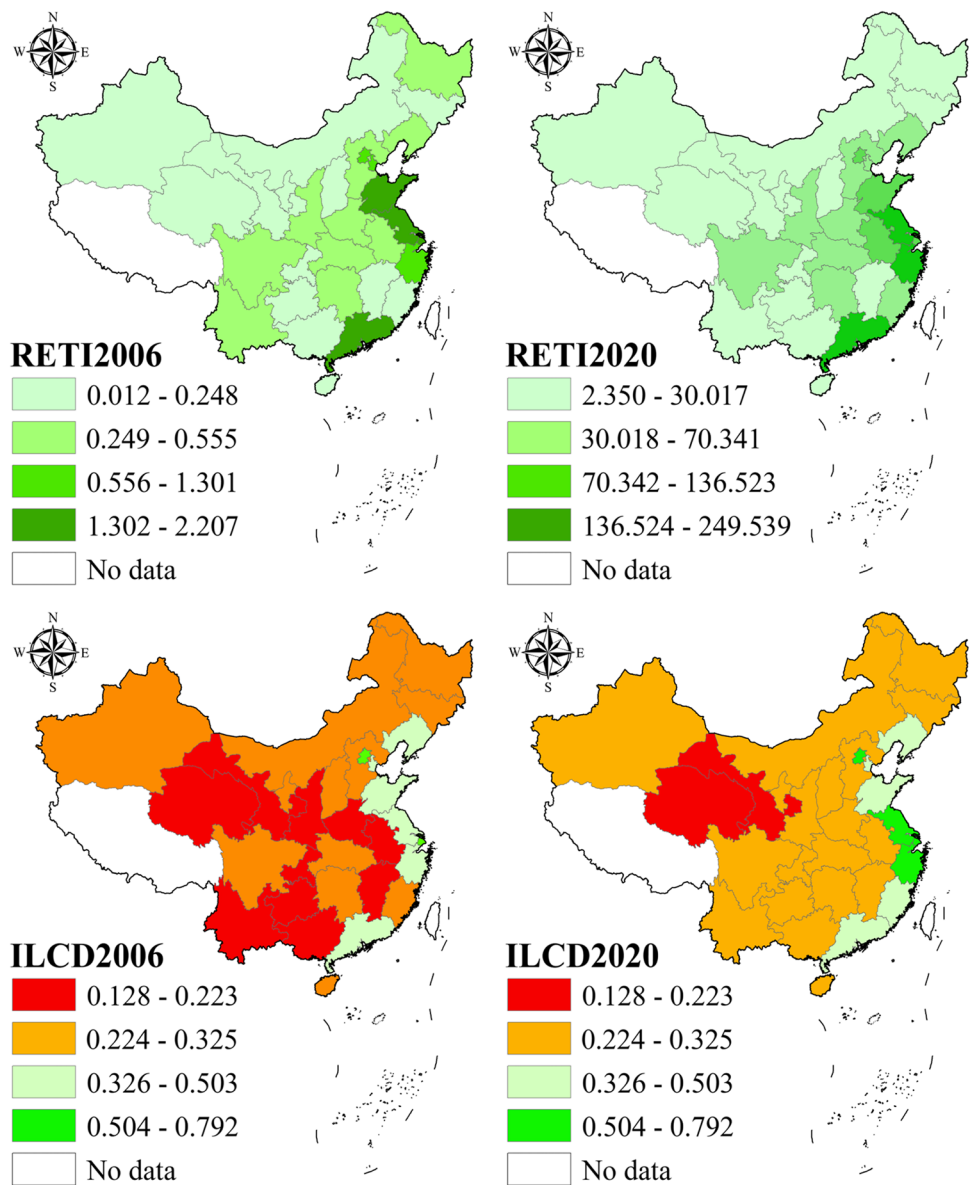
Table 2 Statistical description

Variables	Obs	Mean	Max	Min	SD
ILCD	450	0.321	0.809	0.113	0.143
RETI	450	25.73	291.7	0.013	43.87
POP	450	4524	12,624	547.7	2772
IS	450	1.219	5.297	0.534	0.68
ES	450	0.416	0.748	0.008	0.156
HC	450	82.02	249.2	3.6	50.34

Fig. 2 Temporal trend of RETI and ILCD in China from 2006 to 2020



**Fig. 3** Spatial differentiation of RETI and ILCD in China from 2006 to 2020



of spatial differentiation. Specifically, high-level ILCD regions are mainly concentrated in the southeastern coastal areas, with a distribution pattern of contiguous strips. With their geographical and resource advantages, these regions effectively promote green industrial transformation and upgrading through technological innovation and knowledge spillover, which is conducive to improving the ILCD level (Du et al. 2021a, b). The spatial range of low-level ILCD decreases gradually, and the number of provinces decreases from 10 to 2, decreasing by 80%. The double-core distribution formed by Gansu-Qinghai-Shaanxi-Henan and Yunnan-Guizhou-Guangxi has transformed into a single-core distribution dominated by Qinghai and Gansu. Such areas are highly dependent on resources and the environment. Rapid industrial development consumes a lot of energy and causes intensified environmental

pollution, which is not conducive to promoting ILCD. The regional spatial scope of middle-level ILCD gradually expands, and the number of provinces increases from 12 to 19, with a rise of 58.33%, indicating that the ILCD level gradually improves in most areas but has a big gap with the eastern coastal regions. The above results suggest significant spatial heterogeneity in RETI and ILCD among areas, and exploring their relationship cannot ignore the spatial factors.

### Spatial correlation analysis

To analyze spatial correlation, the Moran's  $I$  index is adopted to examine the spatial correlation of RETI and ILCD and draw LISA cluster maps. Considering possible estimate bias, the four spatial weight matrices, including adjacency

matrix ( $W_1$ ), geographical distance matrix ( $W_2$ ), economic distance matrix ( $W_3$ ), and economic-geographical distance matrix ( $W_4$ ), are adopted to calculate the global Moran's  $I$  index of RETI and ILCD (Table 3). The results show that the Moran's  $I$  index of RETI and ILCD are significantly positive under the four spatial weight matrices, indicating a significant positive spatial correlation between RETI and ILCD. The Moran's  $I$  indexes of RETI and ILCD show an overall fluctuating upward trend, indicating that the spatial aggregation of RETI and ILCD gradually increased.

To reveal the spatial clustering pattern of RETI and ILCD more intuitively, this paper draws the LISA cluster maps of RETI and ILCD in 2006 and 2020 in China (Fig. 4). The results show that the H–H clusters of RETI are primarily in Jiangsu, Shanghai and Zhejiang, the L–L clusters are mainly concentrated in northwest China, and the L–H clusters are primarily in Jiangxi and Fujian. The scope of these three clusters is significantly expanded, and the radiation-driven effect of the high-level RETI areas on the surrounding regions initially appeared. The local spatial correlation of ILCD is mainly H–H and L–L clusters. H–H clusters are primarily concentrated in the eastern region, while L–L clusters are mainly concentrated in the northwestern region, showing an expanding trend in spatial scopes. It is noteworthy that the spatial clustering patterns of both RETI and ILCD have evolved from sporadic faceted distribution to the “Hu Huanyong Line” pattern (Zhang et al. 2018), which may be due to the increasing imbalance of regional economic and social development, leading to the gradually prominent spatial polarization of RETI and ILCD.

The above findings show that RETI and ILCD have evident spatial clustering trends, and the spatial dependence

gradually increases, indicating that it is necessary to take into account spatial effect when exploring the influencing mechanism of RETI on ILCD. Therefore, this paper adopts a spatial panel econometric model to examine the impact of RETI on ILCD.  $W_1$  is used for empirical analysis in the next step, and  $W_2$ ,  $W_3$ , and  $W_4$  are adopted in the robustness test.

## Spatial spillover effect of RETI on ILCD

### Results of model selection

The previous section verified that RETI and ILCD are significantly spatially correlated, so selecting an appropriate spatial econometric model is necessary. As shown in Table 4, the LM, LR, Wald, and Hausman test results indicate that the SPDM with both spatial-time fixed effects should be employed to examine the spatial spillover effect of RETI on ILCD.

### Estimation results of the SPDM

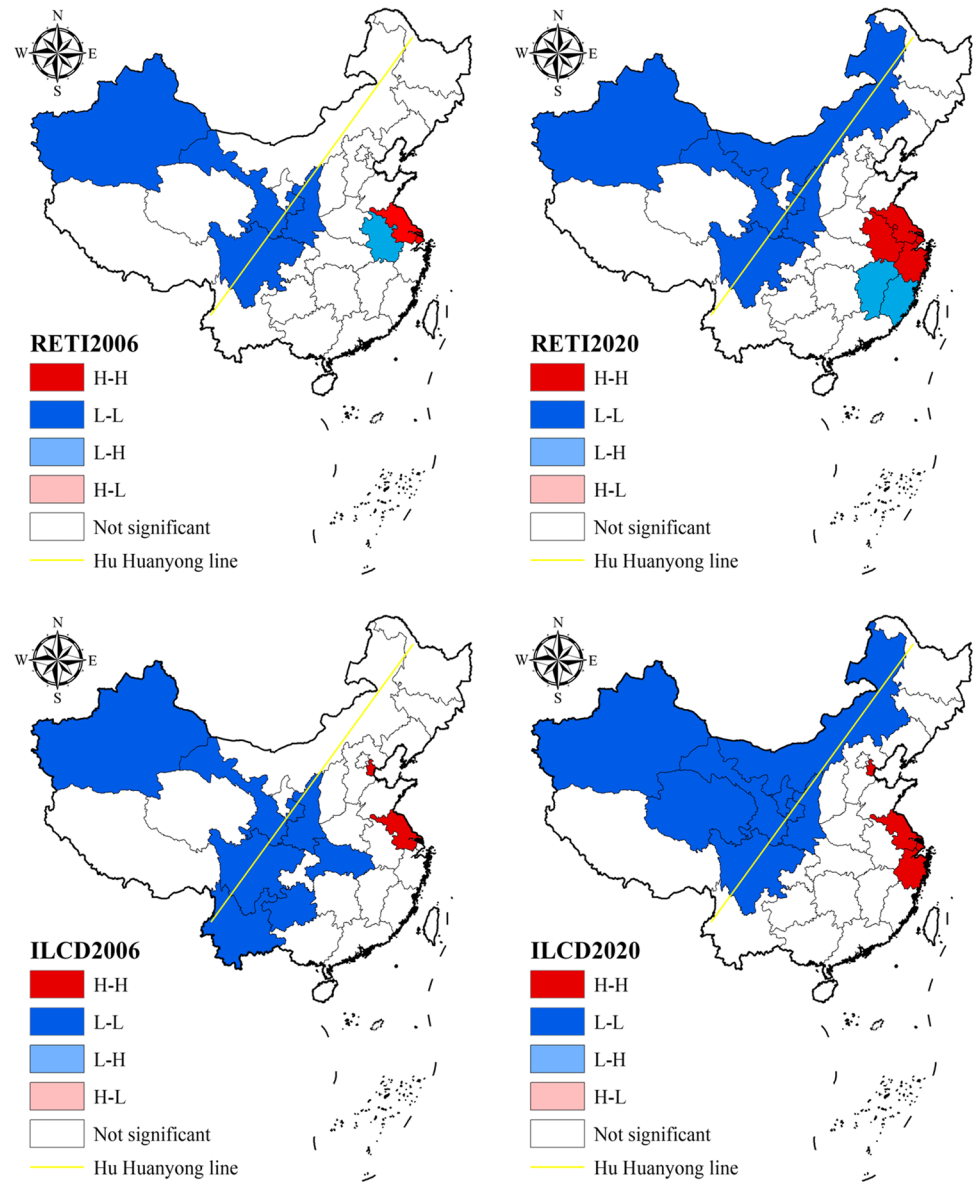
The results in Table 5 show that the spatial autoregressive coefficient of ILCD is 0.271 significantly, illustrating that ILCD has a significantly positive spatial spillover effect, and the regions with a high ILCD have a positive driving impact on neighboring ILCD. Specifically, the coefficients of direct effect and spatial spillover effect of RETI are 0.105 and 0.044 significantly, respectively, demonstrating that RETI significantly enhances the local and neighboring ILCD. The total effect coefficient of RETI is 0.149 significantly, demonstrating that RETI significantly promotes ILCD. In other words, RETI has a significant promoting effect on ILCD

**Table 3** Spatial autocorrelation test

Year	RETI				ILCD			
	$W_1$	$W_2$	$W_3$	$W_4$	$W_1$	$W_2$	$W_3$	$W_4$
2006	0.176**	0.039**	0.370***	0.004**	0.395***	0.119***	0.087**	0.237***
2007	0.285***	0.030**	0.479***	0.019**	0.405***	0.123***	0.089**	0.245***
2008	0.282***	0.035**	0.450***	0.034**	0.408***	0.125***	0.086**	0.245***
2009	0.262***	0.042**	0.383***	0.057**	0.386***	0.120***	0.089**	0.234***
2010	0.261***	0.040**	0.366***	0.073**	0.403***	0.126***	0.105**	0.249***
2011	0.281***	0.049***	0.361***	0.096**	0.436***	0.131***	0.120**	0.262***
2012	0.231**	0.030**	0.311***	0.067**	0.377***	0.105***	0.112**	0.223***
2013	0.258***	0.046**	0.316***	0.124**	0.362***	0.105***	0.112**	0.223***
2014	0.266***	0.040**	0.344***	0.100**	0.326***	0.094***	0.111**	0.204***
2015	0.257***	0.053***	0.343***	0.112**	0.342***	0.101***	0.130**	0.212***
2016	0.296***	0.068***	0.286***	0.155***	0.344***	0.094***	0.130**	0.208***
2017	0.227**	0.047***	0.351***	0.078**	0.327***	0.100***	0.143**	0.200***
2018	0.210**	0.061***	0.278***	0.125**	0.354***	0.107***	0.150**	0.217***
2019	0.263***	0.087***	0.288***	0.166***	0.363***	0.099***	0.144**	0.207***
2020	0.326***	0.100***	0.297***	0.223***	0.389***	0.114***	0.119**	0.241***

\*\*\*, \*\*, and \* denote significance at the 1%, 5%, and 10% levels, respectively

**Fig. 4** LISA maps of RETI and ILCD in China from 2006 to 2020



**Table 4** Selection of the spatial econometrics model

Tests	Statistics	Tests	Statistics
LM(lag) test	6.281***	Wald_spatial_lag	33.740***
Robust LM(lag)test	71.570***	LR_spatial_lag	14.120***
LM(error)test	81.782***	Wald_spatial_error	35.430***
Robust LM(error)test	147.071***	LR_spatial_error	10.620***
Hausman test	1.270***		

\*\*\*, \*\*, and \* denote significance at the 1%, 5%, and 10% levels, respectively

in both local and surrounding areas, and the direct effect is stronger than the spatial spillover effect, which results in a positive superposition effect. It may be due to the fact that mutual imitation and increasingly close economic relations

among neighboring areas are conducive to the spillover of RETI and the dissemination of knowledge, improvement of regional energy structure and optimal resource allocation, which further helps to improve the ILCD level in local and neighboring regions, gradually forming a situation of “good neighborliness.”

In terms of control variables, the coefficients of direct effect and spatial spillover effect of POP are  $-0.092$  at a 1% significance level and  $-0.086$  at a 5% significance level, respectively, demonstrating that increasing population has a negative effect on local and neighboring ILCD. The population expansion leads to a large amount of energy consumption, which aggravates the imbalance between energy supply and demand and is not conducive to promoting ILCD. The coefficients of direct effect and spatial spillover effect of IS are  $0.058$  at a 1% significance level and  $-0.028$  at a 5% significance level, respectively,



**Table 5** Estimation results of SPDM

Variables	Direct effect	Indirect effect	Total effect
lnRETI	0.105*** (22.86)	0.044*** (5.26)	0.149*** (16.08)
lnPOP	−0.092*** (−6.56)	−0.086** (−2.49)	−0.178*** (−5.38)
lnIS	0.058*** (11.31)	−0.028** (−2.09)	0.030* (1.94)
lnES	−0.055*** (−2.91)	−0.071 (−1.40)	−0.126** (−2.18)
lnHC	0.019 (1.60)	0.046 (1.44)	0.065** (2.07)
Spatial rho	0.271*** (4.29)	Variance sigma2_e	0.003*** (14.96)
R <sup>2</sup>	0.895	N	450

\*\*\*, \*\*, and \* denote significance at the 1%, 5%, and 10% levels, respectively. The *t* values are in parentheses

showing that the improving industrial structure enhances local ILCD and hinders neighboring ILCD. It is because optimizing industrial structure contributes to promoting green and low-carbon advantageous industrial clusters, promoting the transformation and upgrading of energy-intensive industries to high-end, diversified and low-carbon industries, thus enhancing local ILCD. However, the clustering of low-carbon industries may produce a siphon effect, leading to the continuous influx of resource elements from surrounding areas into the central region, which brings tremendous pressure on the economic and social development and low-carbon transformation of the surrounding areas and is not conducive to enhancing ILCD (Dong et al. 2014). The direct effect coefficient of ES is −0.055 significantly, demonstrating that the energy structure dominated by coal consumption significantly hinders local ILCD. Therefore, it has important implications for promoting China's ILCD to enhance renewable energy development and accelerate the green and low-carbon energy transformation.

### Spatial threshold effect of RETI on ILCD

#### Threshold effect test

The PTM is used to test whether there is a threshold effect of RETI on ILCD. The results in Table 6 show that after subsampled 500 times by the bootstrap method, there is a

single threshold effect of RETI on ILCD with a threshold estimated value of 0.357 at a 5% significance level, demonstrating that the nonlinear shock of RETI on ILCD has a threshold constraint characteristic, so the threshold effect of RETI on ILCD should be examined.

#### Results of the spatial threshold model

According to the threshold estimated value, the total sample is divided into two groups, which are the growth period ( $RETI \leq 0.357$ ) and the mature period ( $RETI > 0.357$ ). As can be seen in Table 7, the estimation results of PTM demonstrate that the estimated coefficients of RETI in the growth period and mature period are −0.024 and 0.086 significantly, respectively. The total effect estimation results of SPTM show that the coefficient of RETI in the growth period is −0.027 at a 10% significance level and the coefficient of RETI in the mature period is 0.125 at a 1% significance level. The results suggest that RETI may block ILCD during the growth period, but it may promote ILCD during the mature period. By comparing the estimated coefficients of PTM and SPTM, it can be found that the threshold effect of RETI on ILCD will be underestimated if the spatial factors are not considered. Therefore, this paper adopts SPTM to examine the spatial threshold effect of RETI on ILCD.

In terms of direct effects, the coefficient of RETI in the growth period is −0.018, which was significant at the 10% level, indicating that RETI in the growth period hinders the promotion of local ILCD. The coefficient of RETI in the

**Table 7** Estimation results of the spatial threshold model

Variables	PTM	SPTM		
		Direct effect	Indirect effect	Total effect
RETI ≤ 0.357	−0.024*** (−4.66)	−0.018* (−1.78)	−0.009 (−0.20)	−0.027* (−1.69)
RETI > 0.357	0.086*** (3.88)	0.077*** (15.77)	0.048*** (4.68)	0.125*** (10.69)
Control variables	Yes			
R <sup>2</sup>	0.672	0.245		
N	450			

\*\*\*, \*\*, and \* denote significance at the 1%, 5%, and 10% levels, respectively. The *t* values are in parentheses

**Table 6** Estimation results of the threshold model

Type	Threshold value	F value	P value	Critical value		
				1%	5%	10%
Single threshold	0.357	32.76	0.020	35.113	30.429	24.371
Double threshold	1.036	5.65	0.717	31.016	20.438	16.200

mature period is 0.077 at a 1% significance level, illustrating that RETI in the mature period significantly promotes local ILCD. With RETI increasing, the effect of RETI on local ILCD is negatively changed to positive. This may be because in the growth period of RETI, the energy transition in central China is slowly developing, and the immature clean energy technology brings huge cost pressure to the optimization and adjustment of industrial structure, which has a negative impact on local ILCD. However, when RETI enters the mature period, the more mature RETI can effectively lower the cost of industrial clean energy utilization and promote the industrial transformation and upgrading to clean and high-end, which contributes to releasing multiple dividends for the economy, energy, and the environment and brings positive impact on regional ILCD (Feng et al. 2022).

Regarding the spatial spillover effect, the RETI coefficient in the growth period is  $-0.009$  and did not pass significance level in the mature period is  $0.048$  significantly, demonstrating that compared to RETI in the growth period, RETI in the mature period has a significant positive effect on the surrounding ILCD. With the increase of RETI, the spatial spillover effect gradually increased, which may be because of the rapid development of RETI in the central region, the positive externalities of technological innovation gradually become prominent (Liu 2018). The successful practical experience of local low-carbon transformation and development can produce demonstration and imitation effect on the surrounding areas through technology spillover and knowledge dissemination, further promote the acceleration of low-carbon transformation and upgrading and optimization of economic growth mode in the surrounding areas and then promote the improvement of ILCD in the neighboring areas.

### Result of the regional boundary of RETI on ILCD

To further investigate whether the spatial spillover effect of RETI on ILCD has a regional boundary, drawing on the study of Liu et al. (2022), this paper constructs threshold distance matrix  $W_{dij}$  to explore the spatial spillover effect with different geographical distance constraints. The calculation method is as follows:

$$W_{dij} = \begin{cases} \frac{1}{d_{ij}} & d_{ij} \geq d \\ 0 & d_{ij} < d \end{cases} \quad (20)$$

In the threshold distance spatial weight matrix, the initial threshold distance  $d_{ij}$  is set as 200 km, and the incremental distance is set as 200 km and keeps increasing to 2400 km. Furthermore, the changes in spatial spillover effect coefficients at the different distances are visualized (Fig. 5).

As shown in Fig. 5, there are mainly three characteristics of the effect of RETI on ILCD: (1) the distance attenuation

of the spatial spillover effect is prominent, showing a wave-like declining trend. (2) The regional boundary of the spatial spillover effect has obvious heterogeneity. Specifically, the spatial overflow boundary of the whole RETI is 1400 km, that of RETI in the growth period is 1000 km, and that of RETI in the mature period is 1600 km. (3) The effects of RETI on neighboring ILCD in the whole and growth period reach the peak at 400 km, which are 0.118 and  $-0.168$  at a 1% significance level, respectively. Usually, 400 km is within the boundary of provinces, indicating that in the early stage of RETI development, ILCD within the boundary has a significant radiation-driving effect. When the distance goes beyond the provincial boundary, the spatial spillover effect decreases rapidly. It may be due to the intense competition among local governments under the economic decentralization system in China, which hinders the flow of high-quality resource elements (Wu et al. 2020) and is not conducive to the positive spillover of RETI. (4) After 800 km, the attenuation trend of the spatial spillover effect of RETI on ILCD impact in different periods has slowed down. This may be due to the fact that the distance between provinces within China's eight economic regions is mostly around 800 km. As the geographical distance increases, the degree of inter-regional economic, social and environmental linkages gradually decreases, information asymmetry gradually increases, and market segmentation and regional imbalance further intensify, resulting in the positive externalities of RETI cannot be fully exploited and the weaker driving effect on the surrounding ILCD. Overall, the above results provide strong evidence for the spatial distance decay hypothesis and verify that there are obvious regional boundaries for the spatial spillover effect of RETI on ILCD.

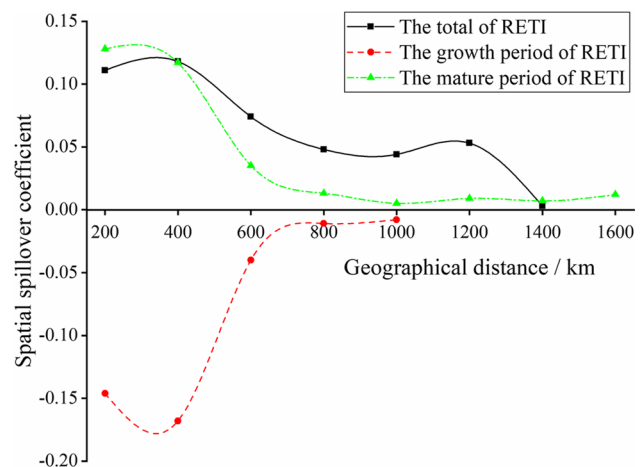


Fig. 5 Regional boundary of the spatial spillover effect

## Heterogeneity analysis

### Time heterogeneity

China's economic development undergoes reform and optimization adjustment every five years. According to the formulation law of economic planning in China, this study divides the sample into three stages: the 11th, 12th, and 13th 5-year plan (2006–2010, 2011–2015, and 2016–2020). The results of the effect of RETI on ILCD in the various stages are shown in models (1) to model (3) in Table 8. It demonstrates that the promotion effect of RETI on ILCD is significantly enhanced over time. It may be due to the National Energy Administration releasing the Thirteenth Five-Year Plan for Renewable Energy Development in 2017, which encourages local governments to accelerate the development of renewable energy through policy guidance. With the continuous maturity of RETI, energy utilization efficiency and energy consumption structure have been greatly improved, while the cost of renewable energy continues to decrease, which is conducive to green economic growth and further promotion of ILCD. Notably, the spatial spillover effect of RETI on ILCD shows fluctuating enhancement, which may be a steady advancement in constructing of a unified national energy market that breaks down barriers to cross-regional energy trading. On the one hand, by stimulating the vitality of market entities, RETI expands the space for clean energy consumption and contributes to achieving green and low-carbon transformation. On the other hand, RETI helps transform the advantages of wind and solar energy resources in the northwest regions into an economic engine to promote the high-quality development of the local economy and society, which is conducive to the promotion of ILCD.

### Regional heterogeneity

Because the previous study confirmed that RETI and ILCD had significant spatial heterogeneity, the impact of RETI on ILCD is further investigated in eastern, central,

western, southern and northern regions. The results in models (4) to (8) in Table 8 demonstrate that the promotion effect of RETI on local ILCD shows a trend of eastern > central > south > north > western, which may be related to the unbalanced regional development in China. The southeastern coastal region has rich resources, location and economic advantages, which help drive RETI R&D into applied research, improving the marketization of RETI R&D, further promoting the green and low-carbon transformation of industries, and thus improving the regional ILCD level. However, the economic development of central and western regions is relatively backward, R&D investment in RETI is lower, energy-intensive industries are clustered, and the infrastructure construction for clean energy supply and consumption is not perfect, which is not conducive to the carbon reduction and enhancement of ILCD. Further, in terms of spatial impact, the spatial spillover effects are significantly positive in the eastern and southern regions, but significantly negative in the central and western regions. It may be because the diffusion degree of RETI needs the accumulation and circulation of human capital, economically developed areas are more likely to attract high-end talents to gather and accelerate the transformation of innovation achievements, which is conducive to the knowledge dissemination and technology spillover to surrounding areas, thus forming a “good neighborliness” situation. However, there is a big gap between the central and western regions in terms of economic development, information technology, policy environment and many other factors, and the conversion and absorption capacity of RETI is limited, which weakens the scale economies effect and environmental benefits of low-carbon technologies, and is not conducive to promoting ILCD in surrounding regions, gradually forming an “unfriendly neighborhood” situation.

### Heterogeneity in resource endowment

Resource-based areas are essential carriers of modern industry in China, with a high share of non-renewable energy

**Table 8** Results of temporal and regional heterogeneity

Variables	(1) 11th 5-year plan	(2) 12th 5-year plan	(3) 13th 5-year plan	(4) Eastern	(5) Central	(6) Western	(7) South	(8) North
lnRETI	0.100*** (14.42)	0.100*** (12.56)	0.103*** (12.85)	0.144*** (17.12)	0.059*** (8.33)	0.013** (2.05)	0.055*** (8.11)	0.041*** (6.04)
W × lnRETI	0.033*** (2.73)	0.058*** (3.93)	0.043*** (2.84)	0.176*** (7.29)	−0.033** (−1.98)	−0.067*** (−4.96)	0.203*** (2.64)	−0.031 (−0.86)
Control variables	Yes							
R <sup>2</sup>	0.919	0.874	0.910	0.825	0.505	0.558	0.394	0.764
N	150	150	150	165	120	165	225	225

\*\*\*, \*\*, and \* denote significance at the 1%, 5%, and 10% levels, respectively. The *t* values are in parentheses

extraction industries and a homogeneous industrial structure, which puts enormous pressure on the sustainable development of the economy, society and the environment (Cao et al. 2017). To further examine whether the differences in resource endowments have heterogeneous effects, referring to the study of (Fan and Zhang 2021), the sample is divided into resource-based and non-resource-based regions. The results of models (1) to (2) in Table 9 show that RETI significantly promotes ILCD in non-resource regions, and has a strong positive spatial spillover effect. However, the promotion effect on resource-based areas is insignificant, and there is even a significant negative spatial spillover effect on the surrounding areas. It may be due to the “Dutch disease effect” caused by resource endowment in resource-based regions and the “crowding-out effect” driven by technological innovation (Su et al. 2021a, b). Excessive dependence on non-renewable energy may reduce the subjective initiative of RETI research and development and industrial green transformation. It is challenging to meet the needs of regional sustainable development, thus hindering ILCD. On the contrary, most non-resource-based regions have a higher level of economic development and invest more in technological R&D and innovation and high-level talent training, which provide good development conditions for R&D and application of RETI, not only promote local ILCD level, but also radiates and drives the ILCD in surrounding areas through knowledge and technology spillover.

### Heterogeneity in marketization level

Schumpeter’s hypotheses suggest that free and competitive markets are conducive to stimulating innovative activities and continuously promoting economic development (Weisman 2021). To investigate whether different marketization has heterogeneous effects, the sample is divided into areas of high marketization and low marketization. The results of models (3) to (4) in Table 9 demonstrate that in the low marketization areas, RETI has a significantly inhibited ILCD

in both local and neighboring areas, and the spatial spillover effect is more significant than the local effect. It may be that (1) improving the marketization is conducive to enhancing the inclusiveness and competitiveness of the market, attracting more innovation enterprises, promoting the aggregation of RETI, accelerating the transformation of innovation output, and thus promoting regional ILCD. (2) A higher level of marketization implies a higher degree of product and factor market development, helps the low-cost transfer of innovation factors between industries, generates an effective organizational structure and division of labor structure, motivates enterprises to invest in innovation and adopt clean energy technologies, which further promotes industrial green transformation and improve regional ILCD. (3) The deepening of marketization further optimize the business environment, improve the relationship between the government and the market, and reduce the occurrence of rent-seeking behaviors, which is conducive to improving regional innovation capacity and resource allocation efficiency, and playing a positive role in promoting ILCD.

### Heterogeneity in environmental regulation

The Porter hypothesis holds that environmental regulation can force enterprises to engage in technological innovation, thus improving competitiveness and promoting economic growth (Wu and Lin 2022). To examine whether different environmental regulation intensities have heterogeneous effects, the sample is divided into strong and weak environmental regulation areas with reference to the study of (Zhong et al., 2021). The results of models (5) to (6) in Table 9 show that in strong environmental regulation areas, RETI has a significant role in promoting ILCD in local and neighboring areas. In weak environmental regulation areas, RETI significantly inhibits local ILCD, but does not significantly affect neighboring ILCD. It may be because stronger environmental constraints force enterprises to develop RETI, optimize energy structure, and improve clean energy

**Table 9** Results of heterogeneity in resource endowment, marketization level and environmental regulation

Variables	(1) Resource-based areas	(2) Non-resource-based areas	(3) Low marketization	(4) High marketization	(5) Weak environmental regulation	(6) Strong environmental regulation
lnRETI	0.008 (1.21)	0.087*** (10.97)	-0.018*** (-2.82)	0.118*** (14.71)	-0.018** (-2.13)	0.124*** (12.57)
W × lnRETI	-0.056*** (-5.42)	0.057*** (3.83)	-0.022** (-2.00)	0.069*** (4.57)	0.003 (0.28)	0.091*** (4.40)
Control variables	Yes					
R <sup>2</sup>	0.524	0.810	0.813	0.561	0.432	0.683
N	135	315	225	225	330	120

\*\*\*, \*\*, and \* denote significance at the 1%, 5%, and 10% levels, respectively. The *t* values are in parentheses

utilization efficiency, which is conducive to promoting local ILCD. With the continuous development of local RETI, the positive externality effect of technological innovation gradually comes to the fore, which effectively encourages ILCD in neighboring areas. However, in areas with weaker environmental constraints, enterprises have lower pollution emission costs and probably only need end treatment to reach discharge standards. Enterprises in such regions lack the motivation for technological innovation, and they are challenging to improve the energy consumption structure, which significantly hinders the development of RETI, and slows down the industrial green transformation and upgrading, thus restricting regional ILCD.

## Robustness test

### Changing the measuring method of the space weight matrix

Considering the estimation bias in weight matrix selection (Xu et al. 2019), the model has been estimated again by replacing the adjacency matrix ( $W_1$ ) with the geographical distance matrix ( $W_2$ ), and economic distance matrix ( $W_3$ ) and economic-geographical distance matrix ( $W_4$ ). It can be seen from models (1) to (3) in Table 10 that RETI significantly promotes local and neighboring ILCD, verifying the robustness of the models.

## Replacing variables

Climate conditions are essential factors in promoting low-carbon development (Xin et al. 2022b). Given the deviation caused by missing variables, climate factors are included in the model for re-estimation. Model (4) in Table 10 demonstrates estimation results. It found that despite the inclusion in the model of indexes such as mean annual sunshine duration, mean annual precipitation and mean annual temperature, the relationship between RETI and ILCD remains unchanged, confirming the reliability of the previous results.

## Endogenous test

Instrumental variables are the primary means to solve potential endogeneity. Referring to the study of Yuan et al. (2020), this paper incorporates the instrumental variables of the explained variable lag one period into the system generalized moment estimation model (SYS-GMM) and estimates again to deal with the potential endogenous problems.

As can be seen from the result of model (5) in Table 10, the time-lag term of ILCD is 0.977 at a 1% significance level, demonstrating the existence of path dependence of ILCD. The estimated coefficient directions of other variables are the same as above, which verifies the robustness of the estimation results.

**Table 10** Robustness test

Variables	(1) $W_2$	(2) $W_3$	(3) $W_4$	(4) Adding control variables	(5) SYS-GMM
L.ILCD					0.977*** (13.10)
lnRETI	0.109*** (24.63)	0.090*** (20.72)	0.100*** (17.94)	0.106*** (24.18)	0.001* (1.72)
$W \times \ln \text{RETI}$	0.105*** (3.10)	0.078*** (5.40)	0.042** (2.21)	0.028** (2.50)	
Control variables	Yes				
Spatial rho	0.037** (2.20)	0.004** (2.05)	0.300*** (2.99)	0.036** (2.51)	
Variance sigma2_e	0.003*** (15.00)	0.003*** (14.99)	0.004*** (13.90)	0.003*** (14.99)	
AR(1)					− 8.43 (0.000)
AR(2)					− 0.32 (0.748)
Sargan					372.51 (0.570)
N	450				420

\*\*\*, \*\*, and \* denote significance at the 1%, 5% and 10% levels, respectively. The t values are in parentheses



## Conclusions and discussions

Based on inclusive growth and sustainable development theories, the ESC analysis framework is constructed from three dimensions of economic growth, social inclusion, and low-carbon development. The improved entropy weight method is used to estimate the ILCD level of 30 provinces in China from 2006 to 2020, and the kernel density estimation and Moran's *I* index are used to describe the spatial and temporal patterns. Based on the combined perspective of spatial spillover effect and threshold effect, this paper examines the spatial spillover effects and the regional boundary of RETI on ILCD in different periods, and further explores the differential spatial effects under the constraints of time, region, resource endowment, marketization level, and environmental regulation. The main conclusions are as follows:

1. ILCD in China presents a distribution of “high in the east and low in the west” and increases steadily. While RETI increases rapidly, presenting a spatial pattern of “low in northwest and high in southeast.” ILCD and RETI have increasing dependences, and their trend of spatial agglomeration has become increasingly prominent.
2. Overall, RETI significantly promotes local and neighboring ILCD, presenting a “good neighborliness” phenomenon.
3. There is significant spatial heterogeneity in the effects of RETI on ILCD in different periods. There is an adverse effect of RETI on local ILCD in the growth period and a positive effect of RETI on local and neighboring ILCD in the mature period. With the improvement of RETI, the impact of RETI on neighboring ILCD gradually increases, showing a significant spatial spillover.
4. The effect of RETI on neighboring ILCD in various periods demonstrates prominent spatial distance attenuation characteristics. The spatial spillover boundary of the whole RETI is 1400 km, that of RETI in the growth period is 1000 km, and that of RETI in the mature period is 1600 km.
5. The effect of RETI promotes ILCD gradually enhances over time, showing a spatial pattern of “eastern > central > south > north > western.”
6. RETI strongly promotes ILCD in non-resource-based areas and areas with high marketization levels and strong environmental regulation, but has a significant inhibition effect on ILCD in regions with low marketization levels and weak environmental regulation.

Based on the above conclusions, the following policy suggestions are put forward for China and other countries to

promote ILCD: firstly, give full play to the role of RETI in promoting ILCD.

The government should stimulate the RETI motivation of enterprises by strengthening policy guidance and R&D subsidies, and promote the development of renewable energy technologies by means of technology introduction, digestion, absorption, and re-innovation. At the same time, it should cultivate a group of distinctive RETI industrial clusters by strengthening the training of renewable energy technology talents and the construction of industry-university-research cooperation platforms to improve energy utilization efficiency and help the development of ILCD.

Secondly, the spatial spillover effect and regional boundary of RETI on ILCD have significant heterogeneity in different periods. Therefore, local governments should formulate scientific and reasonable development plans for renewable energy according to the development stage of regional RETI to promote the high-quality development of renewable energy. At the same time, it is necessary to break administrative and market barriers, promote cross-regional cooperation and exchange mechanism, strengthen the connectivity of human and technical resources, and bring into play the benign “polarization and trickle-down” effect to encourage the process of regional ILCD integration.

Thirdly, pay more attention to the regional heterogeneity in the promotion effect of RETI on ILCD. Differentiated energy transition and low-carbon development policies should be formulated for different regions. For example, it is needed to give full play to the leading role of the eastern region, and provide RETI support for the central and western areas through information disclosure, technology sharing and talent support to promote the green and low-carbon transformation of traditional industries. The western regions have abundant resources such as wind and solar energy, but are short in technology and industrial chain. It is necessary to accelerate the integrated development of new energy infrastructure, build industrial clusters of new energy, promote value chains of the new energy industry to medium–high levels and accelerate collaborative low-carbon development among regions.

Fourthly, local governments should establish a dynamic management mechanism of “one province, one policy” according to the regional resource endowment characteristics, marketization degree and environmental regulation intensity. For example, resource-based areas should break through the restriction of monotonous industrial structure and guide the organic agglomeration of diversified industries. Actively introduce emerging and alternative industries, continuously extend the industrial chain, promote the transformation between old and new driving forces, and inject new growth vitality into regional ILCD. In addition, it is necessary to accelerate the establishment of a modern energy market system and

improve market-based trading mechanisms for renewable energy. Not only should we actively expand the regional renewable energy market, but also vigorously carry out trans-regional transactions of renewable energy, improve the consumption and utilization of renewable energy, and promote the high-quality development of the new energy industry to enhance ILCD. It is worth noting that stronger environmental regulation stimulates the positive externality of RETI on ILCD. Therefore, the government should establish the concept of green development, strengthen environmental supervision, implement diversified environmental regulation policies, and promote the modernization of the environmental governance system and capacity to achieve inclusive development among the economy, society and energy saving and carbon reduction.

This study explores the characteristics, dynamic evolution and influencing factors of inclusive low-carbon development based on Chinese data. However, how to achieve equitable and inclusive low-carbon development is not only a major issue needs to be addressed in China, but also a growing concern in the world. Especially in the face of the spread and recurrence of COVID, countries worldwide urgently need to promote green economic recovery and low-carbon transition to deal with the challenges of economic development posed by the epidemic (Lahcen et al. 2020). The findings of the study could provide decision-making support for inclusive low-carbon development in other countries undergoing economic transition and emerging economies, especially those that are energy-dependent and rapidly industrializing.

In addition, the study still needs to be further improved. Firstly, due to data availability, the analysis of ILCD at the provincial level is explored in depth, and subsequent analyses can sink to the city or industry level. Secondly, the evaluation of ILCD in this paper mainly selects quantitative indicators, ignoring the use of qualitative indicators. The studies can further incorporate qualitative factors such as policies and systems into the analysis framework for a more comprehensive evaluation of ILCD. Finally, future studies can carry out comparative experiments of RETI on ILCD to explore the differences between the developing and developed countries, which contributes to strengthening RETI cooperation in the world and formulating targeted renewable energy development policies according to their national conditions.

**Author contribution** Long Xin (first author): conceptualization, formal analysis, data curation, methodology, writing—original draft. Hui Sun (Corresponding author): supervision, project administration, review and editing, funding acquisition. Xuechao Xia: data curation, software, validation, visualization.

**Funding** This research was supported by the National Natural Science Foundation of China (71963030), Xinjiang Social Science Foundation

of China (21BJY050), Major Projects of Science and Technology Ministry of China (SQ2021xjkk01800), National security collaborative innovation project (22GAZXC03), 2022 “Silk Road” scientific research and innovation project for Postgraduates of School of economics and management of Xinjiang University (SL2022006).

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Data availability** Not applicable.

**Conflict of interest** The authors declare no competing interests.

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