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EDITED BY
Biagio Fernando Giannetti,
Paulista University, Brazil

REVIEWED BY
Jiansong Zheng,
The Hong Kong Polytechnic University, Hong Kong SAR, China
Yu Zhao,
Kyushu University, Japan

*CORRESPONDENCE
Yao Tao,
txy_1996@163.com

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A comprehensive assessment method for the development level of power transition and its application under different regional development measures: a study based on Entropy Weight TOPSIS

Zhanjun Chai[1], Qi Liu[1], Yining Li[1], Chao Li[1], Xiaofeng Xu[2,3], Dunnan Liu[2,3] and Yao Tao[2,4]*

[1]State Grid Inner Mongolia Eastern Power Co., Ltd., Hohhot, China, [2]Beijing Key Laboratory of New Energy and Low-Carbon Development (North China Electric Power University), Beijing, China, [3]School of Economics and Management, North China Electric Power University, Beijing, China, [4]School of Management, Guizhou University, Guiyang, China

To accurately assess the transformation process of China's power sector, this study addresses the limitations of existing literature, which primarily focuses on macro-level or single-dimensional evaluations while neglecting regional disparities. This study constructs a power transition development index based on four dimensions: clean, low carbon, security, and efficiency. By integrating the Entropy Weight Method with the TOPSIS model, it quantitatively evaluates and compares the power transition development levels of 30 Chinese provinces from 2011 to 2022. This reveals their spatiotemporal characteristics and regional disparities, providing a reference for formulating regional energy policies. Results indicate: (1) The security and clean dimensions collectively account for 72.1% of the total weighting, forming the core pillars of power transition. (2) The synthesis transition scores of 30 provinces range from 0.155 (Anhui) to 0.505 (Sichuan), revealing a spatial pattern where resource-rich western regions lead, while central provinces reliant on energy imports and traditional industrial provinces face greater transition pressures. (3) Provincial power transition capabilities steadily improved during the study period, with the synthesis score rising from 0.213 to 0.295—a 38.5% increase—though significant inter-provincial ranking disparities persist. This research proposes policy recommendations to advance China's regional power transition, including strengthening policy coordination, promoting differentiated transition pathways, and accelerating technological innovation. These measures will help provinces more effectively implement emission reduction targets.

KEYWORDS

a comprehensive assessment, Entropy Weight, power transition, regional development level assessment, TOPSIS

1 Introduction

Due to the impacts of climate change and sustainable development goals, most countries worldwide have adopted power transition as a central theme for social development (Yang G. et al., 2024). Electricity, as (Yang G. et al., 2024) the core of the entire energy system, bears a significant historical mission in this process. It must meet the continuously growing energy demands of socioeconomic development while ensuring stable energy supply and achieving carbon reduction and mitigation objectives, thereby advancing the global green transformation (Jiang et al., 2022; Yu et al., 2020; Yao et al., 2023). According to data from the International Energy Agency (IEA), global carbon emissions reached 37.6 Gt in 2024 (IEA, 2025), with the power sector accounting for over 40% of global energy-related carbon dioxide emissions (Li Y. et al., 2024). This indicates that the pace and direction of the power system's transformation directly determine the effectiveness of global carbon reduction efforts and influence the overall restructuring of the world's energy systems (Fan et al., 2025; Zhu et al., 2022).

Given the trend of globalization, China's energy transition must be both urgent and strategic. Power transition development is defined as the transformation of the power sector toward a clean, low-carbon, secure, and efficient energy system. It reflects the coordinated improvement of generation structure, emission reduction, system reliability, and operational efficiency (Chen et al., 2020; Liu et al., 2022). According to the 2024 National Bureau of Statistics data, China's total energy consumption reached approximately 5.96 billion tons of standard coal equivalent, with coal accounting for about 53.2% of total energy consumption, and the share of clean energy sources, including natural gas, hydropower, nuclear, wind, and solar, rose to about 28.6% in 2024 (Statistics, 2024). These figures reflect a continued dominance of fossil fuels in China's energy mix. This fossil-fuel-dominated pattern has resulted in high carbon intensity and significant environmental pressure, indicating that the growth of primary energy demand is largely driven by coal and other fossil fuels.

Meanwhile, secondary energy consumption, mainly electricity, has grown rapidly. Total electricity use rose from 4.96 trillion kilowatt-hours in 2010 to 8.64 trillion kilowatt-hours in 2023 (National Bureau of Statistics of China, 2024), marking an increase of more than 70% in just over a decade. Secondary energy consumption, primarily electricity, has grown rapidly, serving as the main carrier for clean energy integration and end-use energy substitution (Dai et al., 2021; Zou et al., 2022). The share of electricity in total energy consumption has increased steadily, reflecting a structural shift toward electrification and low-carbon development.

Because the power sector accounts for more than 50% of China's energy-related CO_2 emissions, optimizing and decarbonizing the electricity system is essential for achieving the national dual-carbon goals (Fan et al., 2024). Therefore, clean power generation is identified as a strategic focus of China's energy transition, as it directly links the restructuring of primary energy production with the optimization of secondary energy consumption (Nie et al., 2024).

The energy transitions in the European Union and the United States have primarily relied on market-oriented reforms, carbon pricing mechanisms, and long-term institutional continuity (Sitarz et al., 2024). Japan and South Korea have adopted hybrid models that emphasize technological innovation and improvements in energy efficiency (Raymond, 2019; Sun et al., 2019). In contrast, China's energy transition follows a state-coordinated pathway characterized by the rapid deployment of renewable energy, large-scale investment, and an integrated emphasis on energy security (Dogah et al., 2024; Wu et al., 2020). Although this approach has achieved remarkable results in terms of overall scale and transition speed, it has also exposed structural disparities among regions in policy implementation, resource endowment, and system efficiency. Therefore, it is essential to establish a comprehensive quantitative assessment framework that can evaluate the level of power transition across multiple dimensions, clean, low-carbon, secure, and efficient, to more accurately reveal the regional characteristics and developmental stages of China's energy transition.

It is important to note that, due to China's vast territory and the uneven distribution of energy resources, there are significant disparities in the level of power transition development among different provinces (Wu et al., 2021; Cao et al., 2023). The disparities in question are primarily attributable to variations in energy resource endowments, industrial structures, and the composition of regional power systems. For instance, the northwestern region possesses abundant wind and solar energy resources, yet still faces considerable challenges in local grid integration and interregional power transmission (Li J. et al., 2023). Conversely, the eastern coastal region, where electricity demand is highly concentrated, places greater emphasis on system stability, operational reliability, and energy security (Zhang and Zheng, 2020).

This spatial heterogeneity underscores the theoretical and policy significance of systematically assessing and comparing the level of power transition development at the provincial scale. A comprehensive evaluation of this kind not only reveals regional disparities in the transition process but also identifies differentiated pathways for optimizing energy structures, enhancing grid coordination capacity, and advancing the synergistic development of low-carbon power systems across regions (Zhou et al., 2024; Ge, 2023).

2 Literature review

Scholars in China and abroad have conducted extensive research on the measurement, evaluation, and influencing mechanisms of power transition, thereby forming a relatively systematic theoretical and methodological framework. From a research perspective, the use of multidimensional indicator systems has become the mainstream approach for assessing the level of power transition. The Energy Transition Index, proposed by the World Economic Forum, emphasizes balanced coordination between energy affordability, sustainability, and security (World Economic Forum Fostering Effective, 2025; Khan et al., 2022). This provides an important reference point for evaluating the performance of the global energy transition.

Building on this foundation, the academic community has deepened its understanding of the complexities of energy transition, gradually forming a multidimensional and systematic research framework. Existing studies can be broadly classified into three thematic strands. First, conceptual and theoretical analyses have examined the core elements of the "energy trilemma" and the policy trade-offs among energy security, environmental sustainability, and economic development. For instance, Shirazi developed an integrated assessment model that balances clean energy, energy security, and economic efficiency, emphasizing the importance of flexible modeling in shaping effective regional strategies (Shirazi, 2022). Second, methodological studies have advanced quantitative tools and indicator systems for evaluating energy transition performance. For example, Tziogas et al. (2019) employed the Analytic Hierarchy Process to design a multi-layer framework for sustainable power system assessment, offering methodological insights for constructing evaluation models (Recto et al., 2023).

Finally, system-level applications have analyzed how structural optimization and policy mechanisms interact to influence transition outcomes. King et al. explored the dynamic relationships among energy structure optimization, carbon emission reduction, and economic growth, underscoring the need for adaptive policymaking (Karpavicius et al., 2025). Similarly, Karpavicius et al. assessed the sustainability of European power systems through an energy security indicator framework, revealing inherent trade-offs between economic growth and energy security (Tziogas et al., 2019). Overall, while existing research has laid a solid foundation, few studies have systematically integrated the dimensions of clean, low-carbon, secure, and efficient development into a unified quantitative assessment model. This paper aims to fill this gap by applying an entropy-weighted TOPSIS approach to evaluate the regional power transition in China.

In the context of China, scholars have explored energy structure optimization and transition pathways from multiple perspectives, in line with the nation's "dual carbon" goals of peaking carbon emissions and achieving carbon neutrality. For instance, Li P. et al. (2024) examined the impact of renewable energy penetration on economic growth and regional power transition. They highlighted the dynamic interactions between green development and regional disparities (Li P. et al., 2024). Tang et al. employed a three-stage Data Envelopment Analysis model to evaluate energy efficiency, revealing significant variations in provincial energy performance across China (Tang et al., 2023). Furthermore, Li et al. (2020) emphasized the necessity, from an energy security perspective, of conducting region-specific analyses within the national framework to better understand internal heterogeneity and systemic resilience (Li et al., 2020). Together, these studies offer valuable quantitative insights and policy recommendations for evaluating and promoting China's power transition.

From the perspective of methodology and model selection, traditional subjective weighting approaches (such as the Analytic Hierarchy Process, AHP) involve significant human subjectivity in determining indicator weights, making it difficult to achieve objective and comparable evaluation outcomes (Demir et al., 2024). The subjective weighting method based on expert judgment proposed by Zhao et al., while considering the objective attributes of the indicator set, still introduces a certain degree of error. For multi-indicator systems, this can easily distort the influence of each indicator's information content, making it difficult to obtain precise evaluation results (Zhao et al., 2023). As research continues to deepen, scholars have begun to draw upon objective weighting methods to enhance the accuracy and robustness of evaluations in response to the shortcomings of different approaches. They have combined these methods with the Entropy Weight-TOPSIS model for comparative scoring. The Entropy Weight Method utilizes information entropy to derive indicator weights, effectively reducing the interference of subjective factors in evaluations (Kumar et al., 2021). The TOPSIS model is a comprehensive evaluation framework that converts differences between indicators into distances for dimensionality reduction and comparison (Ciardiello and Genovese, 2023). Liu et al. (2022) demonstrated that the Entropy Weight-TOPSIS method can be applied to comprehensive analysis of energy systems, exhibiting stability and interpretability while reflecting system characteristics across multiple regions and time series (Li W. et al., 2023). Li et al.'s research further indicates that the Entropy Weight-TOPSIS method effectively balances the dual objectives of energy security and clean energy, demonstrating strong applicability for evaluating energy policies (Li et al., 2021).

Based on current research, many studies have reached certain conclusions regarding theoretical frameworks and methodological models for power transition. However, several shortcomings remain: First, existing research primarily focuses on national and higher-level scales, lacking provincial-level empirical analyses grounded in power systems, which hinders the accurate reflection of real-world power transition dynamics. Second, multidimensional indicator systems have not been fully established, failing to comprehensively analyze the coupled relationships among energy clean, decarbonization, security, and efficiency. Third, comprehensive measurement methods remain relatively limited and lack objectivity, with insufficient spatial comparability, leading to unreasonable comparisons of power transition progress across different regions.

In order to ensure the objectivity and comparability of the assessment, this study employs the Entropy Weight–TOPSIS method to conduct a comprehensive evaluation of the power transition development levels across 30 Chinese provinces from 2011 to 2022. The study period corresponds to China's 12th to 14th Five-Year Plans, representing a critical phase of institutionalization and policy deepening in the nation's energy transition process. The objective of this research is to ascertain the spatiotemporal evolution characteristics and structural disparities of China's power sector transition across regions, thereby providing empirical evidence to support the optimization of energy policy, the coordination of regional development, and the implementation of the dual-carbon strategy.

1. Propose a multidimensional framework for the evaluation of power transition development. In contrast to the extant literature, which has chiefly concentrated on macro-level or single-dimension evaluations (e.g., clean or low-carbon performance), this framework targets the power sector and integrates four key dimensions: clean, low-carbon, security, and efficiency. The model systematically reflects the structural optimization, carbon reduction, and operational efficiency of provincial power systems, thus offering a comprehensive approach to measuring power transition progress.
2. Conduct a spatial analysis of provincial power transition. Addressing the limitation of prior research that often remains at the macro level and overlooks regional disparities, it

examines 30 provincial-level regions in China through cross-sectional comparison and stratified analysis. The results identify distinctive regional characteristics in energy resource endowments, industrial structures, and power system development stages, thereby enriching the spatial perspective of provincial-level power transition research.

3. Reveal the temporal evolution of China's power transition. Using time-series analysis from 2011 to 2022, it identifies phased patterns and dynamic relationships among key dimensions, offering new empirical insights into the long-term evolution of the power transition.

The research framework of this paper is shown in Figure 1.

3 Indicators and methods

To address these challenges, this study examines data from 30 provinces for the period 2011–2022, utilizing provincial-level power system information. The study period is selected to ensure analytical consistency and policy relevance. The year 2011 marks the onset of China's Twelfth Five-Year Plan, when renewable energy development and carbon reduction targets were formally incorporated into national strategic planning—representing the institutional beginning of China's modern power transition. The year 2022 serves as the endpoint, providing the most recent complete and verifiable provincial dataset required for the Entropy Weight–TOPSIS analysis, thereby ensuring data consistency, integrity, and reliability.

3.1 Indicators

China's regional power transition, the selection of indicators in this study followed a top-down hierarchical process based on the principles of comprehensiveness, relevance, and data availability. The indicator selection processes are as follows:

Step 1: Framework definition. The overall structure of the indicator system was developed with reference to the World Economic Forum's Energy Transition Index (ETI) and China's dual-carbon policy goals. Accordingly, four first-level dimensions, Clean, Low-carbon, Secure, and Efficient, were identified to represent the core objectives of the energy transition. These dimensions correspond respectively to the goals of enhancing renewable substitution, reducing emissions, improving energy security, and optimizing system efficiency (Karpavicius et al., 2025; Yang Z. et al., 2024).

Step 2: Determination of second-level categories. For each primary dimension, secondary subcategories were designed to capture specific operational mechanisms of the power transition. Under Clean, the focus is on renewable energy generation capacity and installed renewable capacity, which directly indicate the degree of renewable energy integration into the power system (Sánchez et al., 2022; Qin et al., 2024). Under Low-carbon, carbon emission intensity, energy structure, and standard coal consumption measure the progress of decarbonization (Tziogas et al., 2019). Under Security, subcategories include energy elasticity, energy supply security, and system stability, which together describe the resilience and adaptability of the energy system (Du et al., 2024). Under Efficiency, power generation efficiency, energy utilization efficiency, and investment-economic coordination evaluate the productivity and economic quality of energy use (Wang et al., 2018).

Step 3: Selection of third-level indicators. The third-level indicators were chosen from authoritative statistical sources. Each indicator was required to (a) be measurable and regularly published at the provincial level; (b) have clear relevance to the second-level subdimension; and (c) collectively ensure that the entire framework reflects the integration of clean development, carbon reduction, energy security, and efficiency improvement.

In designing the indicator system, careful consideration was given to the conceptual coherence and analytical significance of each metric. For instance, both the "Electricity-GDP growth ratio" and the "Energy-GDP growth ratio" indicators are grouped under the same Energy Elasticity dimension but distinguished conceptually. The Electricity-GDP elasticity reflects the responsiveness of electricity consumption to economic growth, thereby measuring the degree of decoupling between energy use and GDP driven by electrification. In contrast, the Energy-GDP elasticity captures the overall dependency of total energy consumption on economic expansion. The comparison of the two provides deeper insight into the structural transformation from general energy dependency to electricity-led decarbonization.

Through this hierarchical organization, the 21 indicators collectively provide a comprehensive quantitative representation of the power transition process. They describe the effectiveness of energy structure optimization and emission reduction while also assessing the reliability, stability, and efficiency of system operations. This structure ensures that the framework captures the multidimensional quality of China's regional energy transition.

The specific indicators selected for this paper are shown in Table 1.

3.2 Entropy Weight-TOPSIS

To objectively evaluate the weighting of each indicator in the comprehensive assessment, this paper employs the Entropy Weight Method and the TOPSIS model for integrated calculation. The Entropy Weight Method assigns weights to indicators based on the degree of information dispersion, as measured by the entropy values of the indicator data (Wu et al., 2022). The TOPSIS model ranks alternatives based on their relative proximity to the ideal solution (Abootalebi et al., 2022), integrating both indicator weighting and comprehensive evaluation.

Entropy Weight Method is a data-driven approach grounded in information theory that effectively mitigates the influence

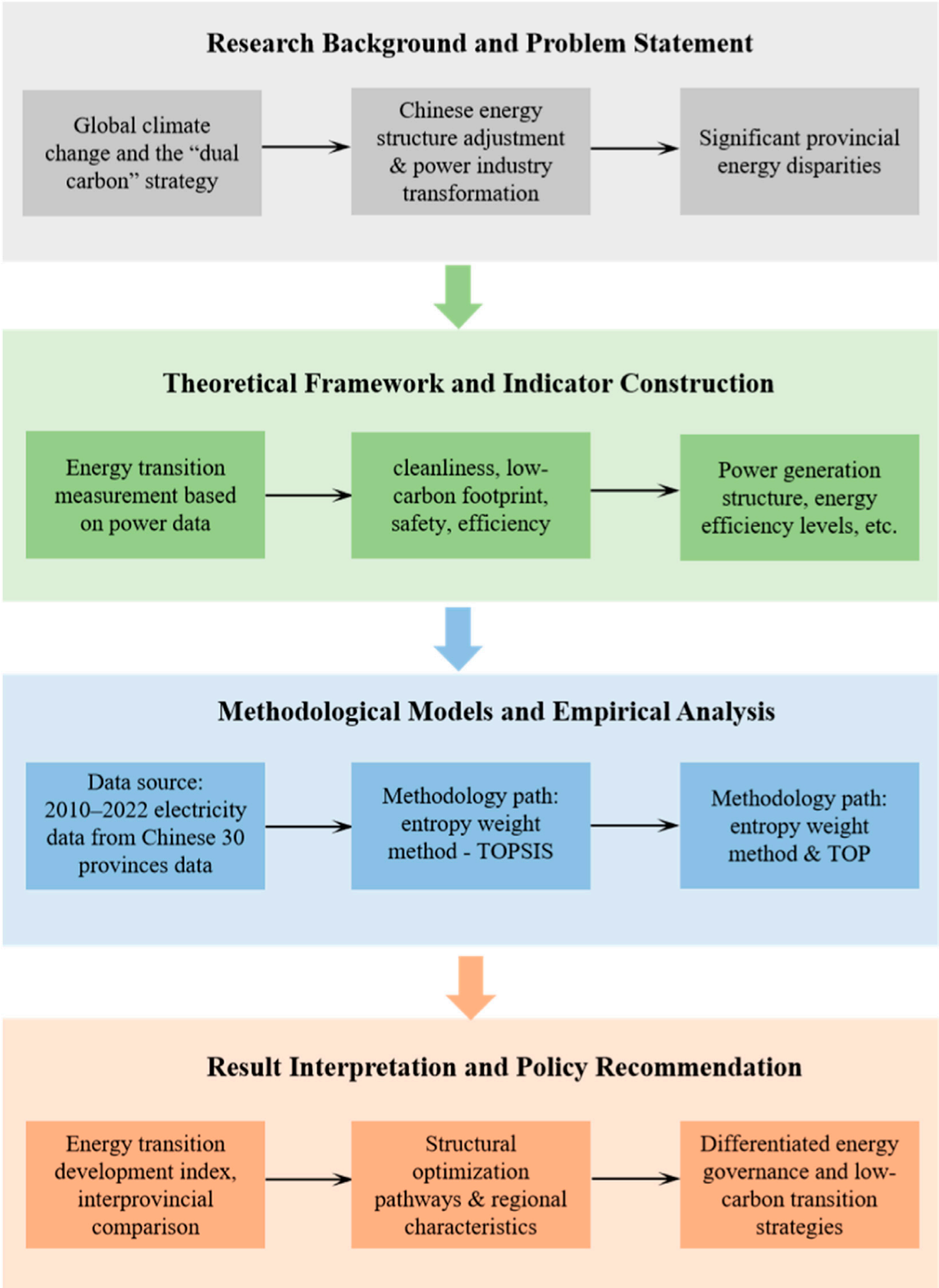

FIGURE 1
Framework diagram.

of subjective factors (Li et al., 2021). The greater the degree of dispersion in indicator values, the more information they provide and the more significant their impact on the comprehensive evaluation, and *vice versa*. The specific calculation steps are as follows.

Step 1: Calculate the information entropy, i.e., the information entropy value of the jth indicator e_j.

$$e_j = -k\sum_{i=1}^{n} P_{ij}\, ln\, P_{ij} \tag{1}$$

TABLE 1 Variables included in each indicator.

Dimension	Sub-dimension	Indicator	Formula	Unit	Direction	Data sources
Clean	Renewable energy generation capacity	Total renewable power generation	Renewable energy generation/Total electricity generation	100 million kWh	+	Sharma and Balachandra (2018)
		Share of renewable generation		%	+	Sharma and Balachandra (2018)
	Installed renewable capacity	Installed renewable capacity	Renewable energy installed capacity/Total installed capacity	Ten thousand kW	+	Sharma and Balachandra (2018)
		Share of renewable installed capacity		%	+	Tziogas et al. (2019)
Low-carbon	Carbon emission intensity	CO_2 emissions per kWh	Total energy consumption/Carbon emissions	Ton/kWh	-	Karpavicius et al. (2025)
		Total carbon emissions		Ten thousand ton	-	Cheng et al. (2025)
	Energy structure	Ratio of total energy use to carbon emissions		%	+	Fang et al. (2025)
		Level of electrification	Electricity consumption/Total energy consumption	%	+	Fang et al. (2025)
		Power generation standard coal consumption		g/kWh	-	Yin et al. (2019)
Security	Energy elasticity	Electricity use *per capita*	Electricity consumption/Total population	kWh/person	-	Karpavicius et al. (2025)
		Energy use *per capita*	Total energy consumption/Total population	Tons of standard coal equivalent/person	-	Du et al. (2024)
		Electricity–GDP growth ratio	Annual average growth rate of electricity consumption/Annual average growth rate of GDP	%	-	Yang Z. et al. (2024)
	Energy supply security	Energy–GDP growth ratio	Annual average growth rate of energy consumption/annual average growth rate of GDP	%	-	Yang Z. et al. (2024)
		Power generation *per capita*	Electricity generation/Total population	kWh/person	+	Karpavicius et al. (2025)
		Energy self-sufficiency rate	Energy generation/Energy demand	%	+	Du et al. (2024)
	System stability	Reserve capacity ratio of power system		%	+	Karpavicius et al. (2025), Lienhard et al. (2023)

(Continued on the following page)

TABLE 1 (*Continued*) Variables included in each indicator.

Dimension	Sub-dimension	Indicator	Formula	Unit	Direction	Data sources
Efficiency	Power generation efficiency	Ratio of power generation to installed capacity	Total electricity generation/Total installed capacity	%	+	Fang et al. (2025)
		Annual generation hours		Hours	+	Sharma and Balachandra (2018)
	Energy utilization efficiency	Electricity utilization efficiency	GDP/Electricity consumption	yuan/kWh	+	Fang et al. (2025)
		Employment share in the power industry	Electricity employment/Total employment	%	+	Qin et al. (2024)
	Investment–Economic coordination	Share of energy industry investment	Year-on-year growth in electricity fixed asset investment/GDP growth rate ratio	%	-	Qin et al. (2024), Yin et al. (2019)

i represents different provinces, j represent specific evaluation indicators. $k = \frac{1}{ln(n)}$ for $e > 0$

Step 2: Calculate the information utility value, i.e., the information entropy redundancy g_j of the jth indicator.

$$g_j = 1 - e_j \tag{2}$$

j represents evaluation indicators, g_j denotes the information entropy redundancy of indicator j, used to measure the relative importance of indicator j; the smaller e_j is, the larger g_j becomes, and the more important the indicator is.

Step 3: Calculate the weight w_j for the jth indicator.

$$w_j = \frac{g_j}{\sum_{j=1}^{m} g_j} \tag{3}$$

j represents evaluation indicators, m denotes the total number of indicators. This formula normalizes all indicators g_j to obtain weight w_j for indicator j.

Step 4: Calculate the composite score

$$S_j = \sum_{j=1}^{m} w_j x_{ij} \tag{4}$$

Step 5: Calculate the distance between the evaluation metrics and the positive ideal solution and negative ideal solution.

$$S_j^+ = \sqrt{\sum_{i=1}^{m} \left(Z_i^+ - Z_{ij}\right)^2 (i = 1, 2, 3 \cdots n)} \tag{5}$$

$$S_j^- = \sqrt{\sum_{i=1}^{m} \left(Z_i^- - Z_{ij}\right)^2 (i = 1, 2, 3 \cdots n)} \tag{6}$$

i represents an evaluation indicator, m denotes the number of indicators (m = 21), j represents different provinces.

Step 6: Calculate proximity

$$C_j = \frac{S_j^-}{S_j^+ + S_j^-} \tag{7}$$

3.3 Data sources

The dataset used in this study was compiled entirely from authoritative and publicly available official statistical yearbooks. Specifically, the data were obtained from the following sources:

1. *China Statistical Yearbook (2012–2023)*, published annually by the National Bureau of Statistics of China;
2. *China Energy Statistical Yearbook (2012–2023)*, compiled by the Department of Energy Statistics;
3. *China Electric Power Yearbook (2012–2023)*, published by the China Electricity Council;
4. *China Electric Power Industry Annual Development Report (2012–2023)*, issued by the China Electricity Council; and

The study covers the period from 2011 to 2022, encompassing 30 provinces, autonomous regions, and municipalities of mainland China. To ensure consistency across multiple data sources, the statistical calibers, definitions, and units were carefully cross-checked. All energy-related data were uniformly converted into tons of standard coal equivalent (tce) or kilowatt-hours (kWh) following the standards set by the National Bureau of Statistics' Energy Balance Table. Economic indicators, such as GDP and fixed asset investment, were adjusted to constant 2015 prices to eliminate inflationary effects and ensure temporal comparability.

The dataset is complete and contains no missing values. All variables were available for the entire observation period across all provinces, and no interpolation or estimation was required.

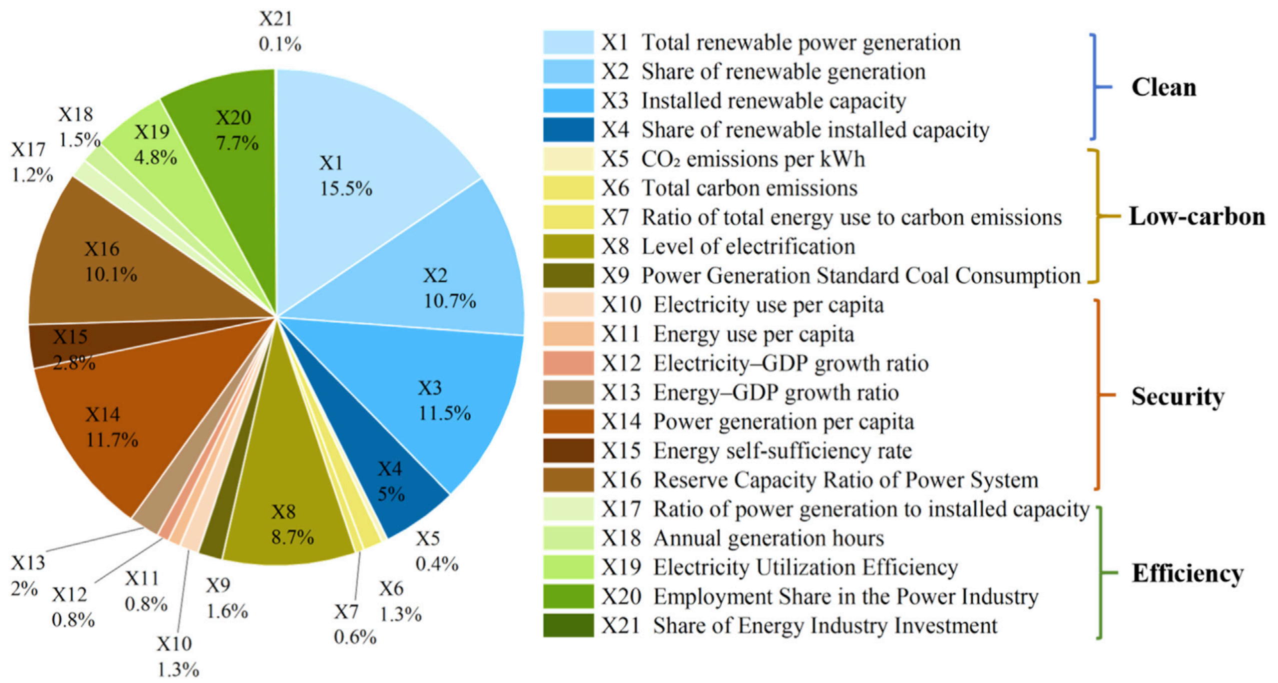

FIGURE 2
Entropy Weight for each indicator.

This unified data compilation process ensures that the indicator framework and subsequent empirical analyses are methodologically consistent.

4 Results

4.1 The development level of the national power transition

The weights for 21 specific indicators were calculated using the Entropy Weight Method (as shown in Figure 2). This result reveals the relative importance of various driving factors in the power industry during the energy transition process. Based on the total weight of primary indicators, the clean dimension (0.426) holds the highest weight, followed by the security dimension (0.295), efficiency dimension (0.154), and low-carbon dimension (0.125) in second, third, and fourth place respectively.

The clean dimension holds absolute centrality with a total weight of 0.426, indicating that developing renewable energy and optimizing power transition the energy structure are the primary prerequisites and solid foundation. Among these, total renewable power generation (X1, 0.155) carries the highest weight, significantly exceeding the share of renewable installed capacity (X4, 0.050). This reflects that the core of the clean energy transition lies in the actual scale of generation. Some regions possess substantial renewable energy installed capacity, yet their actual power generation contributions remain constrained by grid access limitations or technological bottlenecks, thereby affecting the efficiency and effectiveness of the power transition. This underscores the imperative to ensure incremental clean energy capacity expansion to meet growing energy demands, particularly against the backdrop of sustained growth in total energy consumption.

The weight of the security dimension (0.295) underscores the high priority of energy security during the transition process. Among its components, power generation *per capita* (X14, 0.117) carries the highest weight, reflecting a region's energy supply capacity and self-sufficiency. This indicates that sufficient power generation capacity serves as a ballast against various uncertainties during the transition, such as renewable energy fluctuations and extreme weather events. Furthermore, the high weight assigned to the reserve capacity ratio of the power system (X16, 0.101)—a key indicator of instantaneous system balance and reliability—underscores the growing importance of ensuring grid security and supply stability amid rising renewable energy penetration. Meanwhile, the extremely low weighting of the energy/electricity consumption elasticity coefficient (X12, X13) confirms that China's economic development during the study period has moved away from reliance on high-intensity energy and electricity inputs, significantly easing the pressure on energy security posed by its growth model.

The total weight of the efficiency dimension is relatively small at 0.153, but its internal indicators exhibit significant weight variations. The employment share in the power industry (X20, 0.077) emerges as the most influential factor within this dimension, revealing that a large professional workforce is the core element underpinning the planning, construction, operation, and technological innovation of

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the extensive power system. The high weighting of this indicator signifies that the concentration of talent in the regional power sector is closely linked to the efficiency of its transformation process. Concurrently, electricity utilization efficiency (X19, 0.048), serving as a measure of the sector's overall economic efficiency, holds the second-highest weight. This indicates that enhancing end-use electricity efficiency—driving greater economic output with reduced power consumption—represents a critical external pathway for supporting the efficient transformation of the power system. In addition, the weights of the share of energy industry investment (X21) and the ratio of power generation to installed capacity (X17) are both low, indicating weaker direct relevance to energy transition efficiency.

The low-carbon dimension had the lowest overall weighting (0.135), reflecting that China's power sector transition during the study period achieved emission reductions primarily through indirect pathways of clean energy adoption and efficiency improvements. Within this dimension, the ratio of electricity consumption to total energy consumption (X8, 0.087) holds absolute dominance, with a weight significantly higher than that of direct carbon emissions and carbon intensity indicators (X5, X6, X9). This demonstrates that elevating electrification levels on the energy consumption side is viewed as the most critical bridge to achieving deep low-carbonization across society. Only by achieving higher electrification levels can clean electricity from the generation side replace direct fossil fuel consumption on a large scale, thereby fundamentally reducing the carbon intensity of economic activities. Conversely, the low weighting of direct carbon emission indicators indicates that, during the phase where total electricity demand continues to grow, the primary challenge for China's power energy transition lies in optimizing the energy structure rather than direct emissions reduction (Suo et al., 2021).

4.2 Level of power transition development in each region

The power transition development index for each province (scores by dimension from 2011 to 2022) was calculated using an entropy-weighted TOPSIS model, as shown in Figure 3. The clean energy dimension exhibits the most polarized distribution pattern. Sichuan (0.306) and Yunnan (0.291) form the first tier with their high-quality hydropower resources, achieving clean energy scores nearly three times the national average. Provinces like Qinghai (0.182) and Hubei (0.198) constitute the second tier, demonstrating diversified clean development pathways that integrate wind and solar resources with hydropower. Notably, eastern coastal economic powerhouses like Guangdong (0.123) and Fujian (0.123), despite lacking resource advantages, achieved above-average clean scores by vigorously developing high-quality clean energy sources such as offshore wind power and nuclear power. Conversely, megacities like Shanghai (0.007), Tianjin (0.009), and Beijing (0.014) recorded extremely low clean energy scores, reflecting the disadvantages of urban economies in developing local clean energy resources.

From a security perspective, Ningxia (0.146), Hainan (0.142), and Inner Mongolia (0.139) rank among the top three. Their high security scores reflect the special responsibilities and investments required to ensure a stable energy supply. Traditional energy-rich provinces like Xinjiang (0.110), Shanxi (0.082), and Qinghai (0.083) also scored relatively high in security, highlighting their pivotal role in safeguarding national energy security. In contrast, economically prominent provinces such as Zhejiang (0.044) and Jiangsu (0.045) recorded lower security scores, potentially reflecting risks associated with high energy dependence on external sources. The low-carbon dimension exhibits a positive correlation with economic development levels. Qinghai (0.082) leads by a wide margin with nearly 100% clean electricity generation, while Beijing (0.074) ranks second through energy structure optimization and clean end-use energy. Economically advanced regions like Shanghai (0.042), Chongqing (0.041), and Zhejiang (0.040) excel in low-carbon performance, demonstrating the effectiveness of financial and technological advantages in emissions reduction. In stark contrast, traditional energy bases like Inner Mongolia (0.016), Shanxi (0.022), and Ningxia (0.025) rank at the bottom in low-carbon scores, highlighting the immense challenge of transforming high-carbon industrial structures. The efficiency dimension exhibits a dispersed pattern. Provinces like Beijing (0.063), Hubei (0.067), and Gansu (0.064) demonstrated strong performance, reflecting their leadership in energy technology and management innovation. Notably, provinces rich in clean resources like Yunnan (0.033) and Guangxi (0.039) scored relatively low on efficiency, potentially due to the negative impact of renewable energy's intermittency on system operational efficiency.

The synthesis scores for energy transition across 30 provinces ranged from 0.155 (Anhui) to 0.505 (Sichuan). By comparing the synthesis scores across provinces, China's 30 provinces can be categorized into three groups based on their power transition levels, revealing distinct transition patterns. The first category comprises provinces with a synthesis score greater than or equal to 0.28 characterized by clean energy dominance. Among these, Sichuan (0.505) leads the nation by a wide margin, with its performance in the clean energy dimension particularly outstanding, scoring 0.306—far surpassing other provinces. Yunnan (0.457) follows closely behind, achieving a clean energy dimension score of 0.291. This is primarily attributable to its superior renewable energy endowment and clean power generation structure. However, the current production-side carbon accounting fails to fully reflect the substantial low-carbon benefits it delivers to eastern load centers through the "West-to-East Power Transmission" initiative. This implies that, from a national system-optimal perspective, the transformation contributions of these provinces may be underestimated. Correspondingly, as the primary beneficiaries of clean electricity, eastern coastal provinces bear a more critical responsibility to reduce their reliance on distant power sources by enhancing end-use electricity efficiency (e.g., GDP per unit of electricity consumption), deepening demand-side response, and implementing industrial upgrading. Additionally, Qinghai (0.386) excelled in the low-carbon dimension, achieving the highest national score of 0.082, aligning closely with its high proportion of clean energy. Inner Mongolia (0.285) and Ningxia (0.288), exemplars of traditional energy base transformation, scored highly in the security dimension at 0.139 and 0.146, respectively, reflecting their unique role in safeguarding national energy security.

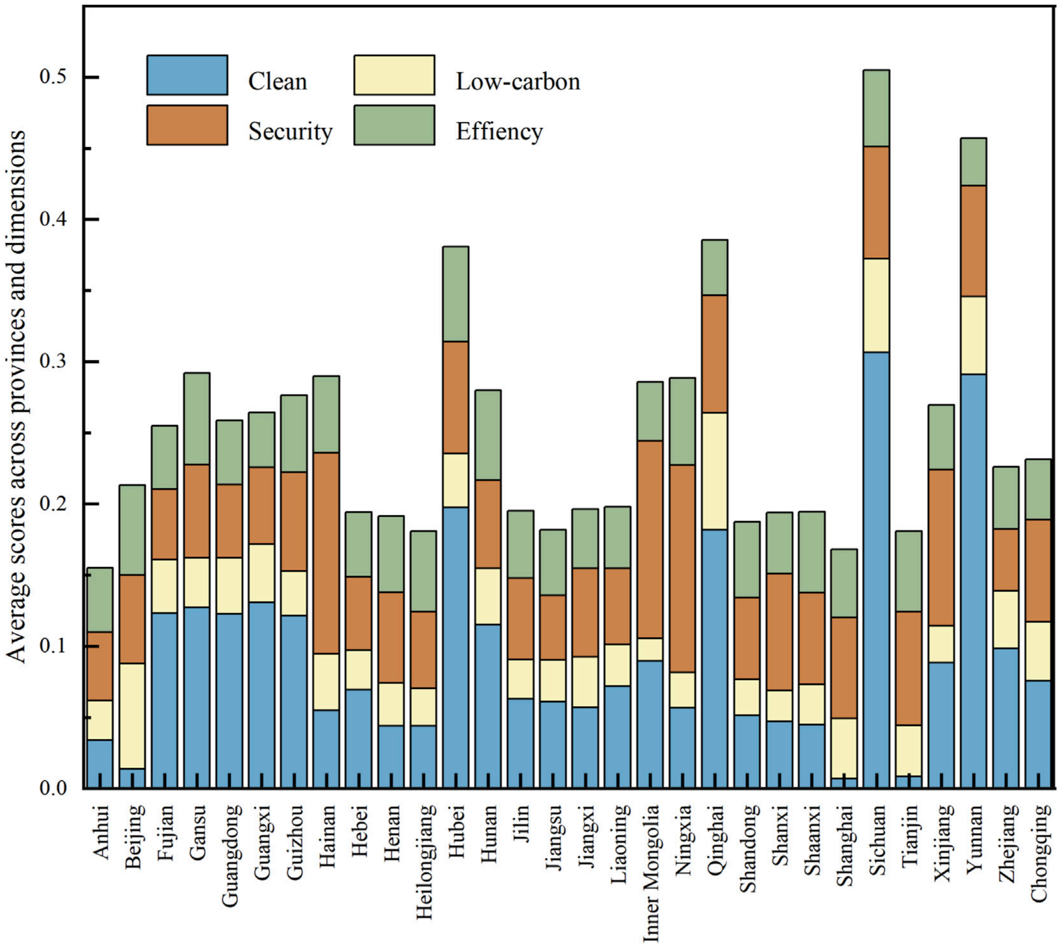

FIGURE 3
Synthesis score by dimension for each province.

The second category of provinces achieved composite scores ranging from 0.21 to 0.28. This group encompasses the majority of provinces, exhibiting significant internal variation. Hubei (0.381) stood out with a clean dimension score of 0.198, approaching the level of the top tier. Gansu (0.292) secured a high clean dimension score of 0.127, highlighting its success in developing wind and solar resources. Guangdong (0.259) and Zhejiang (0.225), as economically strong provinces, demonstrated balanced performance across all dimensions. Their clean energy dimension scores of 0.123 and 0.098, respectively, reflect a development path that compensates for resource constraints through capital and technological advantages. Xinjiang achieved a relatively high score of 0.110 in the security dimension, underscoring its crucial role as a national energy base. Hainan, capitalizing on its ecological island positioning and policy advantages, seeks breakthroughs in low-carbon and efficiency dimensions (Han et al., 2025).

The third category comprises provinces with a synthesis score below 0.20, classified as transformation-focused regions. Among these, Hebei, Shanxi, Liaoning, and Heilongjiang rely heavily on heavy industry and coal. Their substantial traditional energy assets and industrial structures impose significant burdens on their transition (Yang T. R. et al., 2024). Henan and Anhui, as major agricultural and populous provinces, have large energy consumption bases with strong growth rigidity. Limited local clean resources make their transition costly. Shanghai, highly dependent on imported energy with extremely limited local renewable development potential, relies more on external green power imports, cutting-edge energy efficiency technologies, and high-end service sector growth for its transition (Wei et al., 2025). Spatially, resource-rich western provinces lead the power and energy transition, while economically strong eastern coastal provinces rank mid-to-high. Central provinces, being energy importers and traditional industrial bases, face greater transition pressures.

4.3 Dynamic evolutionary trends in the power transition

The synthesis scores for overall power transition and scores across each dimension from 2011 to 2022 are shown in Figure 4. Overall, the comprehensive power transition capability of China's 30 provinces demonstrated a steady upward trend from 2011 to

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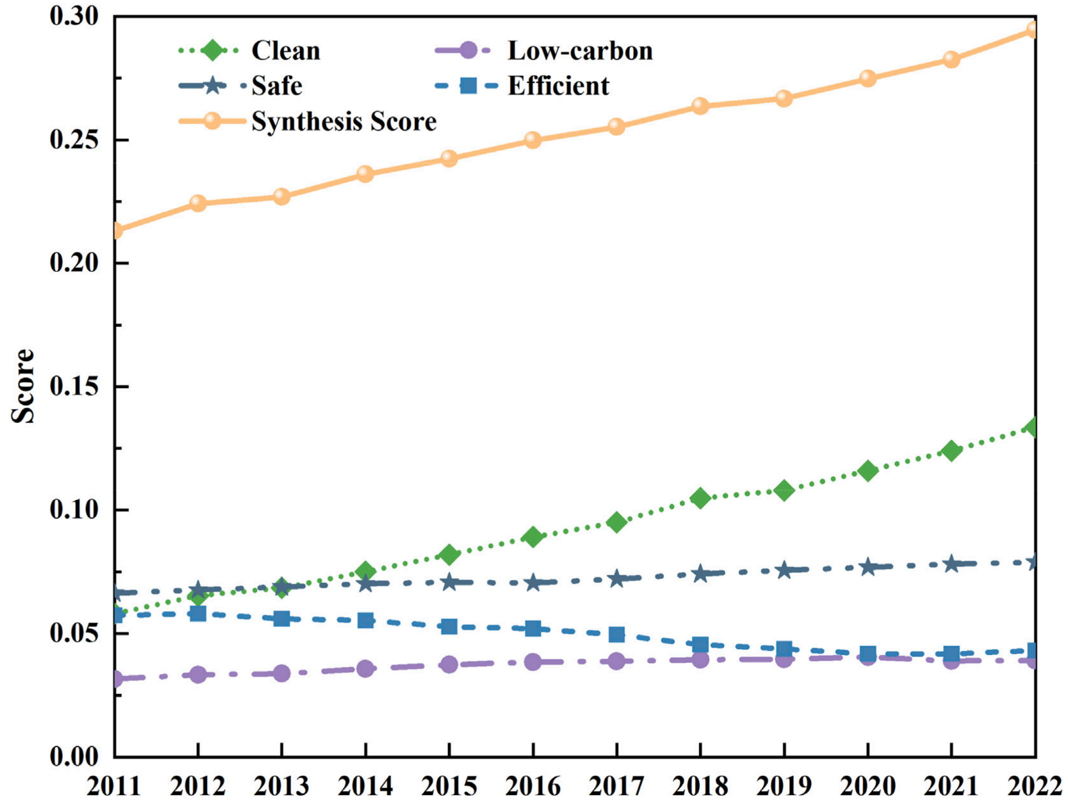

FIGURE 4
National power transition synthesis score, 2011–2022.

2022. The synthesis score rose from 0.213 in 2011 to 0.295 in 2022, representing an increase of 38.5%, indicating significant progress in the transformation of China's energy and power systems. The clean energy dimension saw a significant improvement in its score, while the security and low-carbon dimensions showed slight improvements. The efficiency dimension, however, experienced a decline.

The clean energy dimension score surged from 0.058 to 0.134, representing a staggering 131% increase. Both the growth rate and absolute increment significantly outpaced other dimensions. This not only confirms clean energy as the absolute main theme of this power transition but also highlights its role as the primary driver of overall score growth. This dimension's rapid growth directly stems from the strategic shift of renewable energy sources like wind and solar power from supplementary to primary energy sources. The trajectory demonstrates that China's clean transition successfully adopted incremental substitution as its primary model during the study period. By expanding the total volume of clean energy, it laid a solid foundation for optimizing the entire power system's structure. Future efforts should continue to strengthen support for renewable energy, including further expanding renewable energy installed capacity and enhancing grid integration capabilities for renewable energy.

The security dimension score has steadily increased from 0.066 to 0.079, demonstrating a robust yet gradual upward trajectory. As the second-highest-weighted dimension, its consistent improvement provides indispensable systemic stability to accelerate the clean energy transition. This trend indicates that, while vigorously developing intermittent renewable energy, China has not overlooked the role of traditional energy sources in ensuring supply security and in upgrading grid infrastructure. Per capita energy supply and system reliability continue to strengthen, providing a stable foundation for the transition. Therefore, efforts should persist in advancing energy infrastructure development, enhancing grid stability and reliability, while simultaneously reinforcing energy reserve systems to ensure a secure energy supply.

The low-carbon dimension score shows an upward trend but remains at a low level, rising slowly from 0.032 to 0.039. Its absolute value in 2022 was still less than one-third of the clean dimension score. This indicates that China has made some progress in emissions reduction, but the challenges facing the power system remain severe. Constrained by factors such as industrial structure and energy consumption patterns, the direct emission reduction effects have yet to fully materialize. There is an urgent need to advance deep structural adjustments in industries and accelerate energy conservation and emission reduction upgrades in high-energy-consuming sectors.

The evolution path of the efficiency dimension is most distinctive, exhibiting a U-shaped curve: starting from 0.057 in 2011, it fluctuated downward before bottoming out at 0.042 in 2021, then rebounded for the first time to 0.043 in 2022. The earlier sustained decline was closely linked to the large-scale grid integration of renewable energy. The increased share of power sources with low utilization hours, such as wind and solar, dragged down the overall utilization efficiency on the generation side. This reflects deficiencies in energy utilization efficiency, including insufficient technological innovation and room for improvement in energy management. Therefore, greater investment in energy technology innovation is needed to enhance energy utilization efficiency. The 2022 rebound may signal that China's power transition is gradually shifting toward balancing overall system operational efficiency. This progress stems from market-oriented reforms, accelerated construction of energy storage and peak-shaving facilities, and the application of smart grid technologies, which are beginning to unlock the potential for system optimization and quality-driven efficiency gains (Chen et al., 2025).

Analysis of the TOPSIS comprehensive rankings for provinces from 2011 to 2022 (Table 2) reveals significant variations in the rankings of 30 provinces regarding energy transition development during this period. Sichuan and Yunnan provinces have consistently ranked among the top two in most years, a phenomenon that underscores how abundant high-quality renewable resources provide an inherent advantage for transformation. Sichuan's mature hydropower development and Yunnan's complementary wind-solar-hydro systems have established stable clean energy supply chains. Ningxia, Qinghai, and Inner Mongolia have consistently ranked among the top performers (positions 3–7). These provinces not only possess abundant wind and solar resources but have also transformed their resource advantages into sustained transformation momentum through large-scale base development and early deployment of advanced energy storage technologies. Notably, Inner Mongolia, a major traditional energy province, has steadily climbed in the rankings (from 5th to 4th), demonstrating its successful exploration in coordinating the development of traditional and new energy sources. Xinjiang's ranking has steadily climbed from 17th in 2011 to 7th in 2022, highlighting its immense potential and late-mover advantage as a key national base for wind and solar power. Hebei leaped from 25th to 13th, while Shandong surged from 29th to 12th. These two major industrial provinces achieved rapid progress through vigorous industrial restructuring and breakthroughs in coastal nuclear power and offshore wind energy. Conversely, the declining rankings of Heilongjiang (24th to 28th) and Tianjin (18th to 30th) reflect the transformation challenges faced by traditional energy bases. Monotonous industrial structures, reliance on conventional energy pathways, and lagging development of emerging industries have intensified adjustment pressures during their transition. Tianjin 18th to 30th) reflects the transformation challenges faced by traditional energy hubs. Monolithic industrial structures, reliance on conventional energy pathways, and lagging development of emerging industries have imposed greater adjustment pressures during their transition. Provinces like Anhui have consistently ranked near the bottom, indicating significant obstacles in their energy transition—such as the dominance of high-energy-consuming industries within their industrial structure and insufficient investment in energy transformation (Zhang et al., 2022).

5 Discussion

This study quantifies the overall progress of China's power transition and the interprovincial disparities, while also uncovering the complex underlying driving factors that have shaped its evolution.

Firstly, in terms of the diversity and path dependence of power transition trajectories, the study identifies three distinct pathway models in China's power transition. These are: the resource endowment–driven type, represented by Sichuan and Yunnan; the economic–technological synergy type, exemplified by Guangdong and Zhejiang; and the security–cleansing balance type, typified by Inner Mongolia and Ningxia (Hu et al., 2025). These differentiated pathways vividly reflect the path dependence rooted in each region's initial conditions, such as its natural resource endowment, economic structure, and position within the national energy strategy. While resource-rich provinces lead in the clean dimension, they tend to have lower efficiency scores. For instance, Yunnan faces challenges in renewable energy integration and technological optimisation. In contrast, eastern coastal provinces leverage their capital and technological advantages to achieve a more balanced and resilient development path despite their limited local energy resources (Fang et al., 2025; Zheng et al., 2023).

Secondly, regarding the synergy and trade-offs among various objectives, the analysis of weights and scores indicates that clean currently serves as the primary driving force behind China's energy transition. Nonetheless, the significant emphasis on the security dimension, coupled with its strong performance in certain provinces such as Hainan and Ningxia, affirms that energy security remains the foundational baseline of the transition process (Kim et al., 2025). Amid ongoing growth in total electricity demand, merely expanding clean energy capacity is insufficient for achieving deep decarbonization (Qin et al., 2024). The electrification of end-use sectors and industrial restructuring are also essential. Furthermore, the U-shaped trend observed in the efficiency dimension throughout the study period suggests that initial efforts to enhance clean energy capacity temporarily diminished efficiency. However, as technological maturity and system flexibility improved, efficiency began to recover. These findings demonstrate that the multiple goals of the power transition are not always mutually reinforcing; rather, they may exhibit significant trade-offs at various stages. Consequently, an effective transition strategy must dynamically manage these interdimensional trade-offs to sustain progress and maintain balance.

Finally, in terms of regional equity and national coordination, the study reveals a clear west-high, central-medium, and east-low spatial pattern in terms of provincial power transition levels (Cai et al., 2025). This configuration reflects the objective distribution of energy resources, but also raises important questions about regional fairness and coordinated development. Western provinces primarily serve as national clean energy bases, yet the ecological costs they incur and the economic returns they receive from energy exports suggest that a more equitable compensation mechanism is required. The central region, as the industrial and energy consumption hub, is experiencing significant delays in transition that could hinder the achievement of national carbon neutrality goals. Therefore, establishing a nationwide

TABLE 2 TOPSIS comprehensive ranking analysis of provinces from 2011 to 2022.

Region/Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Anhui	30	30	30	30	30	30	30	30	30	29	29	29
Beijing	13	16	13	15	16	16	15	15	17	20	19	20
Fujian	16	14	16	14	14	9	10	10	11	13	13	11
Gansu	14	13	8	7	7	8	7	7	7	8	8	8
Guangdong	6	7	9	12	12	13	11	12	9	9	9	9
Guangxi	9	9	12	10	10	12	12	11	15	15	20	18
Guizhou	10	10	7	8	8	10	14	14	12	11	11	16
Hainan	11	11	10	9	13	11	9	8	10	10	10	10
Hebei	25	24	28	28	28	29	26	27	20	18	16	13
Henan	28	28	27	29	27	27	28	22	22	21	21	19
Heilongjiang	24	23	19	21	19	22	22	28	29	30	30	28
Hubei	2	2	3	3	4	3	3	3	4	4	4	6
Hunan	8	8	11	11	11	14	13	13	13	12	14	14
Jilin	19	19	18	20	21	19	29	25	28	26	26	25
Jiangsu	23	25	24	25	26	26	24	23	21	19	17	17
Jiangxi	22	22	26	24	25	23	25	29	25	25	25	26
Liaoning	26	26	22	22	22	20	21	20	23	24	23	23
Inner Mongolia	5	5	5	5	5	5	5	6	5	5	5	4
Ningxia	7	6	6	6	6	6	6	5	6	6	6	5
Qinghai	4	4	4	4	3	4	4	4	3	3	3	3
Shandong	29	29	29	27	29	28	20	21	16	16	12	12
Shanxi	21	20	21	19	20	21	18	18	18	17	18	21
Shaanxi	27	27	25	26	23	25	27	26	24	23	24	22
Shanghai	20	21	23	23	24	24	23	24	26	27	27	27
Sichuan	1	1	1	1	1	1	1	1	1	1	1	1
Tianjin	18	18	20	18	18	18	19	19	27	28	28	30
Xinjiang	17	17	14	13	9	7	8	9	8	7	7	7
Yunnan	3	3	2	2	2	2	2	2	2	2	2	2
Zhejiang	12	12	15	17	15	15	16	16	14	14	15	15
Chongqing	15	15	17	16	17	17	17	17	19	22	22	24

coordination mechanism based on the principle of common but differentiated responsibilities is crucial. Policy measures should promote industrial and regional integration, linking the technology and capital strengths of the eastern region with the resource and market advantages of the central and western regions, to foster a balanced and synergistic national energy transition.

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6 Conclusion and policy recommendation

To accurately assess the progress of China's power sector transition and reveal its spatio-temporal characteristics and regional disparities, this study combines the Entropy Weight-TOPSIS. Using 30 Chinese provinces from 2011 to 2022 as the research subjects, it establishes an index for China's power energy transition development based on four dimensions: "clean, low-carbon, security, efficiency." The study measures and compares the energy transition development levels across regions and years, providing a reference for formulating regional energy policies. Key findings are as follows:

1. The combined weight of the security and clean dimensions accounts for 72.1% of the total weight, forming the core pillars of energy transition. This underscores that the primary prerequisite and solid foundation for China's power energy transition remains ensuring adequate energy supply capacity, with clean energy serving as the core guiding principle. However, the power transition currently exhibits relatively low levels in the efficiency dimension (0.154) and low-carbon dimension (0.125), indicating that the current transition model has shortcomings in terms of system economic operational efficiency and immediate carbon emission reduction benefits.
2. The average comprehensive scores for energy transition across 30 provinces range from 0.155 (Anhui) to 0.505 (Sichuan). By comparing the comprehensive scores across provinces, China's 30 provinces can be categorized into three tiers based on their power transition levels. Spatially, resource-rich western provinces lead the electricity and energy transition, while economically strong eastern coastal provinces rank in the middle to upper tiers. Meanwhile, some energy-importing provinces and traditional industrial bases in central China face greater transition pressures.
3. From 2011 to 2022, the overall power transition capability of China's 30 provinces showed a steady upward trend, with the composite score rising from 0.213 in 2011 to 0.295 in 2022—an increase of 38.5%. This indicates significant progress in transforming China's energy and power systems. Specifically, the clean energy dimension saw substantial improvement, the security dimension grew steadily, the efficiency dimension continued to decline, while the low-carbon dimension remained largely stagnant. Significant disparities exist among provinces in their rankings for energy transition development.

These findings call for the development of policy options that integrate transition objectives with identified constraints:

1. Building upon the existing "safe-clean" energy base, incorporate "high-efficiency-low-carbon" incremental capacity. At the national level, top-level design must be refined, and interprovincial coordination mechanisms must be established to facilitate the transmission and consumption of renewable energy. It is recommended to implement a dynamic renewable energy quota system with regionally differentiated targets, thereby balancing clean energy development with energy system reliability.
2. Replace uniform targets with differentiated governance, promote region-specific and adaptive transition pathways. Findings indicate that western resource-based provinces are at the forefront of the transition, while central industrial and energy-importing regions encounter more significant challenges. Consequently, differentiated strategies are essential: western regions should prioritize grid interconnection, enhance storage capacity, and integrate renewable energy, whereas eastern and central regions must expedite industrial electrification, improve energy efficiency, and implement demand-side management. A tiered and regionally tailored approach will facilitate a balanced and coordinated national energy transition, curbing the further expansion of regional development gradients.
3. Focus on enhancing system operational efficiency and accelerating breakthroughs in low-carbon technology innovation. Low scores in efficiency and low-carbon dimensions reveal structural shortcomings in the current power system regarding operational economics and immediate carbon reduction capabilities. To address this, investments and development should be prioritized in smart grids, energy digitalization, and flexible dispatch systems to comprehensively improve overall efficiency across power generation, transmission, and consumption. Simultaneously, there is an urgent need to accelerate the research, development, and application of key low-carbon technologies such as Carbon Capture, Utilization, and Storage (CCUS). Furthermore, carbon pricing and green power trading mechanisms must be refined to provide sustained technological support and market incentives for building an efficient, low-carbon power system.

Coordinated implementation of these measures will not only advance the current level of national power transition but also narrow interprovincial disparities, thereby propelling the clean, low-carbon, safe, and efficient transformation of China's power sector.

7 Limitations and future directions

The primary limitation lies in its reliance on provincial-level macro data. While this analytical scale effectively identifies macro-regional patterns, it overlooks critical variations present at finer administrative levels (such as cities and counties). Factors influencing power transition, including local policy implementation, industrial structure, and resource availability, cannot be fully captured through a provincially aggregated perspective. Furthermore, while the established evaluation framework comprehensively covers established economic and environmental dimensions, it fails to adequately address two rapidly evolving critical areas: social equity and digital transformation. The framework does not systematically incorporate just transition indicators such as employment impacts, energy affordability, or community engagement. Similarly, the enabling role of digital technologies, including smart grids, data analytics, and platform economies, in modern energy systems remains underrepresented.

Consequently, the assessment results may fail to reflect the socio-technical complexity of contemporary transition processes fully. Finally, the carbon emission-related indicators (X5, X6, X7) in this study do not redistribute carbon flows associated with interprovincial power transmission. This may result in underestimating the low-carbon contributions of provinces with net clean energy exports while simultaneously underestimating the transition pressures faced by consumption provinces that heavily rely on external power inputs.

To overcome these limitations and advance research, future work can proceed along the following pathways. First, evaluations at the city and county levels should be conducted to achieve the granularity needed to reveal local drivers, innovative models, and governance challenges. Second, subsequent studies should proactively incorporate social equity indicators (such as distributional effects and participatory governance) and technological innovation metrics (including digital infrastructure and the integration of renewable energy with information and communication technologies). Expanding the framework in this direction will create a more comprehensive assessment tool capable of examining sustainable transition processes across economic, environmental, social, and technological dimensions. Collectively, these approaches will provide more detailed and robust decision support for planning sustainable and inclusive energy. Future research could construct a provincial-level electricity carbon flow matrix for China, employing consumption-side carbon accounting to achieve fair attribution of carbon emission responsibilities and transition benefits at a finer spatial scale. This approach would provide more spatially targeted policy insights.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZC: Funding acquisition, Conceptualization, Writing – original draft. QL: Software, Writing – original draft. YL: Data curation, Writing – original draft. CL: Writing – original draft, Resources. XX: Writing – original draft, Methodology. DL: Supervision, Writing – original draft. YT: Writing – original draft.

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Conflict of interest

Authors ZC, QL, YL, and CL were employed by State Grid Inner Mongolia Eastern Power Co., Ltd.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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