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Research article

The spatial spillover effects of clean energy consumption and production on sustainable economic development in China

Yun Cao [a,b], Peng Jiang [a], Ziyan Gong [a], Kedong Yin [d], Yuchen Wang [c,d,*]

[a] *School of Business Administration, Guangxi University, Nanning 530004, China*
[b] *Key Laboratory of Interdisciplinary Science of Statistics and Management (Guangxi University), Education Department of Guangxi, 530004, China*
[c] *School of Management Science and Engineering, Shandong University of Finance and Economics, Jinan 250000, China*
[d] *Institute of Marine Economics and Management, Shandong University of Finance and Economics, Jinan 250000, China*

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ABSTRACT

The massive consumption of fossil energy has resulted in high CO_2 emissions, posing a formidable challenge to global sustainable economic development (SED). As countries endeavor to shift from fossil to clean energy sources to achieve SED, research on the impact of clean energy is scarce, and quantitative analysis is lacking. This study measured China's SED and used a spatial econometric model to examine the impact of clean energy consumption and production on SED across 30 provinces in China from 2008 to 2020. Results show that (1) China's SED exhibits significant positive spatial autocorrelation characteristics, forming a "point-to-area" development pattern. (2) Clean energy consumption, production, and consumption structure all contribute to the promotion of SED in the region and have positive spatial spillover effects. (3) A considerable regional disparity exists in the spatial impact of clean energy on SED. The eastern and central regions have significant positive spatial spillover effects, whereas the western region is opposite. Notably, the estimated coefficient of the spatial Durbin model is relatively small, reflecting China's ongoing transition to clean energy and its limited role in promoting economic sustainability. Joint efforts and differentiated policies are essential to develop clean energy and sustainable economic.

1. Introduction

Since the Industrial Revolution, the rapid economic growth of all countries worldwide has depended on the consumption of traditional fossil energy sources such as oil and coal [1,2]. However, with the accelerated expansion of the global economy, problems such as energy shortages, security concerns, and environmental degradation have gained increasing prominence, posing a growing threat to human survival and sustainable development. According to data from BP's "Statistical Review of World Energy 2022" (Table 1), global energy demand remains substantial, with global primary energy consumption reaching as high as 595.15 EJ in 2021. In the context of fossil energy, global consumption of resources like oil, coal, and natural gas reached 463.68 EJ in 2020, accounting for 82.21% of total global primary energy consumption in 2020. The total fossil energy consumption in 2021 stood at 489.67 EJ, marking a significant increase of 344.10 EJ from 1965, nearly tripling the consumption. As the world's second-largest economy and largest energy consumer, China takes the lead globally in both total fossil energy consumption and total energy consumption, accounting for

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[*] Corresponding author. School of Management Science and Engineering, Shandong University of Finance and Economics, Jinan 250000, China.
E-mail address: wangyuchen0414@126.com (Y. Wang).

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Table 1
Primary energy consumption structure of the world's major countries in 2020 and 2021.

Primary Energy Consumption Composition (EJ)	2020							2021						
	Oil	Gas	Coal	Nuclear	Hydro	Renewable Energy	Total	Oil	Gas	Coal	Nuclear	Hydro	Renewable Energy	Total
Globe	174.17	138.44	151.07	24.44	41.09	34.80	564.01	184.21	145.35	160.10	25.31	40.26	39.91	595.15
China	28.74	12.12	82.38	3.32	12.50	8.52	147.58	30.60	13.63	86.17	3.68	12.25	11.32	157.65
Japan	6.49	3.75	4.57	0.39	0.73	1.20	17.13	6.61	3.73	4.80	0.55	0.73	1.32	17.74
Germany	4.22	3.14	1.81	0.58	0.17	2.44	12.36	4.18	3.26	2.12	0.62	0.18	2.28	12.64
UK	2.35	2.63	0.20	0.46	0.06	1.35	7.06	2.50	2.77	0.21	0.41	0.05	1.24	7.18
US	32.52	29.95	9.20	7.54	2.67	6.65	88.54	35.33	29.76	10.57	7.40	2.43	7.48	92.97
India	9.08	2.18	17.40	0.40	1.55	1.58	32.19	9.41	2.24	20.09	0.40	1.51	1.79	35.43

Data source: BP's "Statistical Review of World Energy 2022".

26.49% of the world's total energy consumption in 2021. In 2022, China's total energy consumption has reached 5.41 billion tons of standard coal, marking a 2.9% increase compared with the previous year, with coal consumption increasing by 4.3%. Coal and petroleum consumption represent 56.2% and 17.9%, respectively, of the energy consumption mix. However, the extensive consumption of fossil energy has led to a surge in global carbon dioxide (CO2) emissions and global warming, emerging as a primary threat to human sustainable development. Hence, an urgent need exists to counteract the effects of climate change. The development of clean energy, reduction of carbon emissions, and realization of sustainable economic development (SED) have become urgent global priorities [3,4].

Excessive CO2 emissions are considered a major impediment to achieving the objectives of low-carbon economic policies [5] and a stumbling block to sustainable economic development. In China, the total CO2 emissions from fossil energy consumption remain substantial. In 2021, China's CO2 emissions from energy sources reached 10,523 million tons. Comparing China's emissions with those of other countries, including the United States, the United Kingdom, and Germany, China's share of global carbon emissions has risen from 4% in 1965 to 31% in 2021, necessitating immediate action to reduce CO2 emissions (Figs. 1 and 2). That increasing the proportion of clean energy consumption within the total energy mix is an effective and reliable approach to reduce CO2 emissions has been well documented [6]. The main challenge in China's emission reduction efforts today lies in the need to encourage consumption for economic growth, but higher consumption of fossil energy leads to increased CO2 emissions. Effectively addressing this contradiction and promoting sustainable economic development necessitates the vigorous development of clean energy and the promotion of its consumption [7].

Reviewing the history of global energy development, humanity has transitioned through various energy eras, from the fuelwood energy era to the coal energy era and then the petroleum energy era. Now, to facilitate the realization of SED, we stand on the threshold of the clean energy era. Amid the new normal of economic development, controlling CO2 emissions and safeguarding the ecological environment have become a shared consensus among nations worldwide [8]. Governments around the world have implemented a spectrum of clean energy transition policies to achieve SED [9]. For instance, Germany's "Clean Energy Prioritization Act" in 2000, the U.S. "American Clean Energy and Security Act" of 2009, Australia's "Clean Energy Act" in 2011, China's "Renewable Energy Law" in 2005, and the "Strategy for Energy Production and Consumption Revolution (2016–2030)" formulated in 2016, along with the 2022 "14th Five-Year Plan for Renewable Energy Development". These examples underscore those nations fully realized the important role of clean energy in reducing carbon emissions and promoting SED. Thanks to global policies promoting clean energy, the future of clean energy development appears promising. Consequently, an increasing number of scholars both domestic and international focus on the future trends in clean energy, delving into whether it can reduce pollutant emissions, optimize the ecological environment, and expedite economic sustainability.

Renewable energy stands at the core of clean energy, and China boasts abundant renewable energy resources, including solar energy, wind energy, biomass energy, and hydro energy. Today, China leads the world in clean energy development, ranking as the top nation in terms of installed renewable energy capacity and equipment manufacturing [10–12]. In 2021, China's renewable energy witnessed a remarkable growth rate of 33.1%, accounting for 28.35% of global renewable energy, far surpassing other regions. Specifically, China drove significant growth in solar and wind capacity, contributing approximately 36% and 40% of global capacity additions, respectively. Additionally, nuclear power exhibited an approximately 11.6% growth, making China the leader in global nuclear power expansion. This upward trend in China's renewable energy growth is evident in Fig. 3. China's consumption, development, and utilization of renewable energy remain unparalleled globally, with consumption and production reaching 11.32 EJ and 11.21 EJ, respectively, in 2021. These figures account for 28.35% and 31.30% of the global total, far exceeding the rest of the world (Table 2). Nevertheless, in terms of energy consumption structure, China maintains a higher share of coal and oil compared with developed countries like the United States, the United Kingdom, and Germany. To boost the proportion of clean energy consumption, China must continue its strong commitment to clean energy development.

In recent years, the promotion of transitioning to clean energy has emerged as a focal point for SED [13,14]. Scholars, both domestically and internationally, have placed a special emphasis on the important role of clean energy in carbon emission reduction,

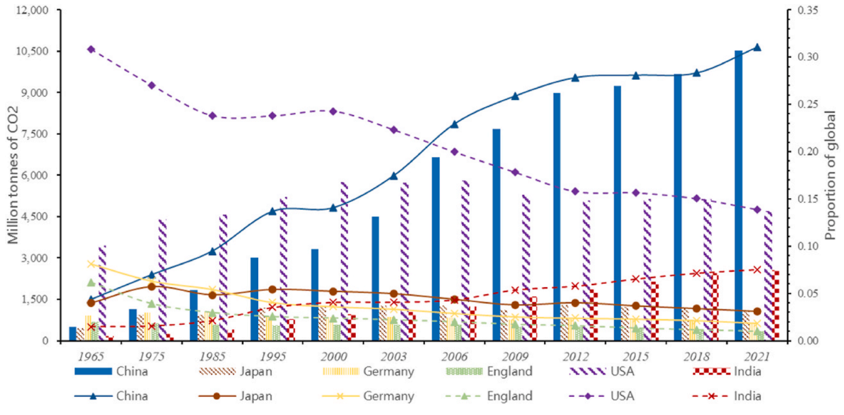


Fig. 1. Trends in CO2 emissions in the world's major countries, 1965–2021.
Data source: BP's "Statistical Review of World Energy".

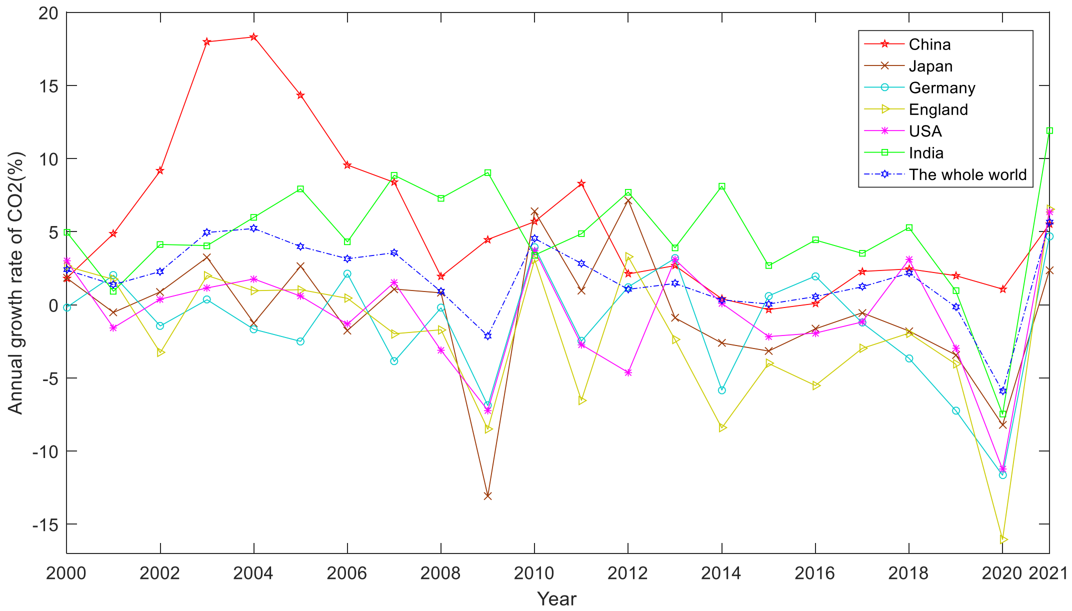


Fig. 2. Annual growth rates of CO2 emissions in major countries of the world, 2000–2021.
Data source: BP "Statistical Review of World Energy".

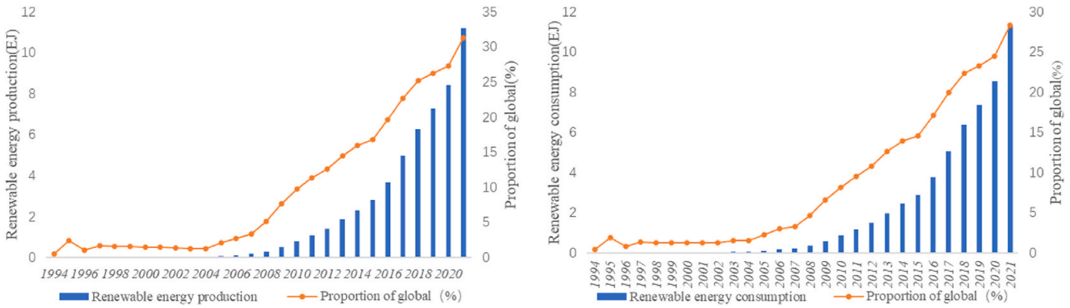


Fig. 3. Trends in renewable energy consumption and production in China and global share, 1994–2021.

Table 2
Renewable energy consumption in the world's major countries in 2021.

Country (region)	Globe	China	Japan	Germany	UK	US	India
Renewable energy consumption (EJ)	39.91	11.32	1.32	2.28	1.24	7.48	1.79
Global share of renewable energy consumption (%)		28.35	3.30	5.71	3.11	18.74	4.48
Growth rate of renewable energy consumption (%)	15.00	33.10	9.90	−6.20	−8.10	12.80	13.20
Average growth rate from 2011 to 2021 (%)	12.60	25.60	14.30	6.30	13.20	8.70	13.90

Data source: BP's "Statistical Review of World Energy".

environmental protection, and SED [15–17]. From an international perspective, Gyamfi et al. [18]confirmed that clean energy contributes to higher levels of environmental quality and hence environmental sustainability in Germany. Gangopadhyay et al. [19] examined the impact of renewable energy consumption on carbon pollution in the USA and found that the US was able to achieve SDG-7 through clean energy consumption. Obobisa [20] assessed the role of the Organization for Economic Co-operation and Development (OECD) on carbon neutrality and sustainable development and found that expanding the use of clean energy is conducive to achieving SED through carbon reduction. As clean energy experiences rapid growth in China, SED has become a paramount concern for the Chinese government [21]. In light of the existence of high CO2 emissions, environmental pollution, and ecological degradation, which violate the principles of sustainability [22–24], particularly following the substantial increase in natural resource exploitation leading to serious environmental problems, the connection between clean energy development and its impact on economic sustainability has progressively captured academic attention [21]. The United Nations' Sustainable Development Goals (SDGs) assert that the utilization of clean energy can reduce the negative environmental consequences associated with economic growth [13]. This has been empirically demonstrated by several scholars, who have found that clean energy investment [25], renewable electricity [26], and natural gas consumption constraints [27] play a positive role in China's realization of SDGs as the country's emphasis on clean and renewable energy rises. To attain high-quality and SED in China, the need to increase the development and utilization of clean energy, increase clean energy consumption, reduce CO2 emissions from fossil energy utilization, and achieve sustainable economic growth is urgent [24,28]. However, fewer studies have explored the relationship between clean energy and SED in China, focusing more on its relationship with economic growth, and the findings are not yet consistent. Second, most studies have neglected the spatial dependence of SED and whether there is a spatial spillover effect of clean energy development on SED. Therefore, clarifying the complex relationship between clean energy and SED in China holds great significance in promoting the transition to clean energy, enhancing environmental quality, and advancing economic sustainability.

The innovative contributions of this paper are mainly categorized as follows.

1. First, most scholars focus on the relationship between clean energy, renewable energy, and economic growth. However, contemporary economic development requires not only GDP growth, but also focuses on high-quality economic development and harmonization of economic and environmental factors, and there is a paucity of explorations on the relationship between clean energy and SED. This paper explores this logic from the perspectives of clean energy production, consumption, and structure.
2. Furthermore, prior research has often neglected the potential spatial dependencies when analyzing the relationship between clean energy development and SED [29,30]. Many issues related to economic and environmental concerns inherently exhibit spatial dependence. Neglecting spatial correlations may result in significantly biased estimation outcomes. Therefore, this paper considers spatial spillover effects when studying the relationship between clean energy and SED.

The remainder of this paper is structured as follows: Section 2 reviews the extant literature on this topic. Section 3 delineates the theoretical mechanisms at play. Section 4 expounds on the methodology and data employed. Section 5 presents the results. Lastly, Section 6 comprises conclusions and policy implications.

2. Literature review

2.1. Definition of clean energy

Clean energy, as an emerging alternative to carbon-intensive fossil fuels, represents the world's most efficient source of energy [31] and has garnered significant attention from countries around the world. Therefore, a clear definition of clean energy can facilitate its development and stimulate scholarly research. The definition of "clean energy" varies across studies and has yet to be standardized. However, existing literature often defines clean energy based on its energy source. One interpretation refers to energy sources other than coal, oil, natural gas, and thermal power, including hydropower, nuclear power, solar power, wind power, and biomass [32,33]. Shi et al. [34], in their assessment of clean energy generation in China's provinces and municipalities, define it as the sum of four types of power generation: solar power, wind power, hydroelectricity, and nuclear power. Some definitions equate clean energy with renewable energy, encompassing all recyclable energy sources [35]. Others are based on energy sources that produce little or no pollutants during development and utilization, emphasizing environmental friendliness and low pollution levels [36]. Certain literature defines clean energy in terms of energy production with no CO2 emissions [37]. Another definition describes clean energy as low-impact energy sources with minimal environmental pollution risks during production and consumption. These energy sources also prevent the migration of elements, such as C, N, and S, which may generate pollution during utilization. Examples of these sources include wind, water, solar, geothermal, and ocean energy [38].

Official Chinese government agencies have not yet given a clear definition of clean energy in official documents. However, the National Bureau of Statistics, relevant energy reports, and policy documents have all referenced the scope of the clean energy definition. At present, China's definition is relatively clear. The National Development and Reform Commission (2022) regards non-fossil energy sources such as wind, solar, hydro, biomass, and geothermal energy as renewable energy sources, with renewable energy sources forming an essential component of clean energy. "The Energy Law of the People's Republic of China" and "The 13th Five-Year Plan for Energy Development" both identify natural gas as a low-carbon clean energy source, given its reduced environmental impact. Consequently, this study adheres to the aforementioned literature and definitions, while also incorporating references to "The Energy Law of the People's Republic of China" and "The 13th Five-Year Plan for Energy Development." Thus, this study defines clean energy as encompassing hydropower, nuclear energy, wind energy, biomass energy, solar energy, geothermal energy, ocean energy, natural gas, and other energy sources.

2.2. Spillover effects of clean energy

Excessive consumption of fossil energy has led to a surge in CO2 emissions, exacerbating global warming and posing a substantial threat to the sustainable development of humanity [39]. Given this context, both domestic and international scholars have directed their attention to energy and environmental issues, with a particular focus on the significant role of clean energy development in a nation's ecological and environmental protection [15]. In empirical studies pertaining to clean energy development, many are predominantly oriented toward investigating the environmental role [40]. Regions are influenced to varying degrees by neighboring areas [41], and neglecting spatial effects may lead to model specification errors and estimation biases [42]. Many studies have demonstrated that environmental pollution exhibits pronounced externalities and regional characteristics, whereas energy, economic factors, and ecological environments are marked by substantial mobility and diffusion, making them susceptible to the influence of neighboring regions [43,44]. Consequently, the use of clean energy may produce spatial spillover effects. In contemporary research, numerous studies have scrutinized the spatial spillover effects of clean energy. For example, Huang and Tian [45]define clean energy as encompassing clean energy production, including hydroelectric power, wind power, solar power, and nuclear power. Their results, as per the spatial Durbin model (SDM), reveal that clean energy exerts a significant inhibitory impact on haze pollution, with a clear negative spatial spillover effect. Herzer [46], utilizing G7 countries as a sample, establishes that clean energy R&D technologies negatively affect both domestic and foreign CO2 emissions, underscoring the spatial spillover effect of clean energy technologies. Su et al. [47] demonstrate the spillover effect of renewable energy in carbon markets. Ashraf et al. [48]present that the consumption of renewable energy in 75 Belt and Road countries significantly influences CO2 emissions. On the contrary, energy intensity targets at the local level and in neighboring provinces can promote renewable energy consumption [49]. These studies underscore the likelihood of spatial spillover effects stemming from the consumption and production of clean energy, emphasizing the importance of considering spatial factors.

2.3. Clean energy and economic growth

The adoption of clean energy is crucial for achieving sustainable development [50], and a dynamic, long-term relationship may exist between economic growth and clean energy. Scholars have increasingly directed their attention to investigating the impact of clean energy on economic growth [51]. However, the findings in these studies remain inconclusive. Some scholars underscore the positive impact of clean energy on economic growth [52], positing that the development of clean energy reduces CO2 emissions, thus fostering SED [53]. For example, Alper and Oguz [54]employ asymmetric causality tests and the autoregressive distributed lag method to demonstrate a causal relationship between economic growth and renewable energy consumption. They find that renewable energy consumption positively impacts the economic growth of all new EU member states. Similarly, Bhattacharya et al. [50] reveal that renewable energy consumption exerts a positive influence on the economic output of 57% of the top 38 countries. Conversely, some scholars argue that clean energy consumption may have a dampening effect on economic growth. For instance, Ozcan and Ozturk [55] contend that no significant causal relationship exists between clean energy demand and economic growth and that energy efficiency policies may potentially hinder a country's economic growth. Still, other scholars posit both positive and negative effects. Dogan and Seker [56]contend that the economic impact of total renewable energy consumption is positive for lower and low-middle quartiles but negative for the middle, high-middle, and high quartiles. Worth noting is that many scholars focus primarily on renewable energy rather than investigating the impact of clean energy on economic growth. However, renewable energy constitutes just one component of clean energy. Additionally, scholars tend to concentrate on the relationship between clean energy and GDP or GDP per capita. However, contemporary economic development necessitates more than mere GDP growth; it also requires a focus on high-quality economic development, harmonizing economic and environmental factors. A SED variable aligns more closely with modern economic development concepts.

Scholars have explored the interplay between clean energy and economic development, yet consensus remains elusive regarding the extent of clean energy's influence on economic development. The existing literature often focuses on the examination of clean energy's impact on GDP. Nonetheless, many scholars select GDP or GDP per capita indicators to gauge the level of economic growth in their studies, assessing economic growth solely in terms of overall economic expansion. However, contemporary economic development criteria extend beyond GDP growth, emphasizing high-quality economic development. Furthermore, proxy variables employed to measure clean energy, such as renewable energy generation, natural gas consumption, the proportion of alternative and nuclear energy in total energy use, combustible renewable energy, waste, electricity consumption, and the Renewable Energy Country Attractiveness Index [50], do not comprehensively capture the essence of clean energy. Consequently, the body of literature on clean energy remains somewhat limited. There are fewer studies on the impact of clean energy development on SED, in terms of direct effects, most of the relevant studies concluded that clean energy contributes to the realization of SED. Li and Lu [35] revealed the effectiveness of natural gas consumption in China's achievement of SED. Qin et al. [26] found that renewable electricity can contribute to the realization of SED through the reduction of carbon emissions. Zahoor et al. [25] argued that clean energy investments while sacrificing economic growth to some extent, improve environmental sustainability, which in turn becomes a determinant of sustainable economic growth. Obobisa [20]found that clean energy utilization can achieve SED by reducing carbon dioxide emissions. Furthermore, prior research has often neglected the potential spatial dependencies when analyzing the relationship between clean energy development and SED [29,30]. Many issues related to economic and environmental concerns inherently exhibit spatial dependence. Neglecting spatial correlations may result in significantly biased estimation outcomes. Studies with some relevance to this paper have shown that clean energy development has suppressed air pollution emissions in neighboring regions [57,58], as well as reduced carbon emissions [33]. However, some scholars hold the opposite view, arguing that clean energy development promotes the increase of carbon emissions in neighboring regions [33], and the beggar-thy-neighbor effect is obvious. Therefore, whether there is a spatial spillover effect of clean energy on SED and whether it inhibits or promotes SED in neighboring regions is difficult to answer from the existing literature and needs to be further explored.

Therefore, a comprehensive indicator system capable of holistically measuring SED levels is necessary. The influence of clean energy consumption and production on SED should also be explored from a spatial perspective. This study makes three major contributions. First, it devises a SED indicator system comprising five dimensions: economic development, scientific and technological innovation, social well-being, environmental governance, and green development. This system offers a dynamic depiction of China's SED process and its future developmental trajectory. Second, considering the spatial effect on SED, a spatial econometric model is deployed to investigate whether China's clean energy development effectively promotes economic sustainability. Third, this study examines the role of clean energy development in fostering SED across different regions, considering regional disparities in clean energy development. Heterogeneity analysis, grounded in energy distribution characteristics, underscores the need for tailored approaches to clean energy development and SED.

3. Theoretical mechanism

3.1. Direct effect

Based on the literature analysis above, it is evident that both clean energy production and consumption can directly impact economic development during the production and consumption processes. Numerous studies have demonstrated that adjusting the industrial structure can facilitate the optimization of the energy structure, enhance ecological environmental protection, and improve the quality of economic development. With the intra-regional transfer of clean energy-related industries in China and the cross-regional flow of clean energy, industrial structure plays a crucial role in the influence of clean energy on sustainable economic growth. Optimizing the industrial structure represents a significant pathway to reducing environmental pollution, increasing the share of clean energy consumption, and achieving energy conservation, emission reduction, and SED.

To further analyze the evolution of China's industrial structure and understand the mechanism by which industrial structure impacts the development and utilization of clean energy for sustainable development, we present the trend in the evolution of China's industrial structure from 1978 to 2021 (Fig. 4).

As shown in Fig. 4, the proportion of China's primary industry demonstrates a decreasing trend, the secondary industry's share gradually declines, whereas the tertiary industry's proportion increases. This trend reflects the ongoing adjustment and optimization of China's industrial structure. Correspondingly, the contribution of China's three major industries to GDP evolves, with the contribution of the primary industry stabilizing, the secondary industry's contribution decreasing, and the tertiary industry's contribution rising. This shift indicates the gradual optimization of China's industrial structure. In line with industrial structure theory and sustainable development theory, the secondary industry is associated with significant environmental pollution. Industries within the secondary sector, characterized by high energy consumption and high pollution, generate substantial exhaust gases and wastewater, resulting in increased CO2 emissions and ecological pollution. During the process of industrial structure adjustment and optimization, the rise in the share of the tertiary industry allows the environmental protection industry to replace high-energy consumption and high-pollution industries. Industrial upgrading entails the transformation of the industrial structure from heavy energy-consuming industries to lighter, less-polluting sectors, reducing environmental pollution. The continuous transfer and optimization of industries can drive high-quality economic development and promote balanced regional development, thus influencing SED.

As shown in Fig. 5, the development and utilization of clean energy lead to the growth of energy-efficient and environmentally friendly clean industries. Clean energy-related industries are an integral part of this process, accelerating industrial advancement, improving production efficiency, and facilitating the transition from high-pollution and high-emission industries to cleaner alternatives. This transformation promotes industrial optimization and upgrading. As clean energy production technology continues to advance, the dependence on traditional fossil energy decreases, and the proportion of clean energy in the energy mix rises. This promotes the production and consumption of clean energy sources such as solar, hydro, wind, and nuclear power. Clean energy production and consumption do not produce environmentally harmful substances, reducing pollution and enhancing ecological quality. Additionally, stringent energy consumption and environmental protection standards lead to the gradual phasing out of high-pollution and high-energy-consumption industries. This results in a decline in the share of secondary production and an increase in the share of tertiary production, fostering the growth of energy-efficient and environmentally friendly clean industries. The rising demand for clean energy further drives the transition of traditional high-energy-consumption and high-emission industries toward cleaner, low-emission alternatives. The structural transformation due to inter-regional industrial transfer and regional industrial restructuring

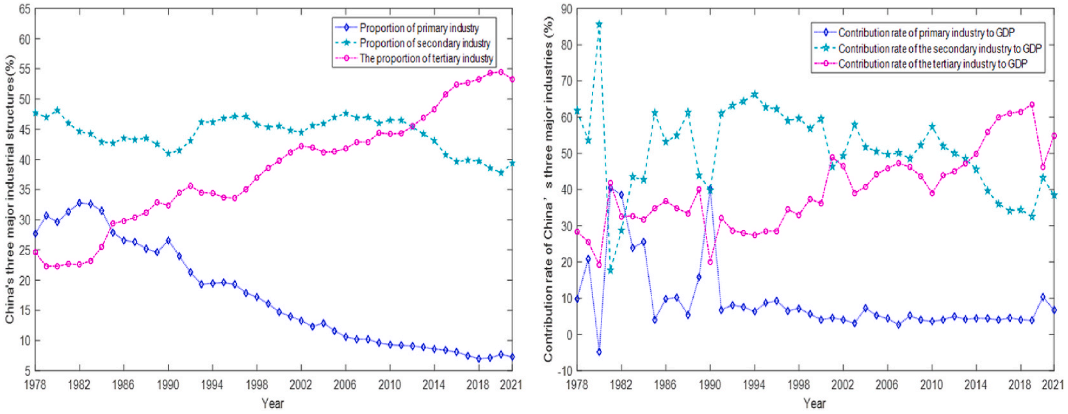


Fig. 4. Evolutionary pattern of China's industrial structure, 1978–2021.

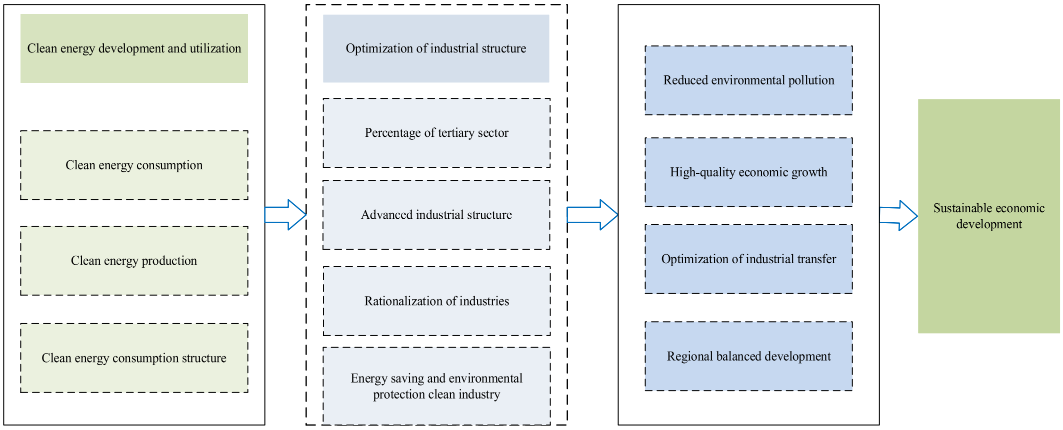


Fig. 5. Mechanisms affecting industrial structure.

promotes balanced regional development, directly affects clean energy consumption share, and optimizes energy consumption structure.

3.2. Spatial effect

As China's economy experiences rapid growth, environmental issues such as excessive consumption of fossil energy, rising CO2

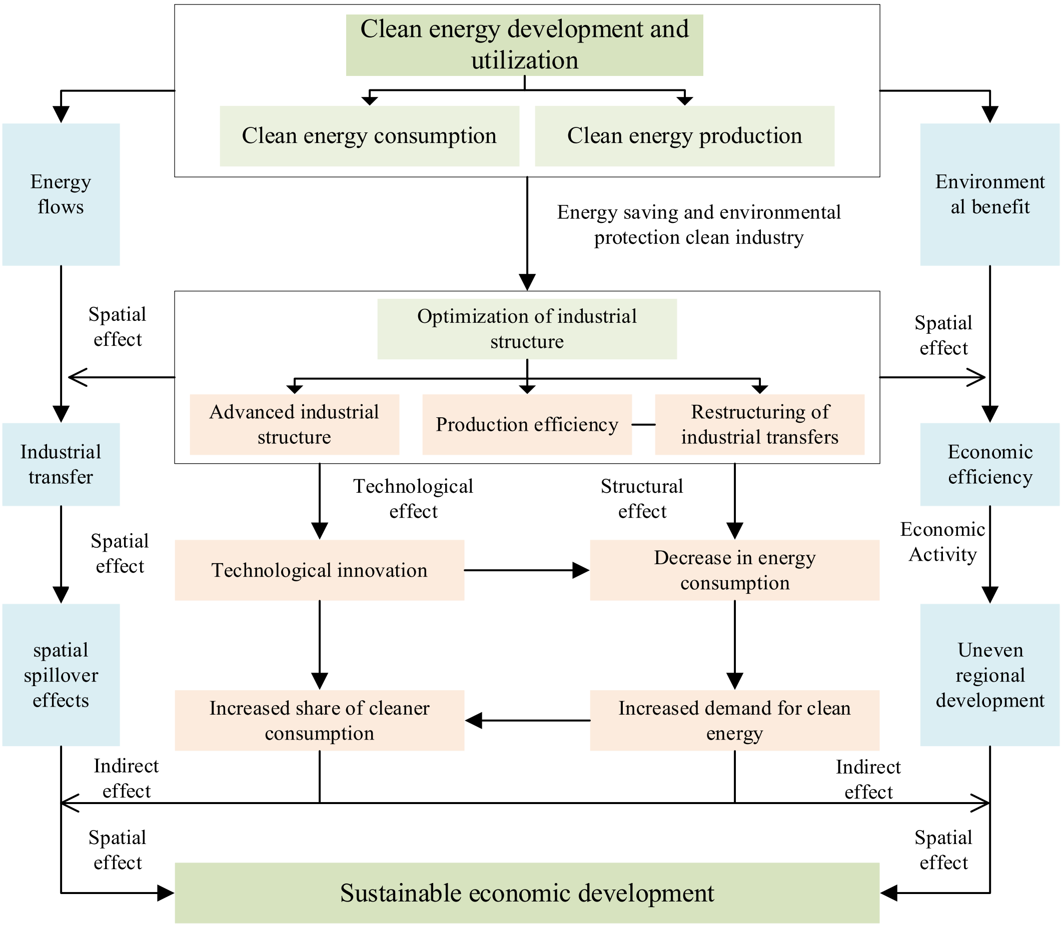


Fig. 6. Mechanisms of spatial effects.

emissions, and climate warming have become increasingly grave. Sustainable development is now a globally recognized economic development model. The role of clean energy in addressing challenges such as energy scarcity, environmental degradation, and promoting sustainability has garnered extensive attention from both society and academia. As regional economic integration in China advances, economic activities and energy distribution between regions occur frequently [59], underscoring the significance of spatial factors in economic activities. On the one hand, economic interactions between regions often form complex network structures, and the economic development of one region can have spatial spillover effects on the economic growth of neighboring regions. On the other hand, initiatives like "Western Electricity Sent to the East," "Western Gas Transmission to the East," and "East-to-East Gas Transmission from Sichuan" have bolstered the cross-regional flow of energy. Consequently, the SED of a region is influenced not only by its own clean energy efforts but also by those of neighboring regions.

Given the spatial agglomeration and regional disparities characterizing clean energy and SED, the incorporation of spatial factors becomes crucial. Constructing spatial econometric models from a spatial influence perspective can shed light on the spatial influence of clean energy development and utilization on SED. This approach facilitates a shift in economic growth models and promotes inter-regional collaboration in environmental governance, sustainable development, and energy policy formulation. Questions arise: Is there spatial correlation between clean energy development and utilization and SED across provincial areas from a spatial perspective? How does clean energy development and utilization impact SED in terms of spatial effects? Addressing these queries not only fosters interregional cooperation in economic and environmental governance, as well as energy security, through policy and management coordination but also contributes to the establishment of a regional community focused on SED from a spatial perspective. It allows for the alignment of regional environmental pollution control with clean energy development and utilization within the energy market mechanism to enhance the level of SED. Therefore, the spatial spillover effect of clean energy development and utilization on SED is not only a subject of academic interest but also a practical challenge that requires resolution in the formulation of energy, environmental, and sustainable policies by governments at all levels.

According to the previous analysis, the development of clean energy in China has reached a leading international level. However, uneven spatial development may engender spatial spillover effects due to the frequent exchange of economic and energy resources among regions. On the one hand, the regional development disparity in clean energy development and utilization is striking, with the western regions showing considerably higher development levels than the eastern regions. The implementation of initiatives like "Western Electricity Sent to the East," "Western Gas Transmission to the East," "Sichuan Gas Sent to the East," and "Sending Electricity to the South" has intensified the flow of clean energy between regions, potentially generating spatial effects. On the other hand, increased clean energy development and utilization levels lead to a reduction in environmental pollution and environmental benefits. Coupled with ongoing industrial structure optimization and adjustment, this reduction in environmental impact may enhance economic efficiency via spatial effects. The introduction of economic regional integration underscores the observable spatial spillover effect on the economy. The impact on SED is reflected in the spatial spillover effect. The mechanisms of the spatial impact of clean energy development and utilization on SED are depicted in Fig. 6.

In summary, clean energy development and utilization may generate spatial spillover effects, influencing economic development through environmental and economic benefits. On the one hand, the development and utilization of clean energy can foster high-quality economic development and impact SED. On the other hand, it may also influence economic development through spatial spillover effects due to regional development imbalances and the spatial flow of the economy, industry, and energy during energy structure optimization and industrial structure adjustment.

In accordance with spatial econometrics theory, the influence of geographical interactions plays a pivotal role, and the sustainable development of China's economy may be affected by the sustainable development of neighboring regions. As economic exchanges between neighboring regions become more integrated, the correlation between the sustainable development of these geographic units strengthens, and the spillover effect of regional economic development impacts the economic development of adjacent regions. With this in mind, this study selects 30 provinces, cities, and autonomous regions in China (excluding Tibet, Hong Kong, Macao, and Taiwan) as its research subjects. A well-designed spatial measurement model is utilized for empirical analysis of the spatial spillover effect of clean energy development and utilization on SED, considering both a national and regional perspective.

4. Methodology

4.1. *Construction of indicators of SED*

China's economic development is characterized by remarkable dynamism, and the economic and environmental landscape is both intricate and volatile. To precisely assess the level of high-quality development in China's economy, a comprehensive set of indicators for SED should be devised. In this study, we designed a comprehensive set of indicators for China's SED, drawing upon the foundations laid by the China Sustainable Development Indicator System. The concept of sustainable development has evolved into a mature framework during China's 11th Five-Year Plan period. Therefore, our selection of variables for the indicator system takes into account the availability of statistical data in China since 2006, reducing subjectivity and enhancing objectivity, scientific rigor, and transparency, aligning with the principles of sustainable development.

Adhering to these principles, this study has developed a SED indicator system with five dimensions: economic development, scientific and technological innovation, social well-being, environmental governance, and green development. To ensure the scientific accuracy, comprehensiveness, and effectiveness of this indicator system, a battery of testing methods, including t-tests, Wilcoxon tests, Cronbach's coefficient tests, Kendall-W coordinated coefficient consistency tests, Friedman tests, and multi-indicator expert empowerment consistency tests, has been applied for testing and optimization. Finally, through a combination of hierarchical analysis, panel entropy weighting, and principal component analysis, portfolio weights have been calculated using the geometric mean, and the results are presented in Table 3.

4.2. Variable selection and data sources

4.2.1. Variable selection

4.2.1.1. Explained variable. The central concept of SED involves the organic integration of environmental, resource, and economic development issues to enhance the environment's quality and maximize economic development. In this study, the level of SED (*SED*) for 30 provinces, cities, and districts in China, calculated using the indicator system, serves as the explained variable to explore the spatial impact of clean energy development and utilization on SED.

4.2.1.2. Core explanatory variables. Clean energy development and utilization can optimize the energy consumption structure and reduce CO2 emissions, thereby promoting high-quality and sustainable economic growth. The core explanatory variables in this study are the levels of clean energy development and utilization in China, which are measured using three variables: clean energy production (*CEP*), clean energy consumption (*CEC*), and clean energy consumption structure (*CES*). Clean energy consumption structure is expressed as the ratio of clean energy consumption to total energy consumption.

4.2.1.3. Control variables. In line with the principles of SED, this chapter incorporates variables such as economic growth, technological level, advanced industry, urbanization level, and environmental regulation as control variables.

Economic growth (GDP per capita) plays a vital role in SED, and this study utilizes GDP per capita (*PGDP*) as the metric to gauge China's economic growth. Technological advancement is a core element of SED, as emphasized by Luo et al. [60]. In this study, the level of technological development is measured by the ratio of regional R&D expenditure to regional GDP. Advanced industry (*AI*) is incorporated as a control variable in the spatial measurement model due to the relatively lower resource consumption and reduced environmental impact of the tertiary industry, as well as its substantial influence on the sustainable development of the economy. The ratio of China's tertiary industry to the secondary industry serves as the measure for advanced industry, and an upward trend in this ratio signifies the optimization and adjustment of China's industrial structure toward low-pollution and low-energy-consumption production methods, contributing to the sustainable development of the economy [61,62]. Urbanization level (*URB*) is another significant factor, as China remains in the process of urbanization. Increasing urbanization not only fosters the transition of the rural population to urban areas and boosts employment rates but also enhances human capital and propels economic growth, as noted by Bakirtas and Akpolat [63]. Fang et al. [64] underscore the positive impact of urbanization on sustainable development. Consequently, this study employs the ratio of regional urban population to total regional population to assess the level of urbanization. Finally, environmental regulation (*ER*) is an indispensable consideration, given its impact on SED [65]. To measure environmental regulation intensity, this study employs the proportion of completed industrial pollution control investment in the secondary industry.

4.2.2. Data sources

In selecting the data sources, data accessibility and continuity must be considered. Given the incomplete data statistics before 2008, this study focuses on the period from 2008 to 2020, using 30 provincial-level administrative regions in China as the research unit. Tibet, Macao, Hong Kong, and Taiwan are excluded from the sample due to missing data issues.

For the indicator of clean energy production, data are referenced from Xu et al. [66] and sourced from the China Energy Statistical Yearbook and statistical yearbooks of provinces, autonomous regions, and municipalities. Clean energy production for each province is determined by the total energy production in the region and the proportion of primary electricity (hydropower) and other clean energy sources (nuclear energy, wind energy, geothermal energy, etc.) to the total energy production. To address incomplete data in some provinces' statistical yearbooks, this study supplements clean energy production data with information from the China Energy Statistical Yearbook, using the ARIMA model for provinces with missing data. Clean energy consumption is calculated similarly to clean energy production. The clean energy consumption structure of each province is expressed as the ratio of clean energy consumption to total energy consumption. These data are obtained from sources including the National Economic and Social Development Statistical Bulletin, China Energy Statistical Yearbook, National Bureau of Statistics, and provincial statistical yearbooks. Data for control variables are sourced from the National Bureau of Statistics, the China Statistical Yearbook, the China Energy Statistical Yearbook, the China Environmental Statistical Yearbook, the China Science and Technology Statistical Yearbook, and provincial energy statistical yearbooks.

4.3. Spatial measurement modeling

Spatial factors are introduced to measure the level of clean energy development and utilization by clean energy consumption, production, and consumption structure. The spatial influence effect of clean energy development and utilization on SED is studied in depth. First, the spatial spillover effect of clean energy development and utilization on the level of SED is investigated by adding spatial factors and spatial lag terms of the explanatory variables. We constructed the Spatial Lag Model (*SLM*), also known as Spatial Autoregressive Model (*SAR*). The specific formula is as follows:

$$\begin{aligned}\ln SED_{it} = {} & \delta \sum_{i\neq j,j=1}^{n} w_{ij} \ln SED_{it} + \alpha + \beta_1(\ln CEC_{it}, \beta_1 \ln CEP_{it}, \ln CES_{it}) + \beta_2 \ln PGDP_{it} + \beta_3 \ln AI_{it} + \beta_4 \ln RD_{it} + \beta_5 \ln URB_{it} \\ & + \beta_6 \ln ER_{it} + \mu_i + \lambda_t + \varepsilon_{it}\end{aligned} \tag{1}$$

where $\ln SED_{it}$ denotes the observed value of SED of the explanatory variables of the i region at the t time, $w_{ij} \ln SED_{it}$ denotes the spatial interaction between the level of SED ($\ln SED_{it}$) and the level of SED ($\ln SED_{it}$) of neighboring units, w_{ij} denotes the spatial weight matrix of the explanatory variables ($\ln SED_{it}$), δ denotes the spatial autoregressive coefficients to be estimated, α denotes the constant term of the model, and β denotes the influence coefficients of the explanatory variables to be estimated. Clean energy consumption ($\ln CEC_{it}$), clean energy production ($\ln CEP_{it}$), and clean energy consumption structure ($\ln CES_{it}$) are the core explanatory variables, respectively. $\ln PGDP_{it}$, $\ln AI_{it}$, $\ln RD_{it}$, $\ln URB_{it}$, and $\ln ER_{it}$ denote the observed values of regional GDP per capita, industrial sophistication, technology level, urbanization level, and environmental regulation of the i region at the t time, respectively, which are the control variables of the model. w_{ij} are the elements of the spatial weight matrix (W), the spatial idiosyncratic effect (μ_i), the period idiosyncratic effect (λ_t), and the random error term (ε_{it}), $\varepsilon_{it} \sim N(0, \sigma_{it}^2)$.

Second, the spatial correlation of the error term was examined by including a spatial error term in the model to capture the spillover effects of clean energy development and utilization on the level of SED. We constructed a Spatial Error Model (*SEM*) with the following formula:

$$\begin{aligned}ln\ SED_{it} = {} & \alpha + \beta_1(ln\ CEC_{it}, \beta_1\ ln\ CEP_{it}, ln\ CES_{it}) + \beta_2\ ln\ PGDP_{it} + \beta_3\ ln\ AI_{it} + \beta_4\ ln\ RD_{it} + \beta_5\ ln\ URB_{it} + \beta_6\ ln\ ER_{it} + \mu_i + \lambda_t \\ & + \varphi_{it}\varphi_{it} = \rho \sum_{i\neq j,j=1}^{n} w_{ij}\varphi_{it} + \varepsilon_{it}\end{aligned} \tag{2}$$

where φ_{it} is the spatial error autocorrelation, ρ is the spatial autocorrelation coefficient, and the rest of the variables have the same meaning as in the Spatial Lag Model (*SLM*).

Finally, as the cases of SLM and SEM may co-exist in the empirical analysis, we constructed the Spatial Durbin Model (*SDM*) for this purpose, which is formulated as follows:

$$\begin{aligned}ln\ SED_{it} = {} & \delta \sum_{i\neq j,j=1}^{n} w_{ij}\ ln\ SED_{it} + \alpha + \beta_1(ln\ CEC_{it}, \beta_1\ ln\ CEP_{it}, ln\ CES_{it}) + \beta_2\ ln\ PGDP_{it} + \beta_3\ ln\ AI_{it} + \beta_4\ ln\ RD_{it} + \beta_5\ ln\ URB_{it} \\ & + \beta_6\ ln\ ER_{it} + \partial_1 \sum_{i\neq j,j=1}^{n} w_{ij}(ln\ CEC_{it}, \beta_1\ ln\ CEP_{it}, ln\ CES_{it}) + \partial_2 \sum_{i\neq j,j=1}^{n} w_{ij}PGDP_{it} + \partial_3 \sum_{i\neq j,j=1}^{n} w_{ij}\ ln\ AI_{it} + \partial_4 \sum_{i\neq j,j=1}^{n} w_{ij}\ ln\ RD_{it} \\ & + \partial_5 \sum_{i\neq j,j=1}^{n} w_{ij}\ ln\ URB_{it} + \partial_6 \sum_{i\neq j,j=1}^{n} w_{ij}\ ln\ ER_{it} + \mu_i + \lambda_t + \varepsilon_{it}\end{aligned} \tag{3}$$

where the meanings of the remaining variables are the same with those of *SLM*, and the ∂ and β of the *SDM* are similar, indicating the coefficients to be estimated by the model. When $\partial = 0$, the *SDM* is converted to a *SLM*; when $\delta = 0$, the *SDM* is converted to a *SEM*; when $\partial = \delta = 0$, the *SDM* is converted to an ordinary linear panel regression model. Therefore, the assumptions of the *SDM* are $H_0 : \partial = 0$ and $H_1 : \partial + \delta\beta = 0$. If the model results reject the assumptions, then the *SDM* is significant and meaningful and can reasonably analyze the actual problem.

5. Discussion of results

5.1. Spatial correlation analysis

Before estimating the spatial econometric model, whether spatial correlation exists in the level of SED must be tested. We use the results of two indices, Moran's I index and Geary's C index, to test for spatial correlation. The formula for global Moran's I is shown below [67]:

$$Moran^{'}sI = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{4}$$

where n indicates the 30 provinces (autonomous regions and municipalities) in China included in the sample; w_{ij} denotes the element of the spatial weight matrix (W), x_i and x_j denote the sustainable development level of i province and j province, respectively; $\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ denotes the mean value of provinces with the same level of sustainable development in the same year; and $S^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2$ denotes the variance of the sample.

The value of Moran's I is in the range of $[-1,1]$, when $|Z| > 1.96$ and $I < 0$, China's level of SED has a negative spatial correlation, indicating that the level of SED of the unit and its neighboring units has a significant difference. When $|Z| > 1.96$ and $I > 0$, the level of SED has a positive spatial correlation, that is, presenting spatial agglomeration effect. When $|Z| > 1.96$ and $I = 0$, no spatial correlation

Table 3
Weighting of SED indicator system based on combination weighting method.

First-level indicators	Secondary indicators	Weight	Third-level indicators	Weight
SED	Economic development	0.2286	GDP	0.2762
			GDP Growth Rate	0.0650
			Degree of Openness to the Outside World	0.2118
			Unemployment Rate	0.1595
			Urbanization	0.1243
			Industrial Structure	0.1632
	Technological innovation	0.3030	Domestic Granted Invention Patents	0.2526
			Research and Development Intensity	0.2343
			Technology Transaction Activity Rate	0.1932
			Number of Universities	0.1187
			Number of Students	0.1350
			Number of University Teachers	0.0662
	Social well-being	0.1246	Gini Coefficient	0.3270
			Infrastructure Level	0.2147
			Number of Health Technicians	0.1645
			Urban–Rural Consumption Disparity	0.1115
			Urban–Rural Income Gap	0.1823
	Environmental Governance	0.0949	Investment in Air Pollution Control Projects Completion	0.2701
			Investment in Wastewater Treatment Project Completion	0.0901
			Investment in Industrial Pollution Control Completion	0.3487
			Harmless Treatment Rate of Household Waste	0.2911
	Green development	0.2489	Energy Consumption Intensity	0.1269
			Energy Consumption Elasticity Coefficient	0.0517
			Per Capita Urban Green Area	0.0482
			Per Capita Water Resources	0.1570
			Forest Area	0.1410
			Forest Coverage Rate	0.1834
			Chemical Oxygen Demand Emission	0.1256
			Sulfur Dioxide Emission	0.1662

is observed in the level of SED. The larger the absolute value of Moran's I is, the more significant the spatial variable correlation is. If the result of Moran's I shows a significant spatial correlation, it indicates that constructing a spatial econometric model for empirical testing is reasonable.

Geary's C index is similar to Moran's I index for testing spatial correlation. It is calculated as shown in Equation (5):

$$C=\frac{(n-1)\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}\left(x_i-\overline{x}_j\right)^2}{2\left(\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}\right)\left[\sum_{i=1}^{n}\left(x_i-\overline{x}\right)^2\right]} \tag{5}$$

The range of Geary's C index is generally $[0,2]$. If $0 < C < 1$, the level of China's SED has a positive spatial correlation; if $C > 1$, the level of China's SED has a negative spatial correlation; when $C = 1$, the level of SED is not spatially correlated.

In this study, the geographic distance weight matrix is selected as the spatial weight matrix, and its element expression is

Table 4
Spatial correlation test.

Year	Moran's I	P-value	Geary's C	P-value
2008	0.329	0.001	0.568	0.002
2009	0.283	0.004	0.646	0.007
2010	0.266	0.006	0.690	0.017
2011	0.334	0.001	0.593	0.002
2012	0.366	0.000	0.551	0.001
2013	0.343	0.001	0.579	0.001
2014	0.412	0.000	0.494	0.000
2015	0.351	0.001	0.606	0.003
2016	0.267	0.006	0.670	0.010
2017	0.314	0.002	0.592	0.002
2018	0.358	0.001	0.559	0.001
2019	0.308	0.002	0.615	0.004
2020	0.317	0.002	0.599	0.003

$$w_{ij} = \begin{cases} \frac{1}{d_{ij}} & i \neq j \\ 0 & i = j \end{cases} \tag{6}$$

where d_{ij} denotes the distance between i province and j province. The geographic distance between different provinces can be calculated from the latitude and longitude coordinates of the capital city of the province.

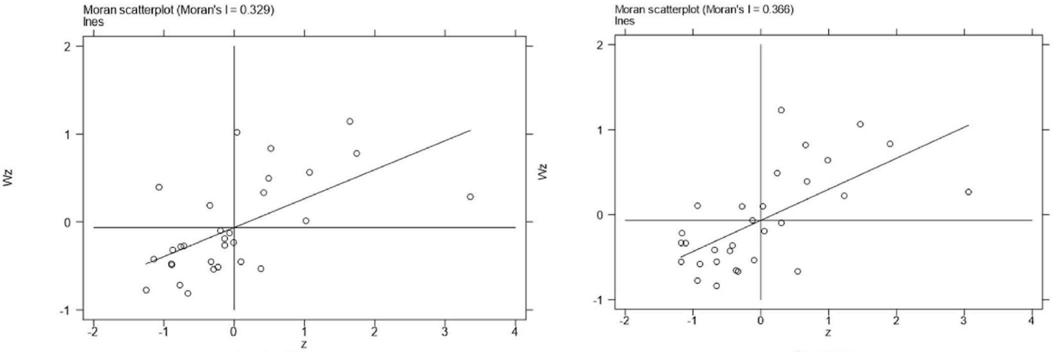
From the test results in Table 4, Moran's I are all positive and all passed the significance level test. Geary's c index are all less than 1 and all passed the significance level test, which indicates that SED has a significant spatial dependence among the 30 provinces (municipalities and districts) in the observation period. Therefore, the spatial correlation of the level of SED should be considered.

To further illustrate the spatial dependence of SED, Moran's I scatterplot is drawn (Fig. 7). As can be seen from the figure, the level of SED in most provinces falls into the spatial positive correlation region in the first and third quadrants, further indicating that the level of SED has a significant spatial spillover effect. The spatial distribution of SED does not exhibit complete randomness, but rather a significant spatial clustering effect.

Fig. 8 shows the spatial aggregation of 30 provinces (cities and districts) in China in 2008, 2012, 2016, and 2020. Most of the provinces are in "high–high" or "low–low" aggregation zones, and very few provinces (districts and municipalities) are in "high–low" or "low–high" aggregation zones. A very small number of provinces (districts and cities) are in "high–low" or "low–high" agglomeration areas. Overall, the regional differences in China's level of SED are significant and non-equilibrium, and the overall spatial and temporal evolution is relatively stable, whereas individual provinces (cities and districts) are subject to large changes. Fig. 8 reveals that the provinces (districts and municipalities) in the eastern coastal region have higher levels of SED, followed by the central and western regions. The clustering characteristics are in line with the actual objective geographic and economic distribution, the areas with faster economic growth pay attention to environmental protection, and the level of SED is also higher, and the level of SED of the provincial economy has a spatial clustering effect among regions. The traditional linear panel regression model requires that the regions are independent, and the spatial correlation exists between the regions with mutual influence, the impact coefficients of the linear model estimation results are biased. Therefore, spatial econometric models should be used to analyze the impact of provincial clean energy development and utilization on the level of SED.

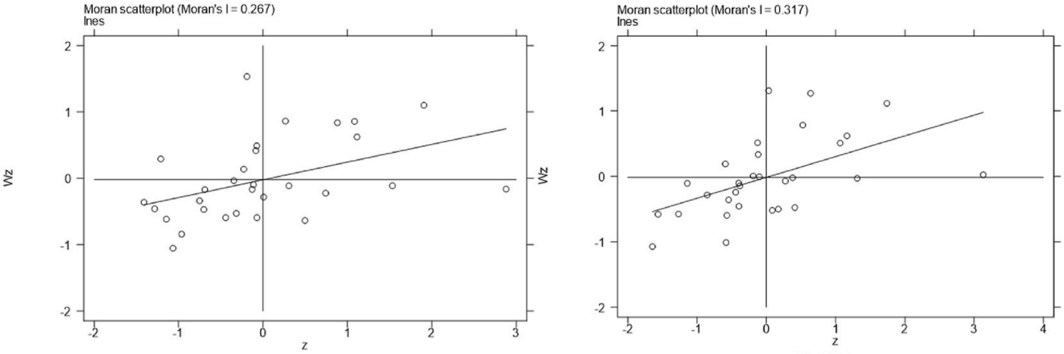
5.2. Model selection and testing

The previous analysis revealed significant spatial spillover characteristics in China's SED, forming a relatively stable spatial correlation network. However, it also highlighted more pronounced spatial disparities. To analyze the spatial impact of clean energy consumption, clean energy production, and clean energy consumption structure on SED, a spatial econometric model is constructed.



(a) 2008

(b) 2012



(c) 2016

(d) 2020

Fig. 7. Moran's I scatterplot of China's level of economic sustainability.

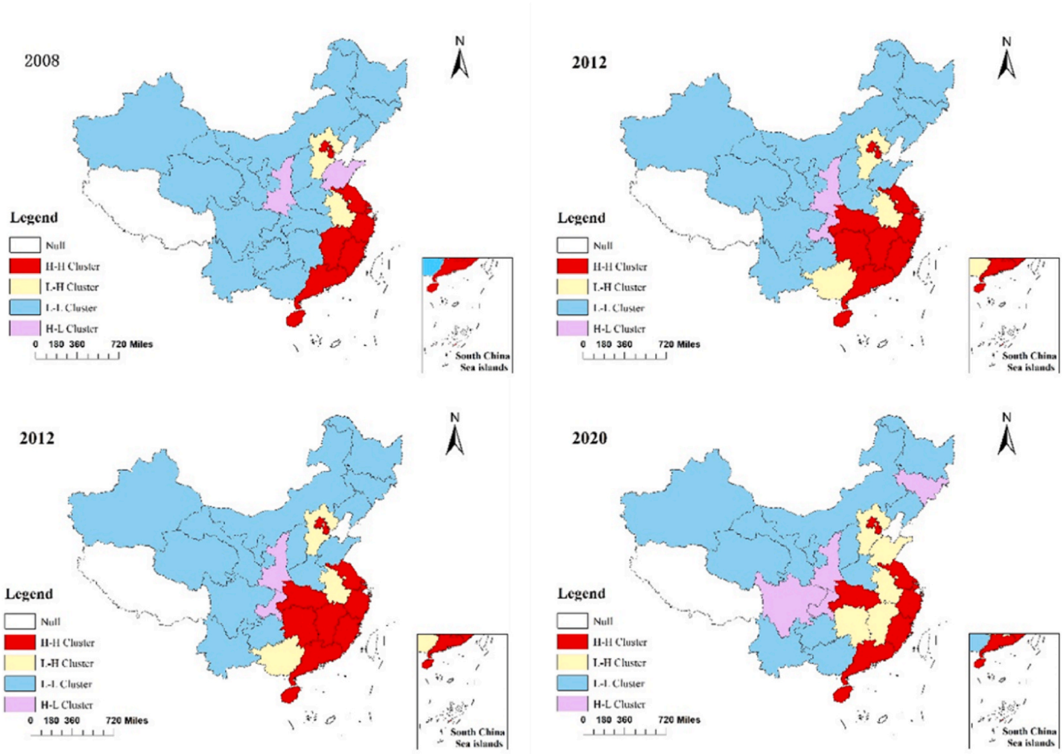


Fig. 8. Evolution of spatial agglomeration patterns for SED in China.

Before delving into that, LM and LR tests are conducted with the three variables as core explanatory variables to select the appropriate model. The LM test comprises four types: LM-Error, Robust LM-Error, LM-Lag, and Robust LM-Lag. The LM test results are summarized in Table 5.

From Table 5, both LM-Error and Robust LM-Error reject the null hypothesis at a 1% significance level, indicating spatial correlation in the model's error term, necessitating the inclusion of spatial factors. The spatial error model is preferred over the ordinary linear regression model. Similarly, the LM-Lag and Robust LM-Lag tests reject the null hypothesis at a 5% significance level, indicating spatial correlation in the explanatory variables. Therefore, the spatial lag model is superior to the ordinary linear regression model.

After confirming the existence of spatial correlation in the explanatory variables and the error term, this study proceeds to use the LR test to determine whether the SDM can be simplified into the spatial lag model and the spatial error model. This helps in selecting the appropriate model. In addition, the LR test (R likelihood ratio test) is employed to decide which form of fixed effects model to adopt. The results of the LR test are displayed in Table 6.

From Table 6, the LR-Lag, LR-Error, LR-Ind, and LR-Time all reject the null hypothesis, indicating that the SDM cannot be reduced to a spatial lag model or a spatial error model. Consequently, the SDM is deemed more suitable for studying the impact of clean energy consumption, production, and consumption structure on SED at the provincial level. The double fixed effects in the chosen model must be controlled.

5.3. *Analysis of results*

5.3.1. *Clean energy consumption*

Following the earlier test, this study employs the SDM with double fixed effects to estimate the spatial spillover effects of clean energy consumption on SED. The estimation results are presented in Table 7.

Table 5
LM test results.

LM test	CEC		CEP		CES	
	Statistic	P-value	Statistic	P-value	Statistic	P-value
LM-Error	196.4860	0.0000	199.6800	0.0000	191.9900	0.0000
Robust LM-Error	192.3750	0.0000	195.2260	0.0000	187.7850	0.0000
LM-Lag	4.3470	0.0370	4.8100	0.0280	4.5370	0.0330
Robust LM-Lag	4.1250	0.0420	4.3250	0.0400	4.3330	0.0380

Table 6
LR test results.

LR test	CEC		CEP		CES	
	Statistic	P-value	Statistic	P-value	Statistic	P-value
LR-Lag	20.0300	0.0027	14.8700	0.0213	20.3300	0.0024
LR-Error	20.2800	0.0025	15.3200	0.0179	20.3000	0.0025
LR-Ind	33.8900	0.0002	29.1400	0.0012	34.5100	0.0002
LR-Time	378.8000	0.0000	369.7700	0.0000	380.6200	0.0000

Table 7
Model estimation results (Consumer perspective).

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Main	Wx	Spatial	Variance	LR_Direct	LR_Indirect	LR_Total
lnCEC	0.0210***	0.0410***			0.0218***	0.0441***	0.0659***
	(0.00442)	(0.00937)			(0.00449)	(0.00928)	(0.0110)
lnPGDP	0.1410***	−0.1860***			0.1370***	−0.1880***	−0.0516
	(0.0295)	(0.0606)			(0.0290)	(0.0633)	(0.0718)
lnAI	0.1110***	0.00173			0.113***	0.0107	0.1240***
	(0.0136)	(0.0265)			(0.0131)	(0.0271)	(0.0305)
lnRD	0.1680***	0.0123			0.1690***	0.0258	0.194***
	(0.0116)	(0.0283)			(0.0112)	(0.0266)	(0.0315)
lnER	0.0105*	−0.0727***			0.0114*	−0.0779***	−0.0665***
	(0.00600)	(0.0108)			(0.00581)	(0.0109)	(0.0105)
lnURB	0.0920*	0.387***			0.101*	0.415***	0.516***
	(0.0552)	(0.0937)			(0.0547)	(0.0993)	(0.101)
rho			0.0677*				
			(0.0698)				
sigma2_e				0.00521***			
				(0.000373)			
Observations	390	390	390	390	390	390	390
R-squared	0.883	0.883	0.883	0.883	0.883	0.883	0.883
Number of id	30	30	30	30	30	30	30

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, with standard error terms in parentheses. Same as below.

As observed in Table 7, the spatial spillover coefficient of the SED level is significantly positive at the 10% significance level, indicating a substantial positive spatial spillover effect on China's SED. This implies that a region's SED is closely tied to the SED of its neighboring regions, reflecting a "point-to-area" development pattern.

Given that the SDM includes a spatial lag term, the estimated coefficients cannot fully elucidate the spatial spillover effect. Consequently, this study dissects the spatial impacts into direct, indirect, and total effects. From the estimated coefficients of clean energy consumption ($\ln CEC$), both the direct and indirect effects are significantly positive at a 1% significance level, suggesting that clean energy consumption in a region not only fosters the improvement of its own economic sustainability but also generates significant positive externalities on the economic sustainability of neighboring regions. This highlights the spatial spillover effect of clean energy consumption on economic sustainability. Clean energy's lack of environmental pollution and its role in reducing carbon emissions contribute to this effect. Since the 12th Five-Year Plan was put forward, China has begun to pay attention to the changes in the way of energy production and utilization and is focusing on the construction of a modern energy system. Policies related to the promotion of the development of clean energy have been introduced one after another, which provides an opportunity for the development and utilization of clean energy to play an active role in the field of SED. Moreover, initiatives like the "West-to-East Electricity Transmission" and "South-to-South Electricity Transmission" have also played a crucial role in promoting SED in neighboring regions. On the one hand, initiatives such as "West-to-East Electricity Transmission" and "South-to-South Electricity Transmission" have prompted the eastern and northern regions to reduce their dependence on fossil energy, which reduces the transfer of polluting industries to the neighboring regions when the environmental performance improves in line with the direction of the environmental regulation and thus promotes the green development of the neighboring regions. On the other hand, with the increase in local clean energy consumption, the saved fossil energy may flow into the neighboring regions, which can easily stimulate economic growth in the short term [32]. Taken together, local clean energy consumption will promote SED enhancement in neighboring regions. At the same time, the transfer of clean energy-related industries and the interregional flow of clean energy resulting from projects such as "West-East Power Transfer" and "Transmission of Electricity to the South" may be the main paths through which clean energy consumption can contribute to the improvement of the level of sustainable development of neighboring economies.

Regarding the estimated coefficients of control variables, the direct effect of economic growth ($\ln PGDP$) is significantly positive, whereas the indirect effect is significantly negative. This indicates that an increase in regional economic growth enhances the region's economic sustainability but produces negative externalities for neighboring regions. The direct effect of the technological level ($\ln RD$) is significantly positive, whereas the indirect effect is not significant, underlining the positive role of the regional technological level in improving economic sustainability. However, the spillover effect on neighboring areas is less apparent. Environmental regulation (ln *ER*) exhibits a significantly positive direct effect, albeit with a small coefficient of 0.0114. The indirect effect is significantly negative, indicating that an increase in environmental regulation promotes a region's economic sustainability but negatively affects the sustainability of neighboring regions, with the spillover effect outweighing the local impact. Urbanization level (ln *URB*) displays significantly positive direct and indirect effects, with the indirect effect having a higher coefficient. This highlights the stronger spatial spillover effect of urbanization level, suggesting an evident spatial correlation. Urbanization promotes employment rates, industry and talent concentration, environmental protection, and green awareness, thereby fostering sustainable urban economic development.

5.3.2. Clean energy production

This study further explores the spatial spillover effects of clean energy production on the level of SED from a production perspective. The SDM is re-estimated, and the results are presented in Table 8.

From the estimation results in Table 8, the estimated coefficients of the direct and indirect effects of clean energy production (ln *CEP*) are both significantly positive at the 1% significance level. This implies that, from a production perspective, clean energy significantly contributes to the sustainable development of both the local and neighboring economies. Although the scale of clean energy production in each Chinese region remains relatively low compared with the consumption perspective, these coefficients still highlight the spatial spillover effect of clean energy production on SED.

With China's advancements in science and technology, the scale of clean energy production has progressively expanded, positioning China as a leader in clean energy production. Clean energy production is accompanied by the development and transfer of the clean energy industry, which, in turn, leads to the adjustment and elimination of enterprises with high energy consumption and high pollution. This reduction in environmental damage promotes high-quality economic development and embodies a positive facilitating effect on sustainability. The indirect effect of clean energy production on SED is significantly positive, primarily reflecting the spatial spillover benefits of clean energy production within a region on the sustainable development of neighboring regions. This is mainly due to the spillover effect created by the flow of economy, technology, and clean energy-related industries across different regions. Although clean energy production in the East lags behind the Central and Western regions, the East experiences faster economic development and higher environmental protection requirements. To meet the higher demand for clean energy consumption in these regions, clean energy must be transported from provinces with higher production. This fosters the flow of clean energy across provinces and results in improved environmental quality in regions with high clean energy demand. Consequently, the production of clean energy in one region affects the environmental quality of neighboring regions, further promoting the sustainable development of their economies. Moreover, resource allocation and the transfer of clean energy and environmental protection industries across regions can also generate spatial spillover effects.

5.3.3. Clean energy consumption structure

The preceding sections demonstrate the significant contributions of both clean energy consumption and production to the sustainable development of local and neighboring economies. However, an examination from a structural perspective is lacking. This study re-estimates the SDM, with the structure of clean energy consumption as the core explanatory variable, and presents the results in Table 9.

The estimation results in Table 9 reveal that the estimated coefficients of the direct and indirect effects of the clean energy consumption structure (ln *CES*) are significantly positive at 1% and 5% significance levels, respectively. This signifies that, from the

Table 8
Model estimation results (Production perspective).

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Main	Wx	Spatial	Variance	LR_Direct	LR_Indirect	LR_Total
lnCEP	0.0207***	0.0224***			0.0214***	0.0258***	0.0472***
	(0.00401)	(0.00690)			(0.00410)	(0.00703)	(0.00836)
lnPGDP	0.156***	−0.0521			0.153***	−0.0433	0.110
	(0.0305)	(0.0614)			(0.0299)	(0.0654)	(0.0747)
lnAI	0.140***	0.00545			0.142***	0.0205	0.162***
	(0.0139)	(0.0273)			(0.0133)	(0.0283)	(0.0303)
lnRD	0.156***	0.00499			0.156***	0.0220	0.178***
	(0.0111)	(0.0278)			(0.0109)	(0.0270)	(0.0315)
lnER	0.0134**	−0.0663***			0.0148***	−0.0730***	−0.0582***
	(0.00586)	(0.0108)			(0.00556)	(0.0112)	(0.0108)
lnURB	0.126**	0.284***			0.136**	0.320***	0.456***
	(0.0560)	(0.0905)			(0.0557)	(0.0992)	(0.102)
rho			0.0932*				
			(0.0684)				
sigma2_e				0.00518***			
				(0.000371)			
Observations	390	390	390	390	390	390	390
R-squared	0.860	0.860	0.860	0.860	0.860	0.860	0.860
Number of id	30	30	30	30	30	30	30

Table 9
Model estimation results (Structural perspective).

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Main	Wx	Spatial	Variance	LR_Direct	LR_Indirect	LR_Total
lnCES	0.0214***	0.0176**			0.0219***	0.0202**	0.0422***
	(0.00402)	(0.00801)			(0.00408)	(0.00797)	(0.00846)
lnPGDP	0.143***	−0.144**			0.139***	−0.143**	−0.00436
	(0.0275)	(0.0593)			(0.0268)	(0.0631)	(0.0724)
lnAI	0.105***	−0.0144			0.106***	−0.00437	0.102***
	(0.0132)	(0.0267)			(0.0128)	(0.0278)	(0.0323)
lnRD	0.166***	−0.00229			0.166***	0.0136	0.180***
	(0.0114)	(0.0283)			(0.0111)	(0.0267)	(0.0320)
lnER	−0.00687	−0.0769***			−0.00823	−0.0837***	−0.0919***
	(0.00607)	(0.0107)			(0.00587)	(0.0111)	(0.0107)
lnURB	0.0937*	0.346***			0.103**	0.380***	0.484***
	(0.0529)	(0.0923)			(0.0518)	(0.0989)	(0.102)
rho			0.0870*				
			(0.0688)				
sigma2_e				0.00518***			
				(0.000370)			
Observations	390	390	390	390	390	390	390
R-squared	0.884	0.884	0.884	0.884	0.884	0.884	0.884
Number of id	30	30	30	30	30	30	30

perspective of energy consumption structure, the clean energy consumption structure plays a significant role in enhancing the sustainable development of both local and neighboring economies. It is evident that the clean energy consumption structure exerts a significant spatial spillover effect on economic sustainability. An increase in the proportion of regional clean energy consumption not only enhances the sustainable development of the local economy but also generates a noteworthy positive externality on the economic sustainability of neighboring regions. This underscores the spatial spillover effect of optimizing the clean energy consumption structure on economic sustainability. However, the coefficient associated with this effect is relatively small when compared with clean energy consumption and production. This may be attributed to the current low proportion of clean energy consumption in each region of China, as the nation's energy consumption structure remains predominantly reliant on fossil energy. Consequently, the impact of the current state of clean energy development on sustainable economic growth is somewhat limited. Looking ahead, concerted efforts should be made to advance clean energy development and maximize its role in promoting economic sustainability.

In addition, to ensure the robustness and reliability of the parameter estimation in the spatial econometric model, this study tested the previously established conclusions using both the economic distance weight matrix and the 0–1 neighbor matrix. The results reaffirmed the consistency of the estimated coefficients for the impacts of clean energy consumption, production, and consumption structure on the level of economic sustainability. This validation underscores the robustness of the findings presented in this study regarding the spatial spillover effect.

Table 10
Regional heterogeneity model estimation results (Consumer perspective).

Variable	East		Central		West	
	Main	Wx	Main	Wx	Main	Wx
lnCEP	0.0005	0.0533***	−0.0167	0.0667*	−0.0149*	−0.0614***
	(0.0108)	(0.0104)	(0.0108)	(0.0358)	(0.0085)	(0.0166)
lnPGDP	0.3670***	0.0042	0.2150***	0.1900	0.5480***	0.9380***
	(0.0478)	(0.0789)	(0.0778)	(0.1620)	(0.0773)	(0.1620)
lnAI	0.1280***	0.0832*	0.1740***	0.3200***	0.1300*	0.2620
	(0.0262)	(0.0431)	(0.0646)	(0.0933)	(0.0696)	(0.1640)
lnRD	0.0636**	−0.2310***	0.0268	0.1830***	0.1770***	0.0321
	(0.0264)	(0.0494)	(0.0419)	(0.0590)	(0.0209)	(0.0628)
lnER	0.0145	−0.0050	−0.0277**	−0.0449**	0.0227**	−0.0529***
	(0.0089)	(0.0138)	(0.0121)	(0.0185)	(0.0097)	(0.0199)
lnURB	−0.0144	0.8390***	0.2120	−0.0409	−0.5350***	−1.7070***
	(0.1110)	(0.3000)	(0.1700)	(0.1300)	(0.1390)	(0.2660)
Direct effects	−0.0050		−0.0104		−0.0074	
	(0.0114)		(0.0138)		(0.0085)	
Indirect effects	0.0488***		0.0719*		−0.0416***	
	(0.0089)		(0.0420)		(0.0120)	
Total effect	0.0438***		0.0615		−0.0490***	
	(0.0142)		(0.0525)		(0.0121)	
Observations	143	143	104	104	143	143
R-squared	0.9150	0.9150	0.7310	0.7310	0.7780	0.7780
Number of id	11	11	8	8	11	11

5.4. Analysis of regional heterogeneity

The research has demonstrated the substantial impact of clean energy on both local and neighboring SEDs from the perspectives of consumption, production, and consumption structure. However, analyzing the spatial spillover effect of clean energy development and utilization on the level of SED using 30 provinces and municipalities in China as research samples alone is insufficient. There are distinct disparities in both clean energy development and economic sustainability among regions in China. The spatial distribution of clean energy development exhibits a prominent west-to-east divide, with a phenomenon of cross-regional clean energy circulation. Economic differences among regions are characterized by an "east high, west low" pattern. To delve deeper into this, the research divides the sample into three major regions: the east, the center, and the west, to explore the spatial spillover effects of clean energy consumption, production, and consumption structure on the level of SED through the lens of regional heterogeneity.

5.4.1. Clean energy consumption perspective

Table 10 reports the results of regional heterogeneity from the consumer perspective.

The results presented in Table 10 highlight significant regional heterogeneity in the influence of clean energy consumption on SED. Examining the estimated coefficients of the total effect reveals that clean energy consumption in the eastern region notably contributes to the overall sustainable development level of the region. In contrast, the western region demonstrates the opposite effect, and clean energy consumption in the central region does not significantly impact the overall level of SED. Furthermore, clean energy consumption in the eastern, central, and western regions does not wield a substantial influence on the sustainable development level of the local economy. Instead, it exerts a significant spillover effect on the sustainable development level of neighboring economies, and this spatial spillover effect exhibits regional heterogeneity. Notably, the spillover effect of clean energy consumption in the eastern and central regions on the sustainable development level of neighboring economies is significantly positive at the 1% and 10% significance levels. This suggests that clean energy consumption in these regions has a notable spatial spillover effect on neighboring provinces and cities, contributing to the enhancement of the sustainable development of their surrounding regions. In contrast, the western region's spatial spillover effect is adverse, with the indirect effect being significantly negative at the 1% significance level. Combined with the performance of its total effect, the level of clean energy consumption in the western region not only fails to promote the overall SED but also inhibits the sustainable development of neighboring economies through local clean energy consumption.

The spatial impacts of clean energy consumption on SED vary significantly across the eastern, central, and western regions. During the sample period of this study, China has approved a total of five clean energy demonstration provinces since 2014, including Sichuan, Gansu, Qinghai, and Ningxia in the western region. Although most of the clean energy demonstration provinces are in the western region, clean energy-related industries require significant human, material, and financial support. This divergence may be attributed to the fact that, despite the western region's advantage in clean energy development, clean energy-related industries require substantial human, material, and financial support. Sustainable economic growth in the western region predominantly relies on technological progress and scientific innovation, as emphasized by Xu et al. [66]. In comparison to the eastern and central regions, the western region faces economic growth challenges, lower levels of technological research and development, and limited scientific and technological innovation capacity. Consequently, the development of clean energy increases the economic burden in the western region. Secondly, local fossil energy savings flow to neighboring regions under the clean energy demonstration province policy. Since the western region is not as well endowed with economy, technology, and manpower as the eastern and central regions, it leads to a smaller short-term

Table 11
Regional heterogeneity model estimation results (Production perspective).

Variable	East		Central		West	
	Main	Wx	Main	Wx	Main	Wx
lnCEP	0.0046	0.0319***	−0.0037	0.0698***	−0.0033	−0.0980***
	(0.00573)	(0.00796)	(0.00854)	(0.0219)	(0.00926)	(0.0250)
lnPGDP	0.3510***	0.0801	0.1890**	−0.1780	0.3760***	0.9980***
	(0.0491)	(0.0762)	(0.0925)	(0.125)	(0.0762)	(0.158)
lnAI	0.1370***	0.0581	0.0465	0.1520**	0.0372	0.0768
	(0.0221)	(0.0378)	(0.0685)	(0.0672)	(0.0684)	(0.156)
lnRD	0.0512**	−0.2060***	0.0391	0.2530***	0.1800***	0.0350
	(0.0258)	(0.0330)	(0.0468)	(0.0558)	(0.0177)	(0.0569)
lnER	0.0170*	−0.0161	−0.0369***	−0.0433**	0.0213**	−0.0506***
	(0.00908)	(0.0138)	(0.0122)	(0.0188)	(0.00944)	(0.0178)
lnURB	0.0718	0.5930***	0.6140***	−0.1150	−0.3260**	−2.3930***
	(0.0809)	(0.188)	(0.0978)	(0.139)	(0.153)	(0.304)
Direct effects	0.0025		0.0004		0.0047	
	(0.0060)		(0.0097)		(0.0073)	
Indirect effects	0.0290***		0.0735***		−0.0807***	
	(0.0075)		(0.0243)		(0.0199)	
Total effect	0.0316***		0.0739**		−0.0760***	
	(0.0078)		(0.0301)		(0.0247)	
Observations	143	143	104	104	143	143
R-squared	0.9010	0.9010	0.7950	0.7950	0.8000	0.8000
Number of id	11	11	8	8	11	11

economic stimulus boost, which in turn reduces the environmental performance and thus suppresses the SED. Additionally, the western region serves as a destination for the transfer of high-energy-consuming industries from the eastern and central regions, accelerating economic growth but also contributing to increased pollution. Hence, the current impact of clean energy consumption on SED in the western region remains limited.

The eastern region experiences faster economic growth while concurrently prioritizing environmental governance and protection. It replaces traditional fossil energy consumption with clean energy, enhancing environmental quality. This transition not only reduces local pollutant emissions but also has spatial impact effects through inter-provincial transmission of clean energy and the relocation of clean energy-related industries. Second, enhances local environmental performance and reduces the transfer of polluting industries to neighboring regions, which in turn enhances the environmental quality of neighboring regions and promotes sustainable economic development in the eastern region. Local fossil energy savings flow into neighboring regions, lowering the cost of development in neighboring regions and stimulating economic growth in the short term. As clean energy continues to develop rapidly, its contribution to sustainable economic growth is expected to increase.

The central region, a significant food supply area, utilizes clean energy sources such as biodiesel, biofuel, and straw power generation, resulting in reduced pollution. The utilization of crop straw supports power generation and biomass energy development in the central region. Moreover, the gradual expansion of clean energy-related production enterprises and the implementation of cross-provincial clean energy consumption policies contribute to the growth of clean energy consumption in the region. This, in turn, enhances the environmental quality of neighboring areas and positively affects the sustainable development of their economies. The reduction in the transfer of polluting industries and the stimulation of the economy of the neighboring areas not only improves the environmental quality of the neighboring areas but also stimulates economic growth in the short term, which in turn has a positive impact on the SED.

5.4.2. Clean energy production perspective

Table 11 presents the results of regional heterogeneity analysis from a production perspective.

Differences are noted in the impact of clean energy production on regional economic sustainability among the three regions. Examining the estimated coefficients of the total effect, clean energy production significantly contributes to the enhancement of SED in both the eastern and central regions. However, the western region exhibits a contrasting performance compared with the eastern region.

Further decomposition of the total effect reveals both direct and indirect effects. The direct effects do not show significance in any of the three regions but indicate spatial spillover effects of varying degrees and directions. Specifically, the spillover effect of clean energy production in the eastern and central regions on the sustainable development level of neighboring economies is notably positive at the 1% significance level. This suggests that clean energy production in the eastern and central regions has a significant spatial spillover impact on the neighboring provinces and cities, ultimately enhancing the sustainable development of their respective economies. In contrast, the spillover effect in the western region exhibits the opposite performance. When combined with the total effect, it becomes apparent that clean energy production in the western region significantly hinders both overall and neighboring economic sustainability.

From the production perspective, the spatial impacts of clean energy development on economic sustainability exhibit significant differentiation due to the western region's distinct characteristics. Despite its abundance of clean energy resources, the western region

Table 12
Regional heterogeneity model estimation results (Structural perspective).

Variable	East		Central		West	
	Main	Wx	Main	Wx	Main	Wx
lnCES	0.0216**	0.0429***	0.0030	0.1900***	−0.0180**	−0.0663***
	(0.0101)	(0.0101)	(0.0123)	(0.0456)	(0.0077)	(0.0151)
lnPGDP	0.3620***	0.0701	0.2740***	0.3220**	0.5810***	0.9070***
	(0.0483)	(0.0810)	(0.0792)	(0.1550)	(0.0681)	(0.1540)
lnAI	0.1480***	0.0511	0.1110**	0.3100***	0.1410**	0.3010*
	(0.0193)	(0.0368)	(0.0563)	(0.0718)	(0.0668)	(0.1610)
lnRD	0.0841***	−0.0828*	0.0251	0.1430**	0.1640***	−0.0071
	(0.0298)	(0.0476)	(0.0407)	(0.0587)	(0.0208)	(0.0601)
lnER	0.0156*	−0.0075	−0.0205*	−0.0200	0.0166*	−0.0492***
	(0.0089)	(0.0139)	(0.0121)	(0.0194)	(0.0095)	(0.0185)
lnURB	−0.1610	0.1980	−0.2040	0.0724	−0.5470***	−1.5280***
	(0.1150)	(0.2960)	(0.2090)	(0.1300)	(0.1230)	(0.2840)
Direct effects	0.0178		0.0182		−0.0095	
	(0.0110)		(0.0170)		(0.0084)	
Indirect effects	0.0346***		0.2070***		−0.0434***	
	(0.0091)		(0.0545)		(0.0120)	
Total effect	0.0525***		0.2250***		−0.0529***	
	(0.0111)		(0.0655)		(0.0096)	
Observations	143	143	104	104	143	143
R-squared	0.9190	0.9190	0.7210	0.7210	0.7750	0.7750
Number of id	11	11	8	8	11	11

lags behind the eastern and central regions in terms of economic development, capital availability, and advanced technology. The rapid economic development in the eastern region is accompanied by elevated environmental standards. In recent years, there has been a trend of "shifting from the east to the west" in China's high-energy-consuming industries as a result of optimal resource allocation. Although the western region boasts abundant clean energy resources, the development of clean energy demands substantial capital, manpower, and infrastructure. Coupled with regional development and industrial optimization strategies, the western region accepts the transfer of high-energy-consuming industries from the east, potentially leading to the transfer of the gradient of environmental pollution from the eastern region. Consequently, as the western region experiences economic growth, it may also witness an increase in environmental pollution. In this context, the environmental improvements brought about by clean energy production in the western region may be counteracted, resulting in a hindrance to the SED of the region and its neighboring areas.

5.4.3. *Clean energy consumption structure perspective*

After examining the impact of clean energy development and utilization on spatial heterogeneity in economic sustainability from both consumption and production perspectives, this study further discusses the spatial influence of the clean energy consumption structure on economic sustainability from a structural perspective. The results are presented in Table 12.

Differences in the impact of the clean energy consumption structure ($\ln CES$) on regional economic sustainability are evident across the three regions, and the findings align with those of the consumption and production scale perspectives. Analyzing the estimated coefficients of the total effect, clean energy consumption in the eastern and central regions significantly contributes to enhancing the overall level of sustainable development. However, the performance of the western region diverges from that of the eastern region.

Further dissection of the total effect reveals both direct and indirect effects. The direct effect lacks significance in all three regions, but significant regional variations in spatial spillover effects exist. Notably, the optimization of clean energy consumption structure in the eastern and central regions exhibits varying degrees of spatial spillover effects at the 1% significance level. This suggests that optimizing the local clean energy consumption structure in the eastern and central regions leads to improved sustainable development in neighboring provinces and municipalities. In contrast, it exhibits a significant negative effect at the 1% significance level in the western region, indicating that optimizing the clean energy structure in the western region not only presents challenges to overall economic sustainability but also hinders the sustainable development of neighboring provinces and municipalities. This may be because, compared with the eastern and central regions, the western region is at a disadvantage in terms of technology, manpower, and capital, and the optimization of the clean energy consumption structure may become an economic burden in the short term, as well as being a place where high-energy-consuming industries are located, which makes it difficult to alleviate pollution in the short term. The optimization of local clean energy consumption structure means that more fossil energy flows to the neighboring areas, resulting in the neighboring areas not only difficult to improve the environmental performance, and backward production methods in the short term, it is difficult to rely on fossil energy to have a clear trend of economic growth. The optimization of the clean energy consumption structure in the western region not only fails to have a significant positive impact on the local SED but also inhibits the improvement of the SED in the neighboring regions.

Regardless of the scale or structural perspective, the development and utilization of clean energy have notable spatial spillover effects on the economic sustainability level, accompanied by apparent regional heterogeneity. Despite coal dominance in China's energy consumption at this stage, the increasing proportion of clean energy consumption gradually displaces fossil energy, addressing various environmental challenges associated with fossil energy consumption. The clean energy structure in the eastern and central regions is progressively promoting economic sustainability. However, inter-regional economic disparities result in technological limitations, reduced investment in research and development, and limited scientific and technological innovation in the western region. This, in turn, places a greater economic burden on the development of clean energy in the western region. Furthermore, in response to inter-regional energy circulation policies like "west to east," the role of clean energy development and utilization in promoting SED in the western region has not yet become apparent.

6. Conclusions and suggestions

6.1. *Conclusions*

The spatial correlation analysis conducted in this study has established that SED exhibits evident spatial spillover effects. Furthermore, the study has revealed that both SED and clean energy development are marked by pronounced spatial development imbalances. Therefore, this study further investigates the spatial impacts of clean energy development and utilization on SED. By constructing the SDM and considering clean energy consumption, clean energy production, and clean energy consumption structure as characterizing variables, we comprehensively evaluate the level of clean energy development and utilization. This analysis is carried out from a regional perspective, focusing on the eastern, central, and western regions. The key findings are summarized as follows.

(1) Spatial autocorrelation test results. China's sustainable economic development demonstrates significant positive spatial autocorrelation. The SED of the majority of spatially neighboring regions exhibits "high–high" or "low–low" spatial agglomeration features, whereas fewer regions display "high–low" or "low–high" spatial agglomeration patterns.

(2) Since the 12th Five-Year Plan, China has begun to emphasize changes in the way energy is produced and utilized and has focused on building a modern energy system. Subsequently, since 2014, China has approved clean energy demonstration provinces in batches to strongly support the development and utilization of clean energy, and the Clean Energy Consumption Action Plan (2018–2020), proposed in 2018, has made it a goal to increase the utilization rate of clean energy across the

country. This series of policies on the development and utilization of clean energy provides an opportunity to play an active role in SED. Parameter estimation results of the SDM on a national scale. The SED of 30 provinces, autonomous regions, and municipalities in China has established a “point-to-area” development pattern. Clean energy consumption, clean energy production, and clean energy consumption structure within China all contribute to the level of SED in their respective regions. Simultaneously, they exert a positive spatial spillover effect on the SED of neighboring regions. Clean energy-related policies, and measures such as “West-to-East Electricity Transmission” and “South-to-South Electricity Transmission” are key to improving local environmental performance through the structure of clean energy consumption, production, and consumption, and to promoting green development and economic growth in neighboring regions, which will in turn act as a catalyst for SED.

(3) The clean energy demonstration province policy is currently China’s main policy in the field of clean energy development. The 13th Five-Year Plan for Energy Development, issued in 2016, includes the construction of clean energy demonstration provinces and regions in the key projects of the energy consumption revolution and plans for key pilot provinces. During the sample period of this study, a total of five demonstration provinces were approved in China, including Zhejiang in the eastern region and Sichuan, Gansu, Qinghai, and Ningxia in the western region. There are significant differences among the demonstration provinces, with Zhejiang in the eastern region being a small energy resource province and a large consumer province, but with a full range of renewable energy sources, and the four demonstration provinces in the western region being rich in renewable energy sources, with significant inter-regional differences in renewable energy abundance and policies. The parameter estimation results of the SDM for the three major regions of China show that the spatial impacts of clean energy development and utilization on SED in the eastern, central, and western regions exhibit significant differences. In the eastern and central regions, clean energy development and utilization not only enhance the overall SED but also exhibit a notable positive spatial spillover effect on neighboring provinces, districts, and municipalities. The direct effect is positive but not significant. The eastern and central regions have a higher level of economic development, and although renewable resources are relatively scarce, relying on policies such as the West-to-East Gas Pipeline and the Rise of Central China, they have been able to promote consistency in the direction of local environmental performance and environmental regulation, thereby reducing the transfer of polluting industries to neighboring regions and promoting the green development of neighboring regions. However, the development of clean energy requires a large amount of capital investment, which inevitably hinders local economic growth in the early stages of development. With the development of local clean energy, the saved fossil energy flows into the neighboring regions, which reduces the development cost of the neighboring regions and stimulates economic growth in the short term. In turn, clean energy development promotes SED in neighboring regions, but the positive effect on local SED will be gradually significant in the long run. In contrast, the spatial spillover effect of clean energy development and utilization in the western region is negative, indicating that the current clean energy development and utilization in the western region do not contribute to the SED of neighboring regions, and the direct promotion effect is also not significant. Although most of the clean energy demonstration provinces are in the western region, sustaining SED growth relies on technological advances and scientific and technological innovations, and the western region has a significant disadvantage in this regard. Secondly, local fossil energy saved under the policy of clean energy demonstration provinces is flowing to the neighboring regions. Since the western region is not as well endowed with economy, technology and manpower as the eastern and central regions, it leads to a smaller short-term economic stimulus boost, which in turn reduces the environmental performance, and thus suppresses the SED.

(4) National-level analysis. Clean energy consumption, clean energy production, and clean energy consumption structure have positive spatial spillover effects on SED at the national level. However, the estimated coefficients of the SDM are relatively small, likely due to the current low proportion of clean energy consumption relative to China’s total energy demand and the relatively small scale of clean energy production compared with the nation’s extensive energy requirements. To significantly enhance regional economic sustainability, both clean energy consumption and production should be increased.

(5) Policy implications. The findings of this paper not only reveal the spatial spillover effect of clean energy development and utilization on SED but also have important policy implications for the inter-regional promotion of SED through clean energy development. On the one hand, SED has formed a “point-to-area” spatial development pattern, and clean energy development also has a positive effect on SED in neighboring regions, indicating that it is important to lead SED in neighboring regions with the radiation of clean energy development in important economic circles. On the other hand, there are obvious differences in the results of the three major regions of China, indicating that differentiated policies should be adopted for the eastern, central, and western regions to develop clean energy in a targeted manner, thus ensuring that the effects of clean energy development on SED are consistent in both the whole and the local areas.

6.2. Limitations and prospects

Although the spatial econometric modeling focuses on the study of spillover effects, which is beneficial to this study in capturing the spatial spillover effects of clean energy development favoring SEDs, there are still some limitations. (1) Limitations of modeling assumptions. The spatial econometric model adopted in this study has the limitation of spatial spillover distance, however, since the sample used is a sample of 30 provinces and cities in China, it is difficult to partition the local space according to the length of spatial distance to avoid this limitation, which generates the limitation of the study. (2) Limitations of the study. Limited to data availability, the provincial and municipal samples used in this study have the disadvantage of having too large a center distance, and the spatial spillover effects thus captured may have errors, which can be overcome to some extent if the study can be carried out with prefecture-level city samples with shorter distances.

If we further examine the spatial spillover effects of clean energy development on SED in urban economic zones with different distance thresholds in terms of local spatial weight matrices, we may get more detailed results, and the spatial spillover effects may be heterogeneous in terms of spatial distance. In addition, the spatial econometric model assumes that different geographic distances will have an effect on different regions, and the spatial econometric model constructed in this paper can reflect the relationship between the objects of different geographic distances, but may not reflect the interaction of the variables themselves. Spatial measurement models based on interaction variables need to be further considered in future research.

6.3. Suggestions

Drawing from the insights gained in this study, we offer two key suggestions aimed at accelerating the clean energy transition, fostering clean energy development, and enhancing China's economic sustainability index.

(1) To strengthen sustainable economic development, the leadership of Beijing–Tianjin and the Yangtze River Delta regions should be leveraged. These regions can serve as pivotal catalysts for enhancing economic connectivity between the central and western regions. The results of the spatial correlation analysis of sustainable economic development reveal that the central and western regions of China exhibit smaller spillover relationships, primarily in the beneficiary role. To address this, it is crucial to bolster economic ties with other regions. In less developed areas, increased investment in environmental protection should be a priority alongside economic development efforts. Effective environmental protection necessitates government support, policy oversight, and the active involvement of key stakeholders. It is essential to fully leverage the leading roles played by Beijing–Tianjin and the Yangtze River Delta in driving sustainable economic development and stimulating economic growth in neighboring regions. While enhancing economic activity linkages, there should be a strong focus on promoting the development of clean energy. This approach will strengthen the spatial spillover linkages between economic sustainability and the flow of clean energy consumption and production, thereby facilitating SED.

(2) The three major regions of China should adopt differentiated development patterns. Over the long term, achieving sustainable economic development in the western region will continue to rely predominantly on technological progress and scientific innovation to drive economic growth. Advancements in technology will reduce the relative cost of energy consumption in comparison to the cost of enterprise production, resulting in the diminishing contribution of the clean energy industry to economic growth. Consequently, the western region should prioritize the training of technical personnel, the adoption of advanced technology, the facilitation of technology absorption and innovation, and the acceleration of clean energy development and utilization to promote sustainable economic growth. In contrast, the eastern region faces geographic limitations with fewer available clean energy resources. Sustainable economic development in this region hinges on environmental governance and green development. Facilitating the exchange of energy and economic activity between the eastern and western regions, increasing the share of clean energy consumption, and propelling high-quality economic development should be the central objectives. The central region, with a moderate availability of clean energy resources, should focus on elevating the technological standards for clean energy development, amplifying clean energy production and consumption, reducing environmental pollution, and enhancing environmental quality to support SED.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Yun Cao: Writing – original draft, Software, Methodology, Formal analysis. **Peng Jiang:** Resources, Formal analysis, Data curation. **Ziyan Gong:** Formal analysis, Data curation. **Kedong Yin:** Writing – review & editing, Funding acquisition. **Yuchen Wang:** Writing – review & editing, Visualization, Investigation.

Declaration of competing interest

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Appendix A. Steps for designing China's SED indicator system

1 Preliminary selection of indicators

As shown in Table 1, the preliminary selection of China's SED indicator system contains five dimensions of secondary indicators: economic development, technological innovation, social well-being, environmental governance and green development, and a total of 46 third-level indicators are designed under the five dimensions.

Table 1
Preliminary selection of China's SED indicator system

First-level indicators	Secondary indicators	Third-level indicators	Unit of measurement	Indicator properties
SED	Economic development	GDP	100 million yuan	Positive
		GDP Growth Rate	%	Positive
		Degree of Openness to the Outside World	Thousand dollars	Positive
		Unemployment Rate	%	negative
		Urbanization	%	Positive
		Industrial Structure	%	Positive
	Technological innovation	Number of patents in force	Item	Positive
		Domestic Granted Invention Patents	Item	Positive
		Research and Development Personnel	Persons/year	Positive
		Internal Expenditure on Research and Development Funds	Ten thousand yuan	Positive
		Local Finance Expenditure on Science and Technology	100 million yuan	Positive
		Percentage of Employees in Science and Technology	Ratio	Positive
		Research and Development Intensity	%	Positive
		Technology Transaction Activity Rate	%	Positive
		Number of Universities	Unit	Positive
		Number of Students	Persons	Positive
		Number of University Teachers	Persons	Positive
	Social well-being	Gini Coefficient	Numerical value	negative
		Engel's coefficient	Numerical value	negative
		Local Financial Expenditure on Education	100 million yuan	Positive
		Per Capita Consumption Expenditure	Yuan	Positive
		Local Financial Expenditure on Social Security and Employment	100 million yuan	Positive
		Per Capita Disposable Income	Yuan	Positive
		Infrastructure Level	Kilometers	Positive
		Number of Health Technicians	Persons	Positive
		Urban-Rural Consumption Disparity	Ratio	negative
		Urban-Rural Income Gap	Ratio	negative
	Environmental Governance	Investment in Air Pollution Control Projects Completion	Ten thousand yuan	Positive
		Investment in Wastewater Treatment Project Completion	Ten thousand yuan	Positive
		Investment in Industrial Pollution Control Complement	Ten thousand yuan	Positive
		Centralized Treatment Rate of Sewage Treatment Plants	%	Positive
		Treatment Capacity of Industrial Wastewater Treatment Facilities	Ten thousand tons/day	Positive
		Treatment Capacity of Industrial Waste Gas Treatment Facilities	Ten thousand cubic meters/hour	Positive
		Operating Costs of Industrial Wastewater Treatment Facilities	Ten thousand yuan	Positive
		Local Financial Expenditures on Environmental Protection	100 million yuan	Positive
		Harmless Treatment Rate of Household Waste	%	Positive
	Green development	Energy Consumption Intensity	Tons of standard coal/ten thousand yuan	negative
		Energy Consumption Elasticity Coefficient	%	negative
		Per Capita Urban Green Area	Hectares (Ten thousand hectares/ten thousand people)	Positive
		Per Capita Water Resources	Cubic meters/person	Positive
		Forest Area	Ten thousand hectares	Positive
		Forest Coverage Rate	%	Positive
		General Industrial Solid Waste Generation	Ten thousand ton	negative

(continued on next page)

Table 1 (*continued*)

First-level indicators	Secondary indicators	Third-level indicators	Unit of measurement	Indicator properties
		Chemical Oxygen Demand Emission	Ten thousand ton	negative
		Sulfur Dioxide Emission	Ten thousand ton	negative
		Number of Days with Good Air Quality Index	Day	Positive

2 Screening of indicators

Preliminary screening of the preliminary selection of indicators was carried out on the basis of criteria such as the statistical annual interval of data for the indicator variable, the connotation of the indicator, the role of the indicator, the degree of correlation between the indicators, the source of data, the method of calculation, and the unit of measurement. China's 11th Five-Year Plan (2006–2010) states that it is necessary to accelerate the transformation of the mode of economic growth, to promote the informatization of the national economy and society, cleaner development, safe development and high-quality development, and to realize sustainable economic growth. The concept of sustainable development has evolved into a mature system during China's 11th Five-Year Plan period. Therefore, the selection of variables for the indicator system needs to take into account the fact that China's statistical data should be selected from 2006 onwards. The period of the SED indicator system constructed in this paper spans from 2006 to 2020. For instance, the data intervals of local financial expenditure on science and technology, the percentage of employees in science and technology, and local financial expenditure on education are from 2008 to 2020, and these indicators are deleted in order to better match the length of the data. On this basis, the variables of the indicator system can be further screened. Taking into account the time of determining the concept of sustainable development, it reduces subjectivity and arbitrariness and enhances objectivity, scientific standardization and transparency.

According to the above principles and methods, the indicator system of China's SED, which includes five themes: economic development, scientific and technological innovation, social well-being, environmental governance, and green development, is initially screened out, as shown in Table 2.

Table 2
Indicator system for China's SED

First-level indicators	Secondary indicators	Third-level indicators	Unit of measurement	Indicator properties
SED	Economic development	GDP	100 million yuan	Positive
		GDP Growth Rate	%	Positive
		Degree of Openness to the Outside World	Thousand dollars	Positive
		Unemployment Rate	%	negative
		Urbanization	%	Positive
		Industrial Structure	Ratio	Positive
	Technological innovation	Domestic Granted Invention Patents	Item	Positive
		Research and Development Intensity	%	Positive
		Technology Transaction Activity Rate	%	Positive
		Number of Universities	Unit	Positive
		Number of Students	Persons	Positive
		Number of University Teachers	Persons	Positive
	Social well-being	Gini Coefficient	Numerical value	negative
		Infrastructure Level	Kilometers	Positive
		Number of Health Technicians	Persons	Positive
		Urban-Rural Consumption Disparity	Ratio	negative
		Urban-Rural Income Gap	Ratio	negative
	Environmental Governance	Investment in Air Pollution Control Projects Completion	Ten thousand yuan	Positive
		Investment in Wastewater Treatment Project Completion	Ten thousand yuan	Positive
		Investment in Industrial Pollution Control Complement	Ten thousand yuan	Positive
		Harmless Treatment Rate of Household Waste	%	Positive
	Green development	Energy Consumption Intensity	Tons of standard coal/ten thousand yuan	negative
		Energy Consumption Elasticity Coefficient	%	negative
		Per Capita Urban Green Area	Hectares (Ten thousand hectares/ten thousand people)	Positive
		Per Capita Water Resources	Cubic meters/person	Positive
		Forest Area	Ten thousand hectares	Positive
		Forest Coverage Rate	%	Positive
		Chemical Oxygen Demand Emission	Ten thousand ton	negative
		Sulfur Dioxide Emission	Ten thousand ton	negative

3 Testing and optimization of indicators

Indicator system design as well as optimization and testing is a fundamental work, which is a crucial part of the whole evaluation process. Among them, the expert assignment quality test is one of the most important links in the testing and optimization of the indicator system. On the basis of analyzing the construction and testing methods of the indicator system, this paper proposes the testing and optimization process of the indicator system design with the quality test of expert assignment as the main body, in order to provide theoretical guidance and wise support for the construction of the comprehensive evaluation indicator system in various fields.

3.1 Indicator quality tests

1. *t Tests*

After obtaining the preliminary screening results of China's SED indicator system, the Delphi assignment method was used to score the importance of the third-level indicators of China's SED indicator system. In this paper, based on the scoring results of 10 experts from the disciplines of environmental science, energy economics, economics, climate economics, management, and statistics on the importance of individual indicators, and according to the steps of the t-tests mentioned above, the t-value and p-value of the expert-assigned values of China's SED indicator system were calculated, and the results are shown in Table 3. From the results of the *t*-test, the p-value of the test for all indicators is greater than 0.05, and the original hypothesis is accepted, which indicates that the quality of expert scoring results passes the consistency test, and the *t*-test results in the retention of the existing indicators.

Table 3
Expert assignment t-tests of China's SED indicator system

Third-level indicators	t-value	P-value	Consistency judgment of expert assignments	Third-level indicators	t-value	P-value	Consistency judgment of expert assignments
GDP	1.1180	0.3466	Consistent	Urban-Rural Consumption Disparity	0.8771	0.4554	Consistent
GDP Growth Rate	1.0000	0.3972	Consistent	Urban-Rural Income Gap	0.4767	0.6811	Consistent
Degree of Openness to the Outside World	1.1180	0.3466	Consistent	Investment in Air Pollution Control Projects Completion	1.2247	0.3052	Consistent
Unemployment Rate	1.5000	0.2165	Consistent	Investment in Wastewater Treatment Project Completion	0.3536	0.7599	Consistent
Urbanization	2.0226	0.1080	Consistent	Investment in Industrial Pollution Control Complement	1.1180	0.3466	Consistent
Industrial Structure	1.1180	0.3466	Consistent	Harmless Treatment Rate of Household Waste	1.8257	0.1411	Consistent
Domestic Granted Invention Patents	1.1180	0.3466	Consistent	Energy Consumption Intensity	1.1180	0.3466	Consistent
Research and Development Intensity	0.4564	0.6938	Consistent	Energy Consumption Elasticity Coefficient	0.7071	0.5447	Consistent
Technology Transaction Activity Rate	−1.5000	0.2165	Consistent	Per Capita Urban Green Area	1.1180	0.3466	Consistent
Number of Universities	−1.9069	0.1265	Consistent	Per Capita Water Resources	0.7071	0.5447	Consistent
Number of students	−0.7071	0.5447	Consistent	Forest Area	1.1180	0.3466	Consistent
Number of University Teachers	1.5811	0.1950	Consistent	Forest Coverage Rate	0.5976	0.6075	Consistent
Gini Coefficient	1.3156	0.2731	Consistent	Chemical Oxygen Demand Emission	−0.5000	0.6666	Consistent
Infrastructure Level	−0.5976	0.6075	Consistent	Sulfur Dioxide Emission	−1.5000	0.2165	Consistent
Number of Health Technicians	0.3953	0.7328	Consistent				

2. *Wilcoxon tests*

According to the indicator scoring results of 10 experts, in accordance with the principle and method of Wilcoxon tests, using SPSS statistical software, the Wilcoxon value and p-value of the expert assignment of China's SED indicator system were calculated, and the results are shown in Table 4. From the results of Wilcoxon tests, the p-value of the test for all indicators is greater than 0.05 and the original hypothesis is accepted, which indicates that the quality of expert scoring results passes the consistency test, and the result of the Wilcoxon tests is the retention of the existing indicators.

Table 4
Expert assignment Wilcoxon tests of China's SED indicator system

Third-level indicators	Wilcoxon value	Wilcoxon's p-value	Consistency judgment of expert assignments	Third-level indicators	Wilcoxon value	Wilcoxon's p-value	Consistency judgment of expert assignments
GDP	−1.0000	0.3170	Consistent	Urban-Rural Consumption Disparity	−0.7430	0.3170	Consistent
GDP Growth Rate	−1.4140	0.1570	Consistent	Urban-Rural Income Gap	−0.4470	0.1570	Consistent
Degree of Openness to the Outside World	−0.8160	0.4140	Consistent	Investment in Air Pollution Control Projects Completion	−1.0000	0.4140	Consistent
Unemployment Rate	−1.3420	0.1800	Consistent	Investment in Wastewater Treatment Project Completion	−0.3780	0.1800	Consistent
Urbanization	−1.8570	0.0630	Consistent	Investment in Industrial Pollution Control Complement	−1.0000	0.0630	Consistent
Industrial Structure	−1.3420	0.1800	Consistent	Harmless Treatment Rate of Household Waste	−1.1339	0.1800	Consistent
Domestic Granted Invention Patents	−1.0000	0.3170	Consistent	Energy Consumption Intensity	−0.8165	0.3170	Consistent
Research and Development Intensity	−0.3780	0.7050	Consistent	Energy Consumption Elasticity Coefficient	−0.5774	0.7050	Consistent
Technology Transaction Activity Rate	−1.1340	0.2570	Consistent	Per Capita Urban Green Area	−1.0000	0.2570	Consistent
Number of Universities	−1.3000	0.1940	Consistent	Per Capita Water Resources	−0.5774	0.1940	Consistent
Number of students	−1.0000	0.3170	Consistent	Forest Area	−1.0000	0.3170	Consistent
Number of University Teachers	−1.1340	0.2570	Consistent	Forest Coverage Rate	−1.0000	0.2570	Consistent
Gini Coefficient	0.8160	0.4140	Consistent	Chemical Oxygen Demand Emission	−0.3780	0.4140	Consistent
Infrastructure Level	−0.5770	0.5640	Consistent	Sulfur Dioxide Emission	−1.1339	0.5640	Consistent
Number of Health Technicians	−0.3780	0.7050	Consistent				

Notes: Wilcoxon test based on negative rank.

3.2 Indicator reliability tests

After completing the quality test of the expert assignment of individual indicators, it is required to carry out the reliability test of China's SED indicator system to achieve the objective of optimizing the screening of indicators. The higher the reliability coefficient is, the more consistent and reliable the evaluation results of the indicators are. The most commonly used measure of reliability is Cronbach's α reliability, and the formula for calculating the reliability coefficient α is based on an earlier internal consistency formula developed by G. Frederic Kuder and M.W. Richardson in 1937.

Usually, the Cronbach's coefficient lies between 0 and 1. If the value of Cronbach's coefficient is less than 0.6, it is considered that the reliability of the indicator system is insufficient; when the value of Cronbach's coefficient reaches 0.7–0.8, it means that the indicator system has considerable reliability, and when the value of Cronbach's coefficient reaches 0.8–0.9, it means that the reliability of the indicator system is very good.

The consistency (reliability) of the expert scoring assignments can be obtained using SPSS software and the test results are shown in Table 5.

Table 5
Cronbach's coefficient test results

Reliability statistics		
Cronbach Alpha	Cronbach Alpha based on normalized terms	Number of indicators
0.8780	0.8760	29

Generally speaking, the degree of consistency of the indicators is related to the expert scoring value of the indicators, and larger values of Cronbach's coefficient indicate greater internal consistency of the indicator system. According to the calculation results in

Table 5, the value of Cronbach's α coefficient is 0.878, which is greater than 0.8, indicating that the indicator system passes the reliability test and the design of the indicator system is reliable.

(3) Indicator consistency tests

1Kendall-W coordinated coefficient consistency tests

After completing the quality, variance, consistency, and reliability tests of the indicator system, the overall consistency of all expert-assigned ratings was tested using the Kendall coordinated coefficient, and the test statistic was the Kendall coordinated coefficient W. The coordinated coefficient W reflects the consistency of all experts' assignments for all indicators and is also an indicator of the degree of reliability and stability of the experts' assignments. In this paper, we use the Kendall coordinated coefficient to test the overall consistency of the assignment scores of all experts. The Kendall coordinated coefficient ranges between 0 and 1; it is close to 1 when all experts are in perfect agreement on the evaluation of the indicator.

In this paper, the Kendall consistency test results of the indicator values can be obtained by using SPSS software, and the results are shown in Table 6. As can be seen from Table 6, Kendall's coordinated coefficient W is 0.536, Kendall's statistic is 150.022, and the p-value is 0. The original hypothesis is rejected, thus rejecting the hypothesis that the expert assignment scores have randomness, which indicates that the consistency of the indicator system is statistically significant, and indicates that the results of the assessment by multiple experts are consistent.

Table 6
Kendall-W coordinated coefficient consistency test results

Number of experts	Kendall W^a	chi-square	degree of freedom	asymptotic significance
10	0.5360	150.0220	28	0.0000

Notes: W^a is the Kendall coordinated coefficient.

2. Friedman tests

The Friedman test is a nonparametric test that can be performed using the rank to determine whether there is a significant difference to more than one overall distribution, with the original hypothesis being that there is no significant difference.

In this paper, the Friedman test results of the indicator values can be obtained by using SPSS software, and the results are shown in Table 7.

Table 7
Friedman test results

Observations	chi-square	degree of freedom	asymptotic significance
450	8269.9100	28	0.0000

From Table 7, we can see that the P-value of the Friedman test is 0, which indicates that it is necessary to reject the hypothesis that there is no significant difference in the overall distribution of the indicator system, which can be regarded as there is a significant difference in the overall mean value of the indicator, and the selected indicator variables are relatively independent of each other, and the overall distribution is different. This indicator system can distinguish the level of SED in different regions of China, and can analyze the differences between different regions.

In summary, the screening results of the indicator system for China's SED are reasonable in terms of the quality test of individual indicators, and the validity, reliability, coordination and consistency test of the indicator system.

4Indicators combination weighting

4.1Hierarchical analysis

The AHP method can quantify the issue of indicator importance and get the final result through decomposition, comparison and synthesis. In this paper, the AHP method is used to assign weights to the third-level indicators and the secondary indicators respectively, and the results are shown in Table 8.

Table 8
Coefficients of consistency test CR

Economic development	Technological innovation	Social well-being	Environmental Governance	Green development	SED
0.0535	0.0765	0.0874	0.0393	0.0547	0.0298

According to the calculation results of the consistency test in Table 8, the consistency coefficient of the third-level and secondary indicators $CR < 0.1$, indicating that the judgment matrix of the hierarchical analysis method is considered to have passed the consistency test, and the design of the weights of the hierarchical analysis method is effective. The results of the weights of China's SED indicator system calculated according to the hierarchical analysis method are shown in Table 9:

Table 9
Weighting of China's SED indicator system based on hierarchical analysis

First-level indicators	Secondary indicators	Weight	Third-level indicators	Weight
SED	Economic development	0.1046	GDP	0.3817
			GDP Growth Rate	0.1012
			Degree of Openness to the Outside World	0.0460
			Unemployment Rate	0.2747
			Urbanization	0.0689
			Industrial Structure	0.1275
	Technological innovation	0.2668	Domestic Granted Invention Patents	0.1875
			Research and Development Intensity	0.4564
			Technology Transaction Activity Rate	0.0805
			Number of Universities	0.1433
			Number of Students	0.0929
			Number of University Teachers	0.0394
	Social well-being	0.0839	Gini Coefficient	0.4616
			Infrastructure Level	0.2686
			Number of Health Technicians	0.1488
			Urban-Rural Consumption Disparity	0.0828
			Urban-Rural Income Gap	0.0382
	Environmental Governance	0.1719	Investment in Air Pollution Control Projects Completion	0.1822
			Investment in Wastewater Treatment Project Completion	0.0521
			Investment in Industrial Pollution Control Complement	0.2985
			Harmless Treatment Rate of Household Waste	0.4672
	Green development	0.3728	Energy Consumption Intensity	0.2408
			Energy Consumption Elasticity Coefficient	0.1002
			Per Capita Urban Green Area	0.0454
			Per Capita Water Resources	0.0276
			Forest Area	0.0454
			Forest Coverage Rate	0.0589
			Chemical Oxygen Demand Emission	0.2864
			Sulfur Dioxide Emission	0.1953

4.2 Panel entropy weighting

In the case where the weights have been determined, the contribution of the indicator is directly proportional to the amount of information it contains, and the amount of information contained in the indicator can be reflected by the information entropy of the indicator. This paper uses the panel entropy weighting method to calculate the weights of China's SED indicator system, and the results are shown in Table 10.

Table 10
Weighting of China's SED indicator system based on panel entropy weighting

First-level indicators	Secondary indicators	Weight	Third-level indicators	Weight
SED	Economic development	0.3241	GDP	0.1292
			GDP Growth Rate	0.0404
			Degree of Openness to the Outside World	0.6482
			Unemployment Rate	0.0411
			Urbanization	0.0656
			Industrial Structure	0.0755
	Technological innovation	0.2625	Domestic Granted Invention Patents	0.3355
			Research and Development Intensity	0.0979
			Technology Transaction Activity Rate	0.3466

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Table 10 (*continued*)

First-level indicators	Secondary indicators	Weight	Third-level indicators	Weight
			Number of Universities	0.0663
			Number of Students	0.1105
			Number of University Teachers	0.0432
	Social well-being	0.0726	Gini Coefficient	0.2987
			Infrastructure Level	0.2168
			Number of Health Technicians	0.0786
			Urban-Rural Consumption Disparity	0.0645
			Urban-Rural Income Gap	0.3414
	Environmental Governance	0.2198	Investment in Air Pollution Control Projects Completion	0.2686
			Investment in Wastewater Treatment Project Completion	0.0407
			Investment in Industrial Pollution Control Complement	0.3488
			Harmless Treatment Rate of Household Waste	0.3419
	Green development	0.1210	Energy Consumption Intensity	0.0145
			Energy Consumption Elasticity Coefficient	0.0029
			Per Capita Urban Green Area	0.1712
			Per Capita Water Resources	0.3556
			Forest Area	0.2389
			Forest Coverage Rate	0.1438
			Chemical Oxygen Demand Emission	0.0348
			Sulfur Dioxide Emission	0.0383

4.3 Principal component analysis

The principal component analysis method can effectively solve the problem of covariance between the indicators, this paper uses the principal component analysis method to calculate the weights of the third-level indicators and the secondary indicators of China's SED indicator system, and the results of the SPSS software show that all of them have passed the KMO and Bartlett tests, which illustrates the effectiveness of the principal component analysis method. The results of the weights of China's SED according to the principal component analysis are shown in Table 11.

Table 11
Weighting of China's SED indicator system based on principal component analysis

First-level indicators	Secondary indicators	Weight	Third-level indicators	Weight
SED	Economic development	0.2462	GDP	0.2086
			GDP Growth Rate	0.0328
			Degree of Openness to the Outside World	0.1554
			Unemployment Rate	0.1753
			Urbanization	0.2076
			Industrial Structure	0.2203
	Technological innovation	0.2775	Domestic Granted Invention Patents	0.1845
			Research and Development Intensity	0.2073
			Technology Transaction Activity Rate	0.1858
			Number of Universities	0.1267
			Number of Students	0.1727
			Number of University Teachers	0.1230
	Social well-being	0.2217	Gini Coefficient	0.1660
			Infrastructure Level	0.1111
			Number of Health Technicians	0.2492
			Urban-Rural Consumption Disparity	0.1698
			Urban-Rural Income Gap	0.3039
	Environmental Governance	0.0158	Investment in Air Pollution Control Projects Completion	0.3075
			Investment in Wastewater Treatment Project Completion	0.2638
			Investment in Industrial Pollution Control Complement	0.3109
			Harmless Treatment Rate of Household Waste	0.1178
	Green development	0.2388	Energy Consumption Intensity	0.1787
			Energy Consumption Elasticity Coefficient	0.1470
			Per Capita Urban Green Area	0.0044
			Per Capita Water Resources	0.1204
			Forest Area	0.0789
			Forest Coverage Rate	0.2225
			Chemical Oxygen Demand Emission	0.0607
			Sulfur Dioxide Emission	0.1874

4.4 Combination weighting approach

In this study, subjective weights are calculated by hierarchical analysis, objective weights are calculated by principal component analysis and panel entropy weighting, and combination weighting is assigned by weighted average, so as to determine the weights of China's SED indicator system. The results of the combination weighting are shown in Table 12.

Table 12
Weighting of China's SED indicator system based on combination weighting method

First-level indicators	Secondary indicators	Weight	Third-level indicators	Weight
SED	Economic development	0.2286	GDP	0.2762
			GDP Growth Rate	0.0650
			Degree of Openness to the Outside World	0.2118
			Unemployment Rate	0.1595
			Urbanization	0.1243
			Industrial Structure	0.1632
	Technological innovation	0.3030	Domestic Granted Invention Patents	0.2526
			Research and Development Intensity	0.2343
			Technology Transaction Activity Rate	0.1932
			Number of Universities	0.1187
			Number of Students	0.1350
			Number of University Teachers	0.0662
	Social well-being	0.1246	Gini Coefficient	0.3270
			Infrastructure Level	0.2147
			Number of Health Technicians	0.1645
			Urban-Rural Consumption Disparity	0.1115
			Urban-Rural Income Gap	0.1823
	Environmental Governance	0.0949	Investment in Air Pollution Control Projects Completion	0.2701
			Investment in Wastewater Treatment Project Completion	0.0901
			Investment in Industrial Pollution Control Complement	0.3487
			Harmless Treatment Rate of Household Waste	0.2911
	Green development	0.2489	Energy Consumption Intensity	0.1269
			Energy Consumption Elasticity Coefficient	0.0517
			Per Capita Urban Green Area	0.0482
			Per Capita Water Resources	0.1570
			Forest Area	0.1410
			Forest Coverage Rate	0.1834
			Chemical Oxygen Demand Emission	0.1256
			Sulfur Dioxide Emission	0.1662

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