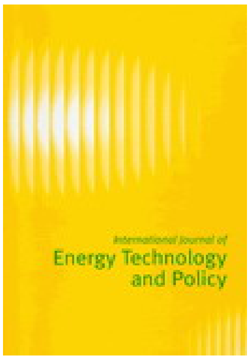

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Construction of a multiscale renewable energy economic evaluation system considering low-carbon economy and energy storage integration

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Construction of a multiscale renewable energy economic evaluation system considering low-carbon economy and energy storage integration

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Abstract: The study collected data on RE and LCE in China from 2014 to 2020, selecting RE utilisation, ecological environment, economic development (ED), and residents' quality of life as primary indicators, further refined into eight evaluation sub-indicators. Using hierarchical analysis, the relative weights of these indicators were calculated, with carbon emission intensity receiving the highest weight of 0.18. Using the constructed evaluation system, the study analysed LCE development trends in China from 2019 to 2023, as well as regional differences between northern and southern China in 2021. Results indicated that while China's overall LCE development level improved from 2019 to 2023, the growth rate declined significantly, from 92% in 2010 to 17% in 2023. The proposed RE economic evaluation system effectively assesses LCE development and highlights the need for balanced regional development to reduce disparities between northern and southern China.

Keywords: evaluation system; renewable energy; low-carbon economy; LCE; analytic hierarchy process; AHP; China's economic development; energy storage integration; multi-scale energy.

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1 Introduction

Human life and social progress are deeply intertwined with energy utilisation, which has undergone significant transformations. Energy serves as the cornerstone of human survival and economic development (ED). However, the rapid increase in global energy demand and heavy reliance on traditional fossil fuels have led to two critical challenges: energy shortages and environmental degradation. Fossil fuels, such as coal and oil, dominate industrial energy consumption. Their finite nature, coupled with excessive exploitation, exacerbates energy scarcity.

Additionally, the combustion of fossil fuels generates substantial carbon dioxide emissions, intensifying global warming and ecological deterioration. The rising global energy demand and high dependence on fossil energy have led to serious carbon emissions and environmental degradation. The low-carbon economy (LCE) emphasises transitioning from fossil to renewable energy (RE) to achieve sustainable development.

The concept of an LCE emerges as a sustainable development paradigm, emphasising the transition from traditional fossil energy to RE. RE, characterised by low energy consumption, minimal pollution, and renewability, is widely recognised as a pivotal driver of LCE. By harnessing RE, sustaining economic growth while mitigating environmental harm is possible. Achieving the objectives of LCE requires a systemic shift in energy utilisation patterns and establishing a robust economic evaluation framework. A comprehensive RE economic evaluation system is essential for assessing the development level of LCE, guiding policy formulation, and promoting balanced regional development to address disparities in energy transition and sustainability.

Energy is the foundation of human survival and ED, and ED relies on energy use, which can lead to carbon emissions issues. With the global energy shortage, the development of RE is a necessary means to achieve an LCE. This article establishes a RE economic evaluation system based on LCE and evaluates the growth level of China's LCE by determining evaluation indicators. This paper innovatively constructs a multi-scale RE economic evaluation system based on a LCE, quantifies the weights of each indicator through the hierarchical analysis method, particularly emphasises the importance of energy storage integration, and analyses the regional differences between northern and southern China, providing a scientific basis for promoting regional balanced development and policy formulation.

2 Related work

The global energy shortage and environmental pollution caused by fossil fuels require shifting from traditional energy forms to RE. Many people analyse the relationship between RE and the economy by constructing an economic evaluation system for RE. Alayi et al. (2022) used microgrid software for the first time to simulate a hybrid wind-solar-fuel cell system in Yazd. The objective was to find an optimal economic system that would provide 15 kWh of electricity per day and assess the uncertainty's impact. Sensitivity analyses were performed on solar radiation intensity and wind speed. The results showed that the optimal system with fuel cells only includes wind turbines. Moraes et al. (2019) have evaluated the technical economy of hydrogen production using an ethanol fuel processor to produce energy. Ethanol fuel is a clean burning fuel with a high octane rating number, which belongs to RE, and ethanol-powered vehicles are economically feasible. Michailos' (2018) research pointed out that current sustainability analysis has explored the potential economic and environmental benefits of converting lignocellulosic sugars into bio-jet fuels. Bagasse is a solid residue in the sugar industry, and the use of bagasse in bio-refining can actively promote sustainable fuel production. Tenhumberg (2020) produced green hydrogen economically and ecologically through water electrolysis. He has evaluated different electrolysis technologies for water. The use of RE can effectively reduce environmental pollution, and the use of RE can achieve sustainable ED. Still, there is no RE economic evaluation system analysis under the LCE.

The use of fossil energy has a significant impact on the environment. LCE is based on RE and realises sustainable ED through efficient energy utilisation. Many people have studied the economic evaluation system of RE under the LCE. Fan and Friedmann (2021) discussed the global steel industry's existing methods and potential decarbonisation approaches. Large-scale deployment is limited by resource availability, infrastructure, and policy incentives. Hunter et al. (2021) pointed out that the significant reduction in wind, solar, and battery costs is accelerating the penetration of RE into the grid. As the penetration rate of variable RE increases to over 80%, clean power systems would require long-term energy storage or flexible low-carbon power generation. He proposed a new storage system using heavy-duty vehicle fuel cells, which can help achieve a very high RE grid. Kong et al. (2021) pointed out that hydrogen energy, as a clean and low-carbon secondary energy, was applied in RE grid-connected power generation, opening up a new way to couple hydrogen storage energy with RE. Wind power fluctuations constrained the capacity of electrolytic cells and fuel cells. Energy is the foundation of socio-ED, but energy use needs to consider carbon emissions and achieve sustainable ED through RE. However, there is a lack of analysis of factors affecting the economic evaluation system of RE. Although previous studies have made progress in RE technology and applications, constructing a RE economic evaluation system is still insufficient, mainly regarding regional differences, energy storage integration, and long-term environmental impact. Existing studies focus on technical feasibility and cost reduction. Still, the effects of policy incentives, social acceptance, and market mechanisms on the economic efficiency of RE are not deeply explored, which limits the comprehensive understanding and promotion of a LCE.

3 Construction of RE economic evaluation system

3.1 Collection of RE economy data

Energy is the material foundation for ED and human survival. Using energy can improve industrial production efficiency, and economic growth relies on energy support. The most commonly used form of energy by humans is fossil energy. Humans' use of fossil fuels has promoted ED, scientific progress, and industrial production efficiency, but the drawbacks of using fossil fuels are also undeniable. As the material basis of the economy and human survival, energy improves industrial production efficiency, supports economic growth, and improves quality of life. However, over-reliance on fossil energy has led to resource shortages and environmental pollution, emphasising the need to switch to RE to achieve sustainable development.

Fossil energy is a hydrocarbon or its derivatives, and fossil energy is formed by the remains of ancient organisms that have evolved over tens of thousands of years (Ghabri et al., 2021). The reserves of fossil energy are limited, and the global overuse of fossil energy has led to a severe shortage of fossil energy reserves. Burning fossil energy also generates much carbon dioxide and waste, seriously polluting the environment. The carbon emissions of fossil fuels are constantly increasing, and excessive carbon emissions are a significant cause of global warming (Peters et al., 2020; Kwakwa and Alhassan, 2018). China's ED speed is breakneck, depending on the use of a large amount of energy, but China's ED also leads to increased carbon emissions. According to statistics, China's carbon emissions data from 2016 to 2020 are shown in Table 1.

Table 1 Carbon emission data of China from 2016 to 2020

Serial number	*Years*	*Carbon emissions (100 million tons)*
1	2016	12.2
2	2017	12.3
3	2018	12.4
4	2019	12.5
5	2020	12.4

In Table 1, the carbon emissions data of China from 2016 to 2020 was described. The carbon emissions from 2016 to 2019 have continuously increased, from 1.22 billion tons in 2016 to 1.25 billion tons in 2019. China's carbon emissions 2020 were 1.24 billion tons, which was 0.1 billion tons less than in 2019. This is mainly because China has improved energy utilisation and introduced the theory of LCE.

LCE is to reduce the use of fossil energy and carbon dioxide generated by energy use through technological innovation and new energy development under the sustainable development theory. RE is an important way to achieve LCE (Li et al., 2022; Balakrishnan et al., 2020).

Table 2 Data on China's RE and LCE from 2014 to 2020

Years	*Per capita gross domestic product (10,000 yuan/person)*	*Per capita carbon emissions (tons/person)*	*Proportion of RE consumption (%)*
2014	1.07	3.2	6.8
2015	1.25	3.4	7.1
2016	1.44	3.5	7.1
2017	1.67	3.6	7.2
2018	2.05	4.2	7.2
2019	2.41	4.3	8.9
2020	2.62	4.4	9.0

This article collected data from the China Energy Statistical Yearbook from 2014 to 2020, as shown in Table 2, to explore the key relationship between RE, ED, and carbon emissions in China.

Table 2 describes China's RE and LCE data from 2014 to 2020. The calculation of RE mainly focused on wind energy, hydropower, and solar energy. The proportion of RE consumption increased from 6.8% in 2014 to 9.0% in 2020. China's economy steadily improved from 2014 to 2020, but per capita carbon emissions also gradually increased (Hussien et al., 2025).

3.2 Economic evaluation indicators for RE

Energy use would promote ED and cause environmental problems, and the deterioration of environmental quality would inhibit ED. The economy, energy, and environment have a mutual relationship. To achieve the sustainable development strategy, people need to vigorously develop RE and change the type of energy to achieve the development of LCE.

LCE is the goal of future social construction. It can ensure ED and limit carbon dioxide emissions by changing energy types, improving technology, and changing people's lifestyles (Zhang et al., 2019; Louche et al., 2019). This article needs to determine the relevant indicators of the RE economy to effectively analyse it and objectively reflect the development level of LCE. The characteristics of LCE are reflected through the analysis of indicators.

Specific requirements must be followed when selecting indicators for the economic evaluation of RE. The indicators must be representative, and selecting representative indicators can provide a more comprehensive evaluation and analysis. In addition, the indicators must also be operable and dynamic, and ED trends can be predicted by analysing their weight.

The use of RE can achieve the development of LCE by reducing carbon emissions. According to the characteristics of LCE and RE, this article selects RE utilisation, ecological environment, ED, and residents' lives as the first-level indicators. Among them, RE utilisation is the basis for achieving an LCE, measured by RE utilisation rate and carbon emission intensity. The purpose of LCE development is to reduce the impact on the ecological environment in the process of ED, which the industrial wastewater attainment rate and the environmental governance investment ratio can measure.

Table 3 Indicator system for economic evaluation of RE based on LCE

Target	*Primary indicators*	*Secondary indicator*
RE economic evaluation system	RE utilisation	RE utilisation rate
		Carbon emission intensity
	Ecological environment	Industrial wastewater reaching rate
		Environmental governance investment ratio
	ED	Per capita carbon emissions level
		Per capita gross domestic product
	Resident life	Per capita green space area
		Number of buses owned by 10000 people

The secondary indicators of LCE can be expressed as per capita carbon emissions and per capita GDP.

The indicator system of RE economic evaluation based on LCE is shown in Table 3.

Table 3 describes the indicator system for the economic evaluation of RE based on LCE. Four first-level indicators were selected: RE utilisation, ecological environment, ED, and residential life. Eight secondary indicators were added: RE utilisation rate, carbon emission intensity, industrial wastewater attainment rate, environmental management investment ratio, per capita carbon emission level, per capita GDP, per capita green area, and the number of public vehicles owned by 10,000 people.

3.3 RE economic evaluation index system

Adhering to the path of sustainable development is necessary to coordinate the relationship between ED, energy, and the environment. LCE development aims to reduce greenhouse gas emissions and achieve low-pollution ED based on RE (Ionescu, 2019; Liang, 2021).

According to the characteristics of LCE, this article has constructed four first-level indicators and eight second-level indicators. This article has constructed a RE economic evaluation system based on LCE to analyse the RE economy comprehensively. Hierarchical analysis is used to quantify the weighting relationships among the indicators to analyse the development status of the LCE. The analytic hierarchy process (AHP) decomposes problems, analyses the membership relationships between influencing factors, determines indicator weights through mathematical methods, and obtains comprehensive evaluation results (Ho and Ma, 2018; Darko et al., 2019).

AHP is a combination of qualitative and quantitative analysis that can be well applied to the economic evaluation system of RE (Piprani et al., 2020). When using the AHP to evaluate the RE economy, it is necessary to standardise the data obtained on the RE economy. This is due to the significant differences in the values of different data types. For example, the raw values of GDP per capita and the number of buses per 10,000 people are very different (Sun et al., 2024). The impact of the disparity of indicator units can be eliminated through standardised processing.

Applying the AHP requires comparing the influence of indicators in pairs. The eight selected secondary indicators are marked as $a_1, a_2, a_3, \cdots, a_8$, and any two of them, a_i and a_j, are selected ($i, j \in \{1, 2, 3, \cdots, 8\}$). The comparison result of the influence of the i^{th} indicator on the j^{th} indicator is:

$$a_{ij} = a_i / a_j \tag{1}$$

On the contrary, the comparison of the influence of the j^{th} indicator on the i^{th} indicator is:

$$a_{ij} = a_j / a_i \tag{2}$$

All indicators are compared in pairs, and the resulting impact results are constructed into a judgement matrix, which is represented as:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{3}$$

In formula (3), n represents the number of indicators.

The consistency test is conducted on the judgement matrix, and the consistency indicator results are:

$$CI = (r - n) / n - 1 \tag{4}$$

The consistency ratio is expressed as:

$$CR = CI / RI \tag{5}$$

In formula (5), RI represents the random consistency index value corresponding to matrix A when its order is 8; $RI = 1.41$.

Therefore, the criterion for determining whether matrix A satisfies consistency is:

$$CR < 0.1 \tag{6}$$

The arithmetic mean of the column terms in matrix A can represent the weight of indicators:

$$w_i = \left(a_{i1} + a_{i2} + \cdots + a_{in}\right) / n \tag{7}$$

In formula (7), w_i represents the relative weight of the i^{th} indicator.

The eight secondary indicators selected in this article are compared in pairs, and their weights are analysed, as shown in Table 4.

Table 4 Weight table of indicators

Target	*Primary indicators*	*Secondary indicator*	*Weight*
RE economic evaluation system	RE utilisation	RE utilisation rate	0.17
	Ecological environment	Carbon emission intensity	0.18
		Industrial wastewater reaching rate	0.12
		Environmental governance investment ratio	0.13
	ED	Per capita carbon emissions level	0.13
		Per capita gross domestic product	0.12
	Resident life	Per capita green space area	0.07
		Number of buses owned by 10,000 people	0.08

In Table 4, the weights of various indicators in the RE economic evaluation system were described, with the highest weight of the carbon emission intensity indicator being 0.18. The AHP method can decompose complex problems through a hierarchical structure, quantify the importance of various factors, combine qualitative and quantitative analysis, simplify the decision-making process, and effectively deal with uncertainty. It is suitable for evaluating the economic feasibility of RE and improving the scientificity and accuracy of decision-making.

4 Evaluation of RE economic evaluation system

Energy is the driving power for social development, but using fossil fuels leads to energy shortages and global warming, and excessive carbon emissions worsen human living conditions. With the increase in the world population, human demand for energy is increasing, and excessive carbon emissions cause global climate change. LCE is a new model of sustainable development strategy, which can achieve sustainable economic growth by using renewable resources and protecting the environment.

China is a populous country with a speedy ED rate. However, the reliance on fossil energy in economic construction is very high, and energy utilisation in industry is low. Pollutants are poorly managed, and people's awareness of environmental protection is not strong enough. Various reasons in China have caused severe damage to the ecological environment.

ED relies on energy use, which also causes environmental damage. Therefore, it is necessary to transform China's energy form. This article constructs an economic evaluation system of RE based on LCE, analyses the utilisation of RE, ecological environment, ED, and residents' lives, and constructs eight evaluation indicators.

The eight evaluation indicators are compared two by two using hierarchical analysis, and the relative weights of each indicator are analysed. This article analyses the growth of China's LCE from 2008 to 2012 and collects index data on LCE. The growth level of China's LCE can be analysed through the AHP. The growth level of China's LCE is the weighted sum of all indicators.

The growth level of China's LCE is divided into four levels. The evaluation criteria for the development level of LCE are shown in Table 5.

Table 5 Evaluation criteria for LCE development level

Grade	*Comprehensive evaluation value*	*Performance*
1	≥0.85	Significant ecological carbon absorption
2	[0.75, 0.85)	Ecological carbon absorption is the average
3	[0.60, 0.75)	No ecological carbon absorption effect
4	<0.60	Excessive carbon emissions

Table 5 shows four levels of LCE development. When the comprehensive evaluation value was ≥ 0.85, ecological carbon absorption was obvious. When it was less than 0.60, carbon emissions exceeded the standard.

This article collected the index data of LCE and weighted them to get the comprehensive evaluation value. According to the comprehensive evaluation value obtained, the development level of China's LCE in 2019–2023 can be analysed.

5 Evaluation system evaluation results

5.1 Development of China's LCE from 2019 to 2023

China has a large population and a rapidly developing economy, which has led to a massive demand for fossil fuels such as oil and coal. However, fossil fuel reserves are limited, and over-reliance on non-RE exacerbates resource consumption and leads to severe environmental pollution and carbon emissions. Faced with the dual challenges of energy security and environmental sustainability, China must accelerate the transformation of its energy structure and promote the development and utilisation of RE. By improving energy efficiency, optimising industrial structure, and developing a LCE, China can achieve green and sustainable development while meeting its energy needs, reduce its dependence on fossil fuels, and ensure future energy security. The development of China's LCE from 2019 to 2023 is shown in Table 6.

Table 6 describes the development of LCE in China from 2019 to 2023, and the data of eight indicators was counted. The intensity of carbon emissions has been increasing, from 2.38 tons per ton of standard coal in 2019 to 2.44 tons per ton of standard coal in 2023, indicating that China's control and management of carbon emissions were insufficient from 2019 to 2023. The utilisation rate of RE in China is constantly improving, thanks to the improvement of energy utilisation technology. The utilisation rate of RE has increased from 7.7% in 2019 to 8.6% in 2023. China's environmental governance investment ratio and industrial wastewater utilisation rate continuously increased from 2019 to 2023. Although China has increased its efforts in environmental governance, the per capita carbon emissions have continued to increase, indicating that China's environmental governance efforts from 2019 to 2023 were insufficient. The rate of industrial wastewater in China has increased from 92.4% in 2019 to 95.4% in 2023. China's per capita carbon emissions level increased from 4.3 tons per person in 2019 to 5.4 tons per person in 2023. China has carried out a variety of LCE development strategies in 2019–2023, but the per capita carbon emission level is still improving.

Table 6 Development of LCE in China from 2019 to 2023

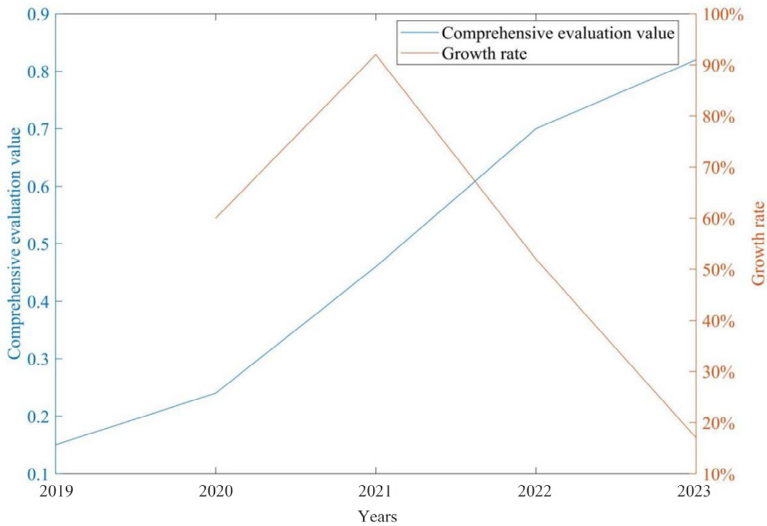
Index	*2019*	*2020*	*2021*	*2022*	*2023*
RE utilisation rate (%)	7.7	7.8	7.9	8.2	8.6
Carbon emission intensity (tons per ton of standard coal)	2.38	2.39	2.42	2.43	2.44
Industrial wastewater reaching rate (%)	92.4	94.0	94.5	94.9	95.4
Environmental governance investment ratio (%)	1.49	1.33	1.36	1.54	1.58
Per capita carbon emission level (tons/person)	4.3	4.4	4.6	5.1	5.4
Per capita gross domestic product (10,000 yuan/person)	2.41	2.62	3.08	3.63	3.98
Per capita green space area (square meters)	9.7	10.8	11.2	11.6	12.4
Number of buses owned by 10,000 people	11.2	11.1	11.3	11.6	12.1

5.2 Dynamic development level of LCE

To effectively analyse the development of LCE in China from 2019 to 2023, obtaining the comprehensive evaluation value of LCE development through the AHP is necessary. China's carbon absorption capacity is analysed, and the month-on-month growth rate is calculated. The higher the comprehensive evaluation value, the higher the development level of LCE is. The higher the link ratio growth rate, the faster LCE's growth level is. The dynamic development level of China's LCE from 2019 to 2023 is shown in Figure 1.

In Figure 1, the dynamic development level of LCE was described, and the development of LCE in China from 2019 to 2023 was described. The horizontal axis represents the year; the left vertical axis represents the comprehensive evaluation value of LCE development; the right vertical axis represents the growth rate. China's development level of LCE in 2019–2023 was constantly improving, from 0.15 in 2019 to 0.82 in 2023, which indicated that China's ecological carbon absorption capacity was gradually increasing. The comprehensive evaluation values of LCE development in 2019, 2020, and 2021 were 0.15, 0.24, and 0.46, respectively, which were all less than 0.60, so China's carbon emissions exceeded the standard in 2019–2023. The main reasons for China's excessive carbon emissions from 2019 to 2021 may be its reliance on fossil fuels, limited efforts in developing RE, and lack of low-carbon environmental awareness. In 2022, the comprehensive evaluation value of China's LCE development was 0.70, which meant that China had made relevant LCE development measures in 2022. However, the ecological carbon absorption capacity was equal to the carbon emission capacity. In 2023, the comprehensive evaluation value of China's LCE development was 0.82, belonging to the general state of ecological carbon absorption. This meant that China had increased the development of LCE, and the ecosystem had a specific carbon absorption capacity. This article also analysed the month-on-month growth rate of China's comprehensive evaluation value; the highest growth rate in 2021 was 92%. However, the growth rate has continuously decreased since 2021, with a growth rate of 17% in 2023. Therefore, China's overall development level of LCE is constantly improving, and the growth rate has been declining since 2021. China also needs to strengthen the development level of LCE.

Figure 1 The dynamic development level of LCE (see online version for colours)



As can be seen from the data in Figure 1, China's overall low-carbon ED level showed an upward trend from 2019 to 2023, with the comprehensive evaluation value increasing from 0.15 to 0.82, indicating that the carbon absorption capacity has been continuously enhanced. However, from 2019 to 2021, the LCE comprehensive evaluation value was lower than 0.60, meaning carbon emissions exceeded the standard. The main reasons may include dependence on fossil fuels, insufficient development of RE, and weak public awareness of low carbon. Although the level of LCE development has been continuously improving, the growth rate has slowed down, indicating that China needs to optimise the industrial structure further, increase investment in RE, and improve carbon absorption capacity to maintain the continued growth of LCE.

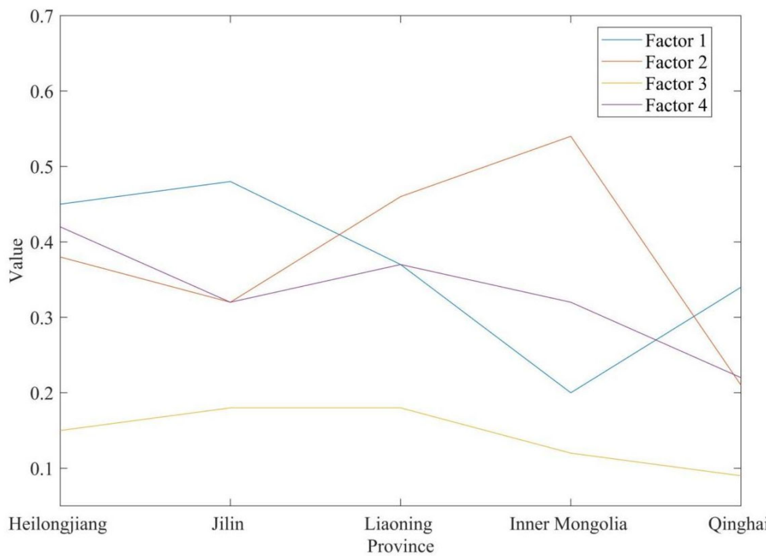
5.3 Comparison of LCE development in several provinces of China

China has a vast region, and the development of LCE in different provinces differs. To effectively analyse the development of LCE in specific provinces in China, this article compared the development of LCE in several provinces in the north and south of China in 2019–2023. A comparison was made using RE, ecological environment, ED, and residents' living standards in multiple provinces. The utilisation of RE, ecological environment, ED, and residents' living standards were represented by factors 1, 2, 3, and 4, respectively.

5.3.1 LCE development in several northern provinces of China

To effectively analyse the development of LCE in northern China, this article selected Heilongjiang, Jilin, Liaoning, Inner Mongolia, and Qinghai in China for analysis. The comparative results of LCE development in Northern China are shown in Figure 2. Zhejiang, Fujian, Guangdong, Jiangsu, and Hainan were selected for the analysis of low-carbon ED because these provinces are located in southern China, with rapid ED, high industrialisation, relatively large energy consumption and carbon emissions, and urgent need for low-carbon transformation. The industrial structures of these five provinces are unique. They can provide diverse research cases for LCE development, thereby comprehensively evaluating the development model and effectiveness of the LCE in southern provinces.

Figure 2 Low-carbon ED in several northern provinces of China (see online version for colours)

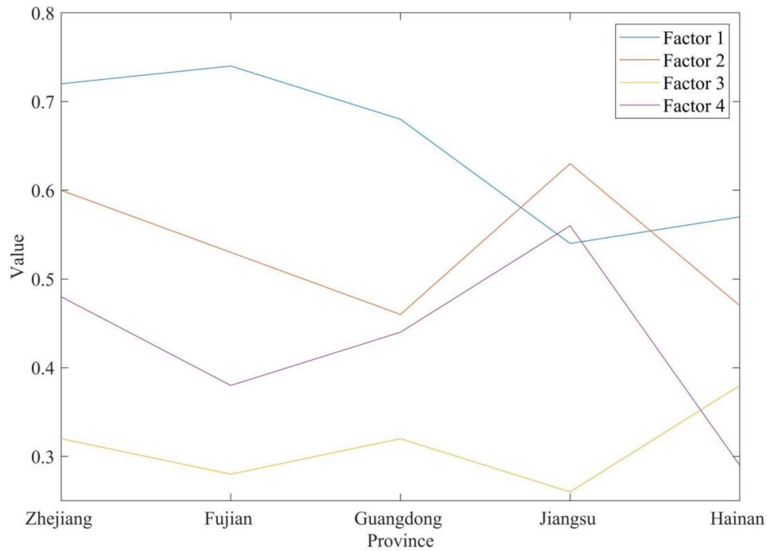


In Figure 2, the development of LCE in several provinces in northern China was described. The horizontal axis shows the five provinces in northern China, and the vertical axis shows the value of factors affecting the development of LCE. The development of LCE in the five northern provinces of China was not significantly different, and all values were below 0.6, which meant that the development effect of LCE in northern China was not very good, mainly because there were many heavy industries in northern China. Most of them still focused on fossil energy. The utilisation value of RE in Heilongjiang Province was 0.45, and the ecological environment value was 0.38. The development level of LCE in several provinces in northern China was not high, so attention should be paid to using RE.

5.3.2 Low-carbon ED in several southern provinces of China

This article selected Zhejiang, Fujian, Guangdong, Jiangsu, and Hainan of China to analyse the development of LCE in several southern provinces of China. The comparison results are shown in Figure 3.

Figure 3 Low-carbon ED in several southern provinces of China (see online version for colours)



In Figure 3, the development of LCE in several provinces in southern China was described. The horizontal axis represents five provinces in southern China, and the vertical axis represents the value of factors affecting the development of LCE. It can be seen that the utilisation of RE in southern provinces was very high, and the ecological environment was also relatively high. This was mainly due to the strong development of RE in southern provinces and their strong ability to handle pollutants. The residents' living standards index was not very high, mainly because the per capita green area was not enough, and the overall greening effect was not good enough. The RE utilisation index in Zhejiang Province was 0.72; the ecological environment index was 0.60; the ED index was 0.32. The RE utilisation index in Fujian Province was 0.74; the ecological environment index was 0.53; the ED index was 0.28. The development of LCE in southern provinces was better than in northern provinces in terms of RE utilisation, ecological environment, ED, and residents' lives. The development level of LCE in the north and south of China was uneven. The southern provinces were better than the northern provinces in RE utilisation.

6 Conclusions

Developing RE to replace traditional fossil energy is a way to develop a LCE. RE is rich in resources. The use of RE can effectively reduce carbon emissions and achieve sustainable development. This article collected data on RE and LCE in China from 2014 to 2020 and summarised four primary and eight secondary indicators to evaluate the development of the RE economy. This article also used the AHP to construct an economic evaluation system for RE. The relative weights of different indicators were analysed by comparing the influence of indicators in pairs. This article used the constructed RE economic evaluation system to analyse the development of China's LCE from 2019 to 2023. The overall development level of China's LCE in 2019–2023 was improving, but the growth rate of LCE in 2021–2023 was slowing down. This article also compared the level of low-carbon ED in several provinces in southern and northern China. The level of low-carbon ED in southern China is overall better than in the northern provinces, and the use of RE in the northern provinces needs to be enhanced. This study reveals the development trends and challenges of the LCE in southern provinces, providing data support for the government to optimise low-carbon policies and promote industrial transformation. It also provides a reference for other regions to promote the coordinated development of the national LCE and achieve green and sustainable growth goals. The limitation of the study is that although the constructed RE economic evaluation system comprehensively considers multiple key indicators, its applicability to certain specific regions or industries may be limited, especially in areas where data is complex to obtain or ED models are unique. In addition, this study mainly relies on historical data in the evaluation process, and the potential impact of future technological advances and policy changes is insufficiently considered, which may lead to inaccurate predictions of future low-carbon ED trends. With the development of technology and changes in the policy environment, optimising and improving the RE economic evaluation system further is imperative. Future research can further explore the effects and economic benefits of combining different energy storage technologies with RE while strengthening the consideration of socio-economic factors, such as public acceptance and market mechanisms, to promote the wider application of RE.

Declarations

These are no potential competing interests in our paper. And all authors have seen the manuscript and approved to submit to your journal. We confirm that the content of the manuscript has not been published or submitted for publication elsewhere.

All authors were aware of the publication of the paper and agreed to its publication.

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