Evaluating Power Market Performance in China on Economic, Security and Environmental Perspectives

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Abstract. In recent years, China has undertaken two rounds of electricity market reforms, establishing provincial electricity markets. However, progress in market development varies across provinces. To provide a unified evaluation of the performance of electricity markets in various provinces, this study aims to construct a comprehensive evaluation system to assess performance from economic, security, and environmental perspectives. This study focuses on the regions governed by 26 power trading centers (excluding Tibet), employing the Analytic Hierarchy Process (AHP) to calculate indicator weights and collecting relevant data from each trading center for analysis. Indicators are linearly normalized and scored, followed by a weighted comparison of scores across provinces. The findings reveal relatively small differences in market development progress among the provinces. Nevertheless, the electricity market currently faces challenges in balancing the three dimensions of economic, security, and environmental performance, reflecting the "energy trilemma" of cleanliness, affordability, and stability. Moving forward, it is essential for the development of the electricity market to simultaneously consider these dimensions to ensure coordinated growth.

Keywords: electricity market reform; performance evaluation; energy trilemma

1 Introduction

China has the world's largest electricity sector, with 2.92 billion kW of installed capacity and 9224.1 billion kWh of electricity consumption in 2023. In 2002, China initiated the first round of power sector reform, splitting the state power company and establishing two major power grid operators and five major power generation companies. To further promote the marketization of the power sector, China launched the second round of electricity reforms in 2015. The reform so far has achieved a number of impressive outcomes. The role of the market in the resources allocation has been significantly enhanced, the wholesale and retail markets have been initially built, the transmission and distribution pricing system has gradually formed, and renewable energy has gradually entered the market. Currently, provincial-level markets across the country have been established, forming a diversified market structure centered on the medium and long-

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term electricity market, supplemented by the electricity spot market, ancillary services market, and capacity compensation mechanisms.

Although provincial electricity markets have been established, their development progress varies and lacks a unified evaluation standard. Additionally, future challenges in provincial electricity market development remain. Building an electricity market requires consideration of three dimensions: economic efficiency, supply security, and environmental sustainability. As a fundamental sector for national development, the cost of electricity impacts the development of various industries, making economic efficiency particularly important. Under the context of the carbon peaking and carbon neutrality goals, China places high importance on the contribution of the electricity industry to both domestic and global carbon reduction, emphasizing environmental sustainability. Energy security is a national security issue, making the security of the electricity system also highly significant.

Existing evaluations of electricity market reforms primarily focus on single dimensions, lacking systematic comprehensive assessments and indicator weighting analysis. For example, in terms of economic efficiency, previous studies have shown that reforms improve labor and fuel efficiency (Davis & Wolfram, 2012[1]; Du et al., 2013[2]; Malik et al., 2015[5]). Regarding supply security, Newbery et al. (2018) [7] suggested that increased system flexibility is needed to address the challenges posed by renewable energy, while Zheng et al. (2021) [10] found that although reforms enhanced technical efficiency, they reduced power supply reliability. In terms of environmental sustainability, Zhang et al. (2018) [9] noted that despite the challenges, reforms still contribute to the integration of renewable energy. Although some studies have employed the Analytic Hierarchy Process (AHP) to evaluate various aspects of electricity markets, there are still shortcomings in indicator weighting and accuracy. For instance, Montakhabi et al. (2022) [6] used AHP to assess the performance of green energy across different energy markets, and Jing et al. (2019) [3] evaluated market fairness and operational conditions using AHP. Yu et al. (2021) [8] combined intuitionistic fuzzy AHP to assess the credit risk of electricity retailers, while Liu et al. (2020) [4] integrated AHP with the entropy weight method (IEWM) for a comprehensive evaluation of the social, environmental, and economic dimensions of electricity markets. However, these comprehensive evaluation methods still have limitations in indicator weighting and accuracy. Existing research has not sufficiently considered the balance of multiple objectives and system integration, nor has it adequately quantified reform outcomes or provided horizontal comparisons across provinces.

This study aims to establish an indicator evaluation system and determine the weight of each indicator using the Analytic Hierarchy Process (AHP), conducting a comprehensive assessment of provincial electricity market development across three dimensions: economic efficiency, supply security, and environmental sustainability. By comparing the development levels of provincial electricity markets at a macro level, we propose relevant policy recommendations. The data used in this study cover 26 provinces under the jurisdiction of the State Grid (excluding Tibet), representing a horizontal assessment of provincial markets. The results show that the differences in the progress of electricity market development across provinces are not significant. Provinces that have advanced faster in the spot market tend to perform better in the economic dimension, but relatively weaker in the security dimension. Most provinces place significant emphasis on security, with high scores in this dimension. However, at the current stage, it is challenging for market development to simultaneously balance economic efficiency, security, and environmental sustainability, aligning with the "energy trilemma" of clean, affordable, and stable energy.

The significance of this paper is reflected in two key aspects. First, to the best of our knowledge, this is the first study to establish a comprehensive evaluation index system for electricity markets that covers the three dimensions of economic efficiency, supply security, and environmental sustainability, providing a thorough cross-sectional assessment of the performance of provincial electricity markets in China. This index system offers a solid foundation for future discussions on the progress of electricity market development, facilitating systematic comparisons between provinces and across different dimensions. Second, the paper provides a comprehensive overview of the current state of provincial electricity market development, helping provinces identify their specific issues and weaknesses, and offering strong support for further advancing power sector reforms in the future.

The remainder of the paper is structured as follows. Section 2 outlines the methods and data used in this study. Section 3 presents the conclusions. Section 4 presents the policy implications.

2 Materials and Methods

2.1 Construction of an Indicator System

This study has developed a performance evaluation indicator system for power market operations, focusing on three key aspects: economic efficiency, supply security, and environmental sustainability. As shown in Table 1, considering China's institutional background and policy objectives, this study has designed 23 specific indicators under these three dimensions to comprehensively reflect the construction and operation status of the power market.

Table 1. Electricity market operation evaluation index system.

Primary Indicators	Secondary Indicators	Tertiary Indicators
Economic efficiency	Market Price	Price Deviation
		Settlement Price Volatility
		Spot Peak-Valley Price Difference
	Market Scale	Proportion of Market-Based Transactions
		Market Participation Rate
	Market Structure	HHI Index
		Top-4 Share
		Platform Account Activity
		Price Cap Transaction Ratio
	Market Integration	Long-Term and Spot Market Integration
		Inter-Provincial and Intra-Provincial Integration

		Wholesale and Retail Market Integration
	Market Efficiency	Market Resource Allocation Performance
		Peak-Valley Difference in Network Load
Supply security	Supply Stability	Proportion of Long-Term Electricity Transactions
		Remaining Supply Rate (RSI)
		Annual Long-Term Contract Signing Rate
	Supply Adequacy	Market Supply-Demand Ratio
Environmental sustainability	Green Premium	Green Electricity Premium Level
	Green Scale	Proportion of Clean Energy Generation
		Proportion of Green Market Transactions
		Average Number of Green Certificates Purchased by Enterprises
		Market Contribution to New Energy Integration

The specific content of the economic efficiency dimension indicators is shown in Table 2. This study evaluates the economy efficiency dimension from five aspects: market price, market scale, market structure, market integration, and market efficiency.

Table 2. Definitions of economy efficiency dimension indicators.

Secondary Indicators	Tertiary Indicators	Index Definitions
Market Price	Price Deviation	The degree of deviation between the long-term average transaction price of different types of market entities and the market average price. The higher the deviation, the more competitive the market is.
	Settlement Price Volatility	This indicator reflects the volatility level of wholesale market prices.
	Spot Peak-Valley Price Difference	The ratio of the difference between the maximum and minimum clearing prices of spot transactions to the average clearing price. The greater the difference, the better the spot price reflects the real-time value of electricity.
Market Scale	Proportion of Market-Based Transactions	The ratio of market-based transaction volume to the total electricity consumption of society.
	Market Participation Rate	The participation of market entities in the market. The higher the market participation rate, the greater the proportion of market liberalization.
Market Structure	HHI Index	The smaller the HHI, the better the market competition.
	Top-4 Share	The larger the TOP-4, the higher the market concentration.
	Platform Account Activity	The activity level of accounts in provincial trading centers.
	Price Cap Transaction Ratio	The proportion of long-term transactions completed at price caps during the statistical period.
Market Integration	Long-Term and Spot Market Integration	The correlation coefficient between the average long-term transaction price and the spot transaction price.
	Inter-Provincial and Intra-Provincial Integration	The correlation coefficient between the average inter-provincial market transaction price and the intra-provincial market transaction price.
	Wholesale and Retail Market Integration	The correlation coefficient between the average wholesale market transaction price and the retail market transaction price.
Market Efficiency	Market Resource Allocation Performance	The absolute value of the correlation coefficient between the operating hours of coal-fired power units and the coal consumption per kilowatt-

		hour of the units. The smaller the coefficient, the better the market resource allocation effect.
	Peak-Valley Difference in Network Load	The ratio of the difference between the maximum and minimum net load of the entire network to the average net load. The smaller the difference, the better the optimization effect of user-side electricity usage.

The specific content of the supply security dimension indicators is shown in Table 3. This study evaluates the safety dimension from two aspects: supply stability and supply adequacy.

Table 3. Definitions of supply security dimension indicators.

Secondary Indicators	Tertiary Indicators	Index Definitions
Supply Stability	Proportion of Long-Term Electricity Transactions	The ratio of the sum of inter-provincial long-term transaction electricity volume and intra-provincial long-term electricity volume from local generation to the total provincial transaction volume. A higher ratio indicates relatively stable power supply.
	Remaining Supply Rate (RSI)	The sum of market shares of other suppliers except for the supplier in question during a specific period. The smaller the value, the stronger the supplier's ability to control the market.
	Annual Long-Term Contract Signing Rate	The ratio of annual transaction volume to long-term transaction volume.
Supply Adequacy	Market Supply-Demand Ratio	The ratio of the total available generation capacity of the entire market to the total load demand.

The specific content of the environmental sustainability dimension indicators is shown in Table 4. This study evaluates the green dimension from two aspects: green premium and green scale.

Table 4. Definitions of environmental sustainability dimension indicators.

Secondary Indicators	Tertiary Indicators	Index Definitions
Green Premium	Green Electricity Premium Level	The ratio of the difference between the average transaction price of green electricity during the statistical period and the local benchmark price of coal-fired power generation to the benchmark price of coal-fired power generation.
Green Scale	Proportion of Clean Energy Generation	The ratio of clean energy generation to the total electricity consumption of society.
	Proportion of Green Market Transactions	The ratio of market-based green electricity purchases by the demand side within the province to the total market-based transaction electricity volume.
	Average Number of Green Certificates Purchased by Enterprises	Total green certificates purchased/Number of industrial and commercial enterprises
	Market Contribution to New Energy Integration	Reflects the situation in which market-based methods promote renewable energy consumption when the renewable energy absorption rate changes, excluding guaranteed purchases

The raw data corresponding to specific indicators was sourced from the provincial power markets.

2.2 Weight Calculation

To assess the relative importance of each indicator, this study employs the Analytic Hierarchy Process (AHP) to assign weights to the indicators. The AHP method first decomposes the decision problem into different levels, including the goal level, criteria level, and indicator level. The goal level represents the highest tier and reflects the ultimate objective of the decision. The criteria level is the intermediate tier, including various standards and criteria needed to achieve the goal. The indicator level is the lowest tier and contains the specific indicators used to measure the criteria. In this study, the goal level focuses on the three objectives: economic efficiency, supply security, and environmental sustainability. The study constructs a judgment matrix based on the hierarchical structure in Table 1 and determines the relative weights of the indicators through pairwise comparisons, resulting in a weight survey questionnaire. Experts from power regulatory agencies, research experts from grid companies, and representatives of power market participants were invited to participate in the survey. The importance of different indicators was anonymously rated, and 58 valid questionnaires were collected. When calculating the weights of each indicator, we also conducted a consistency test of the indicators and determined the weights by solving the eigenvector corresponding to the largest eigenvalue. For inconsistent matrices, the normalized eigenvector corresponding to the largest eigenvalue was used as the weight. The final weights are shown in Table 5.

Table 5. Indicator weights in the evaluation system.

Primary Indicators		Secondary Indicators		Tertiary Indicators	
Economic efficiency	43.06%	Market Price	15.92%	Price Deviation	7.10%
				Settlement Price Volatility	5.24%
				Spot Peak-Valley Price Difference	3.58%
		Market Scale	7.29%	Proportion of Market-Based Transactions	4.29%
				Market Participation Rate	2.99%
		Market Structure	8.49%	HHI Index	3.38%
				Top-4 Share	2.10%
				Platform Account Activity	1.71%
				Price Cap Transaction Ratio	1.28%
		Market Integration	6.94%	Long-Term and Spot Market Integration	3.46%
				Inter-Provincial and Intra-Provincial Integration	2.18%
				Wholesale and Retail Market Integration	1.30%
		Market Efficiency	4.42%	Market Resource Allocation Performance	3.34%
				Peak-Valley Difference in Network Load	1.08%
Supply security	37.21%	Supply Stability	28.19%	Proportion of Long-Term Electricity Transactions	13.72%
				Remaining Supply Rate (RSI)	9.66%

				Annual Long-Term Contract Signing Rate	4.81%
		Supply Adequacy	9.02%	Market Supply-Demand Ratio	9.02%
Environmental sustainability	19.73%	Green Premium	3.91%	Green Electricity Premium Level	3.91%
		Green Scale	15.82%	Proportion of Clean Energy Generation	4.34%
				Proportion of Green Market Transactions	3.20%
				Average Number of Green Certificates Purchased by Enterprises	1.49%
				Market Contribution to New Energy Integration	6.80%

2.3 Determining Indicator Scores

After determining the weights, we perform linear normalization (discrete standardization) to standardize and assign scores to the indicators. Linear normalization is a linear transformation of the raw data, eliminating the influence of dimensions and magnitude, and mapping the data values within a specific range. In this study, the score range is set between [80, 100]. The formula for determining the score is shown in equation (1).

$$\text{Point} = 80 + \frac{x - \min(x)}{\max(x) - \min(x)} \times 20 \tag{1}$$

3 Results and Discussion

3.1 Comprehensive Scores

The comprehensive scores of each province are shown in Table 6. The term "province" in the charts of this paper refers to the areas governed by each provincial power trading center.

Table 6. Comprehensive score situation of each province.

Province	Economic efficiency	Supply security	Environmental sustainability	Comprehensive score
Sichuan	90.6	90.8	92.4	91
Fujian	86.1	95.7	92	90.8
Liaoning	84.5	93.9	87.4	88.6
Hunan	86.6	89.8	89.9	88.4
Hebei	87.3	92.9	80.7	88.1
Gansu	89.8	86.6	85.6	87.8
Jiangxi	85.4	95	79.4	87.8
Jibel	86.6	91.4	83.2	87.7
Shaanxi	84.5	91.8	86.1	87.5
Shanxi	89.6	86.3	85.1	87.5
Hubei	86.3	93.5	78.5	87.4
Anhui	84.8	93.6	79.6	87.1

Xinjiang	83.2	90.3	89.3	87.1
Jiangsu	84.9	93.9	78.9	87.1
Zhejiang	83.9	92.8	82.9	87
Heilongjiang	82.6	94	82.6	86.8
Chongqing	85	89.4	83	86.2
Tianjin	81.5	93	81.2	85.8
Mengdong	82.1	91.6	82.6	85.7
Henan	84.4	91.9	76.6	85.7
Jilin	81.3	93.5	79.5	85.5
Shanghai	83.1	90.6	77.1	84.7
Ningxia	84.8	87.1	78.5	84.4
Qinghai	79.9	84.4	87.6	83.1
Capital	80.1	89.8	76.5	83
Shandong	86.3	82	76.5	82.8

3.2 Economic Efficiency

Fig. 1 shows the scores of each province in terms of economic efficiency. The analysis of this dimension scores across provinces reveals the following conclusions.

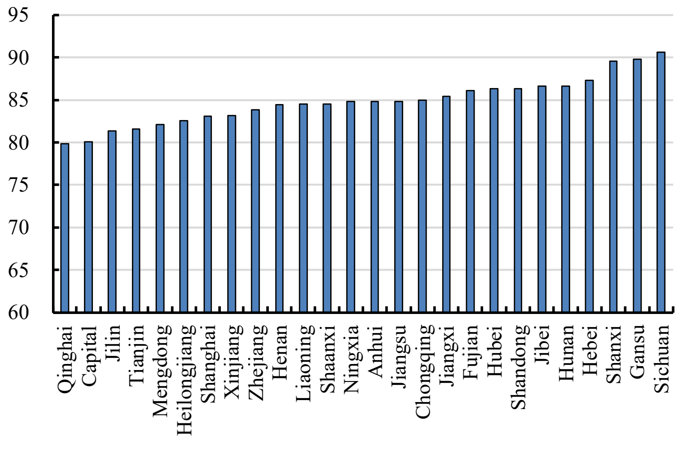

Fig. 1. Scores for economy efficiency dimension by province.

First, the score differences among provinces are relatively small, indicating that the development of the economic dimension is fairly consistent across regions. Sichuan has the highest score of 91, while Qinghai has the lowest at 80, with only a modest difference between them. This may be because, under the impetus of market mechanisms and policies, the improvement in economic efficiency across provinces has been relatively balanced, resulting in similar levels of development.

Second, provinces with more advanced spot market development generally achieve higher scores. For example, Shanxi, which has officially launched its spot market, scores 90 and ranks third. Gansu (90) and Shandong (86), which have conducted long-term continuous trials of the spot market, also score high. These provinces perform well in indicators such as spot peak-valley price differences and market integration. This can be attributed to their relatively well-developed market mechanisms, which enable spot market prices to accurately reflect real-time supply and demand, thereby optimizing resource allocation. Additionally, prices in the medium- and long-term market, wholesale market, and retail market are better aligned with the spot market, enhancing overall market integration.

3.3 Supply Security

Fig. 2 shows the scores of each province in terms of supply security. The analysis of this dimension scores across provinces reveals the following conclusions.

First, safety is the foundation of market construction, and provinces generally place significant emphasis on this dimension in market development, resulting in high scores across the board. For example, Fujian has the highest safety dimension score of 96, while Shandong, with the lowest score, is still at 82. Overall, 20 provinces scored above 90, accounting for 77% of the total.

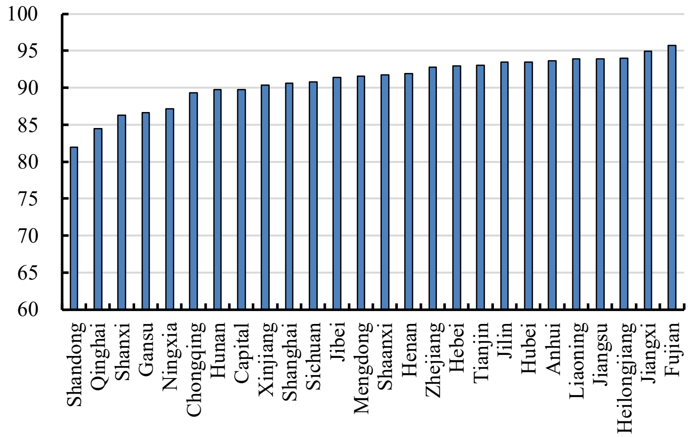

Fig. 2. Scores for supply security dimension by province.

Second, provinces with well-developed spot markets tend to have poorer performance in this dimension. For instance, Gansu (87), Shanxi (86), and Shandong (82) scored significantly lower than other provinces. This may be due to the high proportion of spot market transactions in these regions, which can lead to substantial fluctuations in electricity supply at different times. This variability can result in negative prices during periods of excess supply and shortages during periods of insufficient supply. Additionally, these provinces also have lower scores in proportion of long-term electricity transactions and annual long-term contract signing rate, indicating a difficulty in balancing spot and long-term markets in practice.

Third, the supply security scores of exporting provinces may be lower than expected, as being an exporter does not necessarily guarantee their own electricity safety. For example, Xinjiang (90), Ningxia (87), Gansu (87), Shanxi (86), and Qinghai (84) all have relatively low scores and rank lower overall. This might be because these provinces have committed to large amounts of electricity exports and are obligated to fulfill these contracts, which can lead to insufficient electricity supply within the province.

3.4 Environmental Sustainability

Fig. 3 shows the scores of each province in terms of environmental sustainability. The analysis of this dimension scores across provinces reveals the following conclusions.

First, there is a significant gap in the scores among provinces in this dimension. For example, Sichuan scored the highest with 92, while the capital scored the lowest with only 76. This may be related to differences in industrial structures and varying levels of willingness to purchase green electricity across provinces. For instance, Sichuan has abundant clean energy resources and a relatively concentrated industrial sector, leading to stronger demand and willingness among enterprises to purchase green electricity. In contrast, the capital's economy is mainly driven by the service and high-tech industries, with lower overall energy consumption, resulting in relatively lower demand for green electricity.

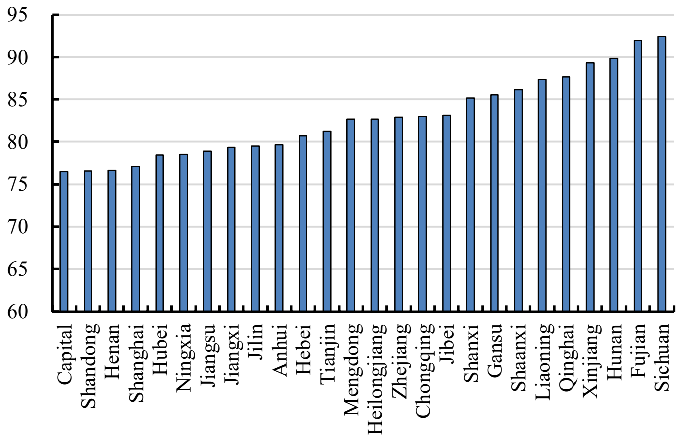

Fig. 3. Scores for environmental sustainability dimension by province.

Second, provinces with well-developed clean energy tend to perform better in this dimension. For example, Sichuan, which ranks first nationwide in hydropower capacity, scored 92, ranking first overall. Provinces with significant wind power capacity, such as Xinjiang (89), Jibei (83), and Mengdong (83), also performed well. Similarly, Xinjiang (89), Qinghai (88), and Gansu (86), which are rich in solar energy resources, achieved high scores. This is likely because these provinces have stronger renewable energy generation capacities, and their policies and infrastructure are more conducive to supporting clean energy development.

Third, provinces with large green electricity transaction volumes also tend to score well in this dimension. For example, in 2023, Jibei (83) had the highest green electricity transaction volume, reaching 19.65 billion kWh, accounting for 32.2% of its total transaction volume, ranking first nationwide. It can be observed that its performance is also relatively good. Its strong performance can be attributed to its more mature green electricity market mechanisms, which make it easier for electricity users to purchase green electricity, resulting in higher transaction volumes. Jibei's proportion of green market-based transaction electricity scored a full 100, further supporting this assumption.

4 Conclusions

4.1 Research Findings

Although the provincial evaluation results we have provided may not be perfect, they offer a valuable basis for discussion, allowing for a general comparison between provinces and drawing relevant conclusions.

First, the progress in market development across the provinces shows relatively small differences. It can be observed that the highest-scoring province is Sichuan (91), which performs well across all three dimensions, showing a balanced development. Fujian (90.8) and Liaoning (88.6) also perform excellently, particularly in the safety and green dimensions. The three provinces with the lowest comprehensive scores are Qinghai (83.1), the Capital (83), and Shandong (82.8).

Second, among the provinces with more advanced spot market development, some have achieved higher scores, while others are noticeably lower. For example, Gansu (87.8) and Shanxi (87.5) have performed well overall in the electricity market, whereas Shandong's score is only 82.8, significantly lower. Analyzing the scores across the three dimensions reveals that although Shandong performs relatively well in the economic efficiency dimension, it lags significantly behind other provinces in the supply security and environmental sustainability dimensions. This highlights the issues and areas for improvement in Shandong's future electricity market development.

Third, current market development faces the challenge of balancing three dimensions: economic efficiency, supply security, and environmental sustainability, akin to the "energy trilemma" of achieving cleanliness, affordability, and stability. For example, Jiangxi scores high in economic efficiency (85.4) and supply security (95) but has a significantly lower score in environmental sustainability (79.4). In practice, developing the electricity market often requires trade-offs. For instance, reducing energy costs might necessitate compromises in supply security and environmental sustainability; enhancing system safety and stability often limits the use of green energy. The prioritization and policy choices for each dimension inevitably impact the performance of the other dimensions, thereby affecting the overall performance of each province.

4.2 Policy Implications

Based on the research findings, we propose the following policy recommendations for the future development of the electricity market.

To further enhance economic efficiency, provinces should focus on optimizing market pricing mechanisms and advancing spot market reforms. Specifically, provinces with lower economic efficiency should improve market mechanisms to ensure that market prices more accurately reflect supply and demand conditions. Additionally, it is important to strengthen the integration of the spot market with medium- and long-term markets, wholesale markets, and retail markets to ensure price coordination and further optimize resource allocation.

Enhancing supply security remains a key task for the future. Provinces with lower supply security scores should increase investment in grid infrastructure, particularly by accelerating the replacement of aging equipment to improve the reliability of electricity supply. Additionally, the capacity pricing mechanism should be further promoted to mitigate the impact of spot market fluctuations on supply security, strengthening system stability and emergency response capabilities. Moreover, improving supply chain management will also enhance flexibility, contributing to a higher level of supply security.

To enhance environmental sustainability, especially in provinces with weaker green performance, it is recommended to accelerate the development and utilization of green energy. Provinces should focus on developing renewable energy sources such as wind and solar power to promote the green transformation of the energy sector. Additionally, efforts should be made to improve green electricity market mechanisms, encouraging businesses and individuals to actively purchase green electricity. Furthermore, supporting innovation and the application of clean energy technologies will help continuously increase the share of green electricity in the energy mix, thereby strengthening environmental sustainability.

The development of the electricity market requires a balance between economic efficiency, supply security, and environmental sustainability. When formulating policies, provinces should take all three dimensions into account to ensure coordinated development. High-performing provinces should be encouraged to share their successful experiences to help lower-performing regions improve. Additionally, implementing differentiated policies and tailoring optimizations based on each province's specific performance will contribute to the steady improvement of the overall electricity market.

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