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Measurement and Promotion Strategy of China's Power System Regulation Capacity

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Abstract: Power system regulation capacity is the key factor affecting the development and consumption of renewable energy. Based on China's policy to promote the consumption of renewable energy, this paper constructs an evaluation index system of power system regulation capability covering four dimensions: the supply side, grid side, load side, and support system. The entropy method is used to measure the power system regulation capability of 30 provinces during the 13th Five-Year Plan period. The results showed: (1) The national average power system regulation capacity index is 0.18, and only less than one-third of provinces scored higher than the average. (2) The contribution of each dimension is significantly different, and the supply side regulation capability was the highest (0.315). The regulation capability of the eastern region is stronger than that of the central region and the western region. From the perspective of subdivided fields, this study focuses on exploring five areas of power system regulation capacity construction, including electric vehicle energy storage, thermal power flexibility, regional power grid regulation, electric vehicle market, and grid construction, to tap greater development potential.

Keywords: power system regulating capacity; entropy method; regional heterogeneity; renewable energy consumption policies; environmental sustainability

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1. Introduction

In recent years, China's development of variable and renewable energy has been rapid. By 2019, China's cumulative installed capacity of wind power and photovoltaics reached 210 million kilowatts and 204 million kilowatts, respectively. Non-fossil energy accounted for 15.3% of energy consumption. Despite the rapid expansion of renewable energy generation, the power system is unable to effectively accommodate the newly added green energy, leading to significant curtailment of wind and solar power in some regions.

The main reasons for these issues lie in the other two important components of the power system: the grid and electricity demand, which have failed to keep pace with the rapid expansion of generation capacity. Regarding the transmission network, on the one hand, due to the physical characteristics of electricity being generated and consumed simultaneously, the grid cannot effectively store surplus green electricity. On the other hand, the regions with abundant green energy resources may not spatially align with areas of high electricity demand. Without a robust cross-regional transmission network, excess green electricity cannot be efficiently delivered to the areas that need it. In terms of electricity demand, both the demand and variable renewable energy exhibit strong fluctuations and randomness. The peak generation of green electricity often coincides with periods of low demand, making it difficult to integrate and consume green energy effectively.

In summary, simply increasing the scale of green electricity generation is not enough to significantly increase the proportion of green electricity in the power system. It requires the coordinated development of the transmission network and electricity demand side. Additionally, the support of the power industry and power market systems is necessary to ensure the development of these three subsystems. In 2018, the National Development and Reform Commission and the National Energy Administration of China jointly issued guidance [1] emphasizing the improvement of the power system's regulation capacity and operational efficiency. The focus is on enhancing system flexibility and adaptability from the demand side, power source side, and grid side, addressing the challenges of renewable energy integration and promoting green development. This demonstrates China's determination to develop a power system capable of accommodating more green energy.

To solve problems, it is essential to first identify them. To enhance the regulation capacity of a power system, it is necessary to clarify the elements involved and their relative impacts. Moreover, it is important to identify the regions where the power system requires particular attention and determine possible directions for development. Only with a clear direction can the power system be effectively developed and improved. Following this logical framework, this paper primarily aims to answer the following questions: 1. What is the essence of power system regulation capacity, and how should the evaluation system for power system regulation capacity be constructed? 2. What are the important factors influencing power system regulation capacity, and which ones have development potential and operability? 3. What is the level of power system regulation capacity in different regions of China, and how can they effectively enhance their power system regulation capacity from various aspects?

The existing research has mainly focused on evaluation systems that are similar to the concept of power system regulation capability. (1) Power system reliability: The safe operation of the power system forms the foundation for studying the power system regulation capability in this research. Early studies on the comprehensive evaluation of power systems primarily focused on power system reliability [2–5]. These evaluations considered various factors, including independent faults, common cause failures, correlated failures, weather effects, load curve models, uncertainty and correlation of bus loads, multi-area applications, fault sensitivity and repair rates, incoherence, and safety limits. (2) Power system flexibility: Building upon reliability, some studies have examined the evaluation of power system flexibility. Flexibility refers to the ability of the power system to handle changes and uncertainties in generation and demand, forming the basis for integrating variable renewable energy sources. Existing research has considered multi-objective and uncertainty factors [6], demand-side impacts [7], large-scale energy storage [8], investment and operating costs of power plants [9], among other factors. (3) Comprehensive evaluation system of power system: The power system regulation capability studied in this research is a comprehensive evaluation system of a power system. In addition to reliability and flexibility, it also encompasses economic and social factors that support power development. Existing research on comprehensive evaluation systems of power systems varies based on different research objectives, resulting in different evaluation frameworks. For example, Pu Tianjiao [10] considered factors such as power balance adequacy, optimized resource allocation, energy conservation and emission reduction goals, to construct a power balance evaluation indicator system. Zhou Yifan [11] depicted the regional power development level based on five aspects: economic-energy coordination, power generation level, power consumption level, power supply level, and power development potential. Shen Min [10] evaluated the power industry environment of a country by considering the current state of power development, the sustainability of the power industry, and power development potential. Hao Yongkang [10] established a comprehensive performance evaluation system for distribution network asset lifecycle management. Zhao Defu [12] evaluated the power development level of 11 countries from 17 aspects. Cui Jinrui [13] established a hierarchical evaluation system for power markets. Wang [14] summarized the theories and methods applicable to national economic evaluation of UHV power grid. Han [15] established an overall concept for the estimation of environmental impacts from PCPP under nominal and partial loads with combined thermodynamic analysis and life cycle assessment (LCA) methodology. He [16] constructed a comprehensive evaluation index system for the level of clean energy development by considering policies and regulations, energy supply, environmental impact, energy consumption, technology, economy and so on. Held [17] presented a Qualitative Comparative Analysis (QCA) of e-mobility policies in 15 European cities in order to identify policy configurations on the national and local, urban level. Ioannidis [18] estimated energy supply diversity and concentration for 44 islands in order to provide an island specific benchmark approach for energy supply security. Kucukvar [19] investigated material footprints of Turkey's and UK's national energy development plans by applying a global, multiregional input–output (GMRIO) model. Li [20] build the evaluation indicator system of the energy saving and emission reduction effects for electricity retailers and gained the combination weights by means of analytic hierarchy process and entropy weight method. Li [21] constructed a regional electrical energy substitution potential evaluation index system, based on comprehensive consideration of the influencing factors and regional differences in the potential of electrical energy substitution. Lin [22] proposed a risk identification and analysis model of NEPS based on the D numbers theory and decision making trial and evaluation laboratory (DEMATEL) method. Ji [23] considered four parts, the technical performance, economic benefit, ecological impact, and social benefit, and designed a multi-angle evaluation index system of the wind-PV-ES and transmission system.

Extant research is characterized by the following problems. First, most studies incorporate some indicators related to power system regulation capacity into the evaluation system. As a part of the overall evaluation goal, few studies focus on the problems related to power system regulation capacity, such as power peak shaving, green power consumption, and power system flexibility. Second, the existing studies lack richness in terms of data and fail to provide a comprehensive characterization and evaluation of multiple indicators in various regions. Third, the existing research index weights are mostly determined by a subjective weighting method, and the use of an objective weighting method is lacking. Fourth, most of the existing studies involve evaluations and comparisons between countries; however, few have been evaluated and analyzed within the context of Chinese provinces and regions.

Compared with previous studies, the advantages of this paper are as follows: First, we clarified the conceptual category of power system regulation capacity and constructed a hierarchical multi-index evaluation system by focusing on power system regulation flexibility carrying out a comprehensive assessment from the supply side, grid side, load side, and support system side. Compared to the research on the reliability and flexibility of power systems, the definition in this study is more comprehensive, with reliability and flexibility being sub-concepts studied in this paper. In contrast to other research on the comprehensive evaluation of power systems, the focus of this study is specifically on the regulation capability of the power system. Second, 34 different types of datasets from Chinese provinces were selected to characterize and evaluate the regulation capacity of power systems in each region. Compared to previous studies, this paper has made efforts to obtain a larger amount of industry data whenever possible. Third, the objective weighted entropy method was used to construct the evaluation system, which avoids the subjective bias caused by human factors. Fourth, from the regional perspective, this paper comprehensively considered factors such as coordinated development, resource endowment constraints and advantageous conditions, and provides suggestions for a development strategy for each region. While previous studies often focused on specific regions or countries as their research subjects, this study considers the relationships and variations among multiple regions.

The paper makes contributions in both technological innovation and practical problem-solving. In terms of technological innovation, it proposes a methodology for constructing an index system, identifying key indicators, and recognizing potential areas for improvement. This methodology enhances the accuracy and relevance of the evaluation method. The paper first constructs an index system and employs the entropy weight method to determine objective weights. Then, by considering objective weights as one dimension and incorporating a subjective dimension of importance based on reality, it jointly selects key indicators. Finally, based on the key indicators, clustering methods are utilized to identify potential areas for improvement. This methodology combines the objectivity of the entropy weight method with real-world information, resulting in a more accurate evaluation method. In addressing practical problems, the paper focuses on evaluating the regulation capability of a regional power system. It analyzes the concept and connotation of the power system regulation capability and constructs a three-level evaluation index system based on this analysis. By employing the entropy weight method, the paper identifies key indicators that affect the regulation capability of power systems. Additionally, it utilizes clustering methods to analyze potential key areas for improving and enhancing the regulation capability of power systems in different regions of China. The findings of this paper provide valuable guidance for the development of regulation capability in China's power systems.

2. Purpose and Direction of Power System Regulation in China

Based on the theoretical framework of power system composition and the practical needs of developing the power system in China [1], this paper provides the following definition for power system regulation capability:

Power system regulation capability refers to the ability of a power system to adjust the balance quickly and effectively between power generation and electricity consumption in the face of the variability and uncertainty of renewable energy and electricity load. It encompasses coordinated measures from the power generation side, power grid side, load side, and supporting systems, aiming to accommodate a greater amount of renewable energy, ensure electricity demand satisfaction, and maintain the safe and stable operation of the system.

According to this definition, this paper elaborates on the connotations of power system regulation capability from the perspectives of supply side, grid side, load side, and support system side.

Supply side: The development of power generation-side regulation capability needs to consider existing thermal power units, newly added flexible generation units, and the overall power generation scale. Improving the flexibility of existing thermal power units and enhancing their regulation capability can enable them to better cope with the variability of renewable energy. Optimizing the power generation mix and increasing the proportion of flexible power sources can provide more dispatchable electricity resources. Additionally, increasing the overall capacity can ensure that the system has sufficient generation capacity to balance supply and demand.

Grid side: To enhance the grid-side regulation capability, several aspects need to be considered, including coordinated development between power sources and the grid, interregional transmission capacity, and grid infrastructure. By strengthening the coordinated development between power sources and the grid, ensuring synchronized planning, implementation, and commissioning, it is possible to avoid investment and resource waste. Enhancing grid infrastructure, improving transmission stability, and focusing on the construction of power grids in key areas for renewable energy and ultra-high voltage transmission, as well as establishing interprovincial and interregional transmission corridors, can contribute to enhancing the grid's regulation capability. Simultaneously, undertaking distribution network construction and renovation, promoting the development of smart grids, can further improve the grid's flexibility and controllability. Developing shared peak-shaving and reserve resources within regional grids and expanding the space for renewable energy generation are also important measures to enhance the grid's regulation capability.

Load side: To enhance the load-side regulation capability, two main aspects need to be considered: flexible loads and load-side energy storage. Developing various types of flexible loads and advancing reforms on the demand side of electricity sales can enable rapid and flexible demand response, making the load more controllable. Improving the intelligence level of electric vehicle (EV) charging infrastructure and exploring the utilization of EV energy storage can not only promote the development of EVs but also provide potential for energy storage and flexible regulation. By increasing the deployment of flexible loads, such as demand response programs and smart appliances, and implementing reforms that allow consumers to actively participate in load management, the load-side regulation capability can be enhanced. Additionally, leveraging the role of EVs as mobile energy storage units can contribute to load balancing and grid stability.

Support system side: To achieve development in the aforementioned three areas, it is essential to concurrently develop the supporting systems, which mainly include the power equipment industry, compensation for ancillary services, and the power market. Improving the level of efficient and intelligent power equipment and promoting the development of key equipment technologies can enhance the performance and reliability of critical equipment for regulation capabilities. Enhancing the compensation mechanism for ancillary services and establishing a sharing mechanism for the participation of power generation companies and users in ancillary services can provide more flexible support to the power system's regulation needs. Establishing a power market that combines medium- to long-term contracts and spot market trading can leverage an elastic pricing mechanism to unleash the flexibility of the system. This facilitates optimized resource allocation and the effective operation of the market.

3. Index System, Data, and Methods

3.1. Index System of Power System Regulation Capability Measurement

In this section, we will construct the index system for assessing the regulation capability of the Chinese power system. The selection criteria for these indicators are primarily based on the following:

Based on the theoretical framework of power system engineering and the definition provided by the National Development and Reform Commission (NDRC) in consideration of China's specific context, the regulation capability of the power system is divided into four components: power source, power grid, load side, and supporting system.

Considering the definition of power system regulation capability and the specific contents of the four components discussed in Section 2, we select factors that may have an impact on the power system's regulation capability. This forms the basis for constructing secondary and tertiary indicators.

Finally, we consider the availability and feasibility of data sources and select indicators that have readily available and highly accurate data.

The finalized index system for assessing the regulation capability of the Chinese power system is presented in Table 1.

Table 1. Index system and weight of power system regulation capacity.

Primary Index	Secondary Index	Tertiary Indicators	Indicator Description	Attribute
A: Supply Side	A1: Thermal Power Flexibility	A11: Retrofittable Capacity of Thermal Power Units	Thermal Power Unit Capacity of 600,000 Kw and Below/Total Installed Capacity of Thermal Power	+
		A12: Coal Mine Density	Number of Coal Mines/Area	+
		A13: Standard Coal Consumption for Power Supply	Standard Coal Consumption Per Kwh	–
		A14: Decommissioning Capacity of Thermal Power Units	Decommissioned Installed Capacity of Thermal Power Units/Total Installed Capacity of Thermal Power Units	+

Table 1. *Cont.*

Primary Index	Secondary Index	Tertiary Indicators	Indicator Description	Attribute
A: Supply Side	A2: Flexible Regulation of Power Supply Construction	A21: Pumped Storage Capacity	Pumped Storage Capacity/Installed Capacity of Hydropower	+
		A22: Gas-Fired Power Generation Investment	Cumulative Investment in Gas Power Generation/Cumulative Investment in Thermal Power	+
	A3: Power Capacity	A31: Capacity-Load Ratio	Total Installed Capacity of Power Supply/Maximum Load	+
		A32: Unit Utilization Hours	Annual Total Power Generation/Installed Capacity of Power Generation Equipment	–
		A33: Power Purchase Cost	Total Electricity Purchase Cost/Electricity Purchase	–
		A34: Renewable Energy Power Capacity	Renewable Power Installed Capacity/Total Installed Capacity	–
		A35: Ratio of Renewable Energy to Thermal Power	Renewable Power/Thermal Power Generation	–
		A36: Renewable Energy Power Consumption	Renewable Power Consumption/Electricity Consumption	+
B: Grid Side	B1: Coordination Between the Source and The Power Grid	B11: Power Generation Per Unit Transmission Line Length	Power Generation/Transmission Line Length	+
	B2: Grid Construction	B21: Purchase and Sale Price Difference	Average Selling Price–On-Grid Price	+
		B22: Power Distribution Capacity	Transformer Capacity Below 1000 Kv/Area	+
		B23: Power Distribution Capacity	Transmission Line Length Below 1000 Kv/Area	+
		B24: Transmission Network Loss	Transmission Network Loss Rate	–
		B25: Reliability of Power Supply	35/66 Kv Power Supply Reliability	+
		B26: Shut-Down Time	Average Outage Time	–
		B27: Inter-provincial power output	Inter-provincial power output/Power Generation	+
		B28: Inter-provincial power input	Inter-provincial power input/Power Generation	–
		B29: Uhv Access	Uhv Grid Access/Power Generation	+
	B3: Intelligent Scheduling	B31: Industrial Power Consumption	Industrial Power Consumption/Total Power Consumption	+
		B32: Abandoned Wind Rate	Wind Abandonment Rate of Wind Power Generation	–
	B4: Grid Regulation	B41: Remaining Utilization Hours of Thermal Power	Designed Annual Utilization Hours of Thermal Power–Actual Utilization Hours	+

Table 1. *Cont.*

Primary Index	Secondary Index	Tertiary Indicators	Indicator Description	Attribute
C: Load Side	C1: Flexible Power Load	C11: Electricity Consumption	Electricity Consumption/Terminal Energy Consumption	+
		C12: Maximum Load Utilization Hours	Electricity Consumption/Annual Maximum Load	+
	C2: Electric Vehicle Energy Storage	C21: Electric Vehicle Quantity	Electric Vehicle Ownership/Civil Vehicle Ownership	+
		C22: Charging Points	Charging Points/Area	+
		C23: Internet Development	Number of Websites/Mobile Internet Users	+
D: Support Side	D1: Power Equipment Industry	D11: Electrical Machinery And Equipment Innovation	Electrical Machinery And Equipment Innovation/GDP	+
		D12: Electrical Machinery And Equipment Scale	Electrical Machinery And Equipment Scale/GDP	+
	D2: Power Ancillary Service Compensation	D21: Power Ancillary Service Compensation Cost	Power Ancillary Service Compensation Cost/Generated Energy	+
	D3: Power Market	D22: Power Market Scale	Medium- and Long-Term Electricity Direct Trading in Electricity Market/Total Trading Capacity	+

Note: The + and − signs in the attribute column indicate the positive and negative direction of the indicators. Positive indicators have bigger values indicating a stronger regulation capability of the power system Negative indicators have smaller values indicating a stronger regulation capability of the power system.

3.2. Data Sources

Due to the availability of data, this study selected data from different sources according to the 13th Five-Year Plan period (2016–2020) in order to construct a dataset for evaluating the power system regulation capacity.

The data used in this paper were sourced from the Statistical Data Collection of China's Power Industry, the China Power Yearbook, China Statistical Yearbook, China Science and Technology Yearbook, provincial statistical yearbooks, bulletins issued by the national energy administration, industry organizations and associations, and provincial news reports. Missing data were supplemented by linear interpolation. Tibet, Hong Kong, Macao and Taiwan were not included in the sample. The descriptive statistical data can be seen in Table 2.

Table 2. The descriptive statistics of the raw data.

Index	Number	Min	Max	Mean	Std.	Source
A11: Retrofittable Capacity of Thermal Power Units	30.00	0.22	1.00	0.59	0.18	"Compilation of Statistical Data on China's Electric Power Industry"
A12: Coal Mine Density	30.00	0.00	37.91	6.85	9.13	"China Statistical Yearbook"
A13: Standard Coal Consumption for Power Supply	30.00	209.00	393.00	310.87	26.72	"Compilation of Statistical Data on China's Electric Power Industry"
A14: Decommissioning Capacity of Thermal Power Units	30.00	0.00	0.07	0.01	0.01	"Compilation of Statistical Data on China's Electric Power Industry"

Table 2. *Cont.*

Index	Number	Min	Max	Mean	Std.	Source
A21: Pumped Storage Capacity	30.00	0.00	2.26	0.29	0.46	"China Electric Power Yearbook"
A22: Gas-Fired Power Generation Investment	30.00	0.00	1.00	0.16	0.31	"China Electric Power Yearbook"
A31: Capacity-Load Ratio	30.00	0.54	4.26	1.94	0.95	"China Electric Power Yearbook"
A32: Unit Utilization Hours	30.00	2578.00	4563.00	3691.03	473.01	"China Electric Power Yearbook"
A33: Power Purchase Cost	30.00	240.42	556.52	386.14	85.61	"China Electric Power Yearbook"
A34: Renewable Energy Power Capacity	30.00	0.05	0.86	0.39	0.22	"China Electric Power Yearbook"
A35: Ratio of Renewable Energy to Thermal Power	30.00	0.06	5.37	0.98	1.39	"China Electric Power Yearbook"
A36: Renewable Energy Power Consumption	30.00	0.06	0.83	0.29	0.21	"China Electric Power Yearbook"
B11: Power Generation Per Unit Transmission Line Length	30.00	0.00	0.09	0.04	0.02	"China Electric Power Yearbook"
B21: Purchase and Sale Price Difference	30.00	96.50	242.55	188.36	42.57	"China Electric Power Yearbook"
B22: Power Distribution Capacity	30.00	0.01	2.33	0.25	0.44	"China Electric Power Yearbook"
B23: Power Distribution Capacity	30.00	0.04	1.16	0.40	0.26	"China Electric Power Yearbook"
B24: Transmission Network Loss	30.00	2.89	8.72	5.92	1.44	"China Electric Power Yearbook"
B25: Reliability of Power Supply	30.00	99.62	99.94	99.80	0.08	"China Electric Power Yearbook"
B26: Shut-Down Time	30.00	5.28	33.59	17.39	6.87	"Compilation of Statistical Data on China's Electric Power Industry"
B27: Inter-provincial power output	30.00	0.00	0.53	0.18	0.16	"Compilation of Statistical Data on China's Electric Power Industry"
B28: Inter-provincial power input	30.00	0.00	0.98	0.15	0.21	"Compilation of Statistical Data on China's Electric Power Industry"
B29: Uhv Access	30.00	0.00	0.64	0.04	0.12	News reports and bulletins from various provinces
B31: Industrial Power Consumption	30.00	0.29	0.90	0.67	0.13	"China Electric Power Yearbook"
B32: Abandoned Wind Rate	30.00	0.00	0.43	0.07	0.12	"China Electric Power Yearbook"
B41: Remaining Utilization Hours of Thermal Power	30.00	0.09	2.91	0.49	0.55	"China Electric Power Yearbook"
C11: Electricity Consumption	30.00	0.09	0.25	0.17	0.04	"China Statistical Yearbook"
C12: Maximum Load Utilization Hours	30.00	3292.99	10,406.62	6219.30	1577.09	"China Electric Power Yearbook"
C21: Electric Vehicle Quantity	30.00	0.00	0.07	0.01	0.02	News reports and bulletins from various provinces
C22: Charging Points	30.00	0.00	6.45	0.45	1.30	News reports and bulletins from various provinces
C23: Internet Development	30.00	0.00	0.02	0.00	0.00	"China Statistical Yearbook"
D11: Electrical Machinery And Equipment Innovation	30.00	0.00	0.00	0.00	0.00	"China Science and Technology Yearbook"
D12: Electrical Machinery And Equipment Scale	30.00	0.01	0.20	0.06	0.05	"China Science and Technology Yearbook"
D21: Power Ancillary Service Compensation Cost	30.00	0.74	2390.03	115.08	432.13	News reports and bulletins from various provinces
D22: Power Market Scale	30.00	0.00	75.00	28.80	17.92	Data released by provincial electricity markets.

3.3. Methodology

3.3.1. Research Process and Flowchart

Based on the essence of power system regulation capability, this paper first constructs an objective evaluation system for power system regulation capability, calculates the objective weights of evaluation indicators, and then combines the reality and logical analysis to classify the development potential of the indicators. Based on the analysis of objective weights and development potential, key indicators with high weights and strong development potential are identified. Finally, through cluster analysis, the positions of each province in these key indicators are analyzed, and potential development areas with development potential and high efficiency in improving power system regulation capability are identified.

The specific research flowchart is as follows (Figure 1).

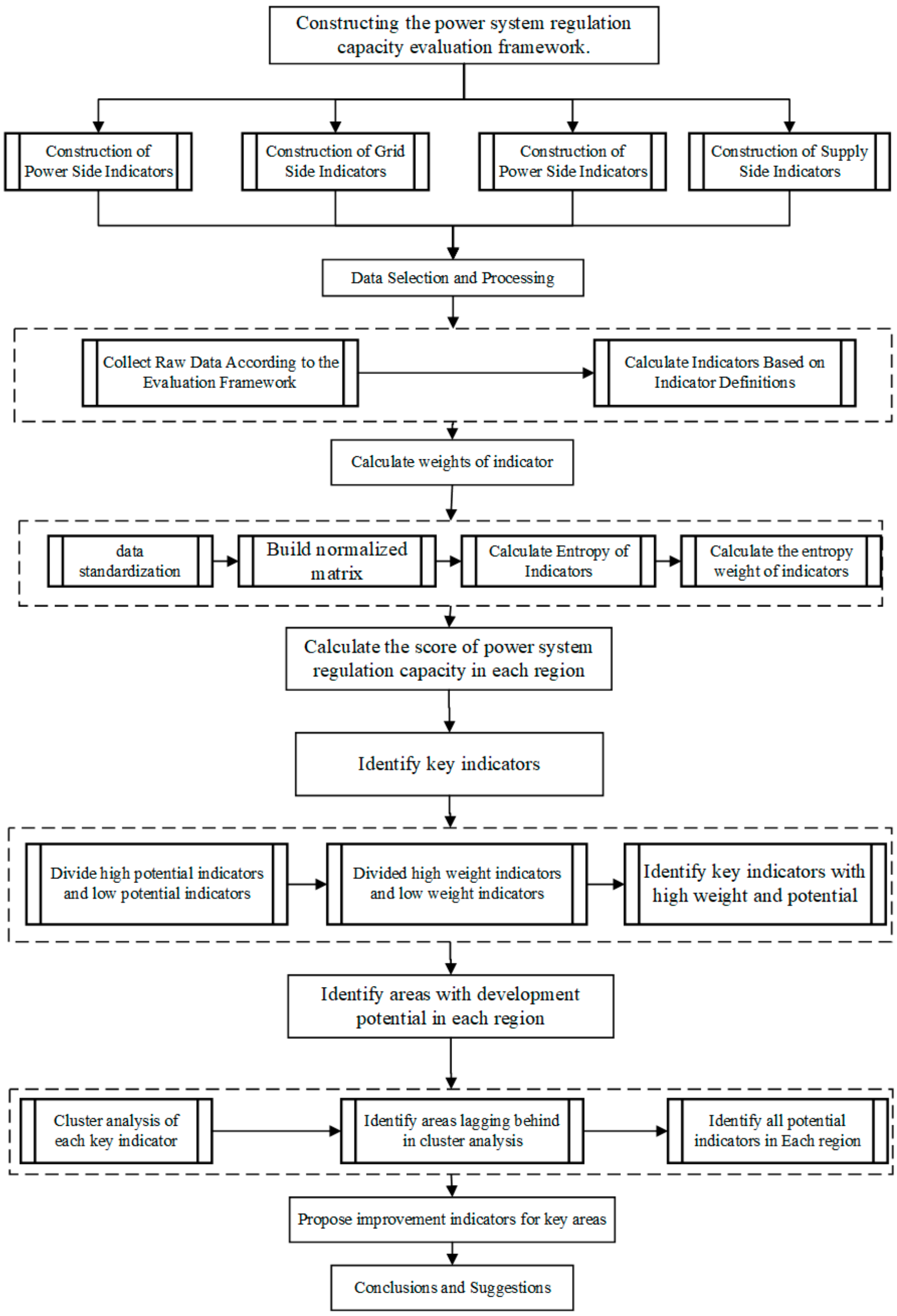

Figure 1. The flowchart of the research.

3.3.2. Calculation of Weights for Power System Regulation Capability Indicators and Scores for Power System Regulation Capability of Each Province

This article employs the entropy weight method to measure the power system regulation capability of 30 provincial-level divisions in China. Entropy was originally derived from the field of thermodynamics as a concept. Claude Shannon first introduced the concept of entropy into information theory and referred to it as information entropy [24]. The information entropy defined by Shannon is a concept independent of thermodynamic entropy but possesses the fundamental properties of thermodynamic entropy, known as generalized entropy. The entropy weighting method is an objective weighting approach that calculates the entropy weight of each indicator based on the degree of variation of each indicator. It then adjusts the weights of each indicator through entropy weighting, resulting in a more objective indicator weight.

The fundamental theory of information theory suggests that information is an objective measure of the level of order in a system, while entropy is an objective measure of the level of disorder in a system. The magnitudes of both quantities are equal, but they have opposite signs, making them a pair of opposites. If a system can be in multiple different states, with each state occurring with a probability of $P_i(\mathrm{i} = 1, 2, ...n)$, then the entropy of that system is defined as $H(X) = -\sum P(x)ln(P(x))$.

In the equation, $H(X)$ represents the entropy of the random variable X, and $P(x)$ represents the probability of the random variable X taking the value x.

The product $P(x)ln(P(x))$ calculates the product of the probability and its logarithm for each possible value. Summing up the results for all possible values and taking the negative of it yields the entropy of the random variable X.

In the calculation formula of entropy, the logarithmic function is used to emphasize the relative change in probabilities rather than absolute change. This is because the logarithmic function has a compressing and amplifying effect, which can amplify smaller probability values while compressing larger probability values, making their impacts more balanced.

In this article, the indicators are standardized based on whether they have a positive or negative impact on the regulation capability of the power system. Higher values of positive indicators indicate a stronger regulation capability of the power system, such as the amount of ultra-high voltage access and the volume of long-term direct electricity transactions in the power market. Specific positive indicators are marked in Table 1.

This article utilizes the entropy weight method to calculate the weights of the indicators of the power system regulation capability. Subsequently, the scores for each province are determined based on these weights. The specific steps are as follows:

(a) Perform extreme value normalization on the raw data.

$$x_{ij} = \frac{r_{ij} - min\{r_{1j}, \ldots, r_{nj}\}}{max\{r_{1j}, \ldots, x_{nj}\} - min\{r_{1j}, \ldots, r_{nj}\}} \quad (1)$$

Negative indicators have smaller values indicating a stronger regulation capability of the power system, such as wind curtailment rate and unit purchasing cost. Specific negative indicators are marked in Table 1.

$$x_{ij} = \frac{max\{r_{1j}, \ldots, r_{nj}\} - r_{ij}}{max\{r_{1j}, \ldots, r_{nj}\} - min\{r_{1j}, \ldots, r_{nj}\}} \quad (2)$$

(b) Construct the normalization matrix P_{ij}.

P_{ij} represents the proportion of the j-th indicator in the i-th region, which, in the context of information theory, can be interpreted as the probability of occurrence or the weight of that indicator.

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \quad (3)$$

The validity of Formula (3) is based on the following assumptions. 1: All indicators have a positive orientation. 2: The indicator values between the evaluated objects are comparable. 3: The evaluated objects have equal importance. Step (a) ensures the validity of assumptions 1 and 2. Following the fundamental idea of the entropy weight method, which focuses solely on evaluating the evaluated objects based on objective data, we maintain this assumption, considering equal importance among the evaluated objects.

(c) Calculate the entropy value E_j for the j-th indicator.

Zelany initially proposed the use of entropy to assess the importance of indicators to aid in decision-making. He provided a definition for indicator weights: "A weight, assigned to the i-th attribute as a measure of its relative importance for a given decision problem, is directly related to the average intrinsic information, generated by a given set of alternatives through the i-th attribute, as well as to its subjective assessment by the decision maker" [25,26]. Therefore, when calculating the relative importance of indicators, the traditional entropy measurement method is adjusted as follows:

$$E_j = -k\sum_{i=1}^{n} P_{ij} ln\left(P_{ij}\right) \tag{4}$$

where $k > 0$ and $E_j \geq 0$. Additionally, if $P_{ij} = 0$, it is necessary to specify $P_{ij}\ln\left(P_{ij}\right) = 0$.

When all x_{ij} are equal for a given j, then $p_{ij} = \frac{1}{n}$, and E_j reaches its maximum value, denoted as $E_{\mathrm{j}_{max}}$. It is evident that $E_{\mathrm{j}_{max}} = \mathrm{k}\ln n$. If we set $k = \frac{1}{\ln n}$, then $E_{\mathrm{j}_{max}} = 1$ and $0 \leq E_j \leq 1$ for all $j \in J$. This normalization of entropy values facilitates comparative analysis. Therefore, we set $k = \frac{1}{\ln n}$.

(d) Calculate the entropy weight ω_j for the j-th indicator.

The value $1 - E_j$ represents the inherent contrast intensity of j-th indicator [26]. The higher the $1 - E_j$ is, the more important the j-th indicator is for the power system regulation capability [27–29]. The objective weight for each index can be obtained by

$$\omega_j = \frac{1 - E_j}{\sum_{j=1}^{m}\left(1 - E_j\right)} \tag{5}$$

where m is the number of indicators.

(e) Calculate the power system regulation capacity T.

$$T_i = \sum_{j=1}^{m} \omega_j P_{ij} \tag{6}$$

3.3.3. Identification of Key Indicators for Power System Regulation Capability

Since entropy does not reflect the subjective importance of indicators but rather depicts the amount of information contained objectively, it may not be entirely applicable in real situations. On the one hand, some indicators with high entropy weights may be constrained in certain regions due to resource endowments and other reasons preventing their development. On the other hand, some indicators with low entropy weights may be a result of provinces being in a common low development stage. Therefore, in this paper, based on the real situation and experiential judgment, indicators are further categorized into high-potential and low-potential indicators according to their development potential. By combining these categories with entropy weights, it becomes possible to identify key indicators that have both high weights and high potential.

Specifically, this paper establishes three main criteria for categorizing indicators into high potential and low potential:

(a) Whether the indicator is decisively influenced by resource endowments. Indicators that have an upper limit determined by resource endowments are classified as low-potential indicators. Examples of such indicators include installed capacity of gas and hydro power and regional coal mine density.

(b) Whether further investment in the indicator brings relatively low economic benefits. Some indicators have already reached high levels in all provinces, and the potential for further improvement and the associated benefits are limited. Therefore, they are considered low-potential indicators. Examples of such indicators include the capacity for retrofitting thermal power units, power consumption per unit of standard coal, unit utilization hours of power units, maximum load utilization hours, unit purchasing cost of electricity, average price difference between purchased and sold electricity, electricity generation from transmission lines per unit length, power supply reliability, transmission network loss rate, and average power outage duration.

(c) Whether the indicator represents new development directions for power system regulation capability. Certain indicators related to new energy technologies, power market development, and other relevant factors, should continue to be developed regardless of the regional development level. Therefore, they are considered high-potential indicators. Examples of such indicators include the amount of ultra-high voltage grid connections, inter-provincial transmission volume, compensation cost for power ancillary services, volume of medium to long-term direct electricity transactions in the power market, number of charging stations, number of electric vehicles, level of internet development, proportion of renewable energy power consumption, scale of electrical machinery and equipment manufacturing industry, and investment in R&D in the electrical machinery and equipment manufacturing industry.

For indicators not mentioned above, they are considered high-potential indicators to avoid potential omissions during the selection process.

The high-potential indicator set mentioned above is defined as $IP_h = \{j|jis\ a\ high-potential\ indicator\}$, and the low-potential indicator set is defined as $IP_l = \{j|j\ is\ a\ low-potential\ indicator\}$. Based on the median weight M_ω, indicators with weights greater than the median are considered high-weight indicators, and their set is defined as $IW_h = \{j|\omega_j \geq M_\omega\}$. Indicators with weights less than the median are considered low-weight indicators, and their set is defined as $IW_l = \{j|\omega_j < M_\omega\}$.

Finally, the identified key indicators are the intersection of high-potential indicators and high-weight indicators, which is the set of key indicators $IK = IP_h \cap IW_h$.

3.3.4. Identification of Key Areas for Power System Regulation Capability in Each Region

In this paper, the K-means algorithm is used to perform cluster analysis on the data $x_{i,j_{IK}}(i \in I)$ of each key indicator $j_{IK} \in IK$. Each indicator is clustered into K clusters, denoted as S_k, where $k = 1, 2, \ldots K$, K is the predetermined number of clusters, and then the mean of each cluster is calculated. The region belonging to the cluster with the lowest mean is identified as the region with development potential in that indicator. For these regions, the indicator is recognized as a key development indicator for those regions.

The specific steps for each key indicator $j_{IK} \in IK$ are as follows:

(a) Initialization: Randomly select K initial cluster centers μ_k, where $k = 1, 2, \ldots K$.

(b) Assign data points: Calculate the Euclidean distance between each data point and each cluster center.

$$D_{x_{i,j_{IK}},\mu_k} = \sqrt{\left(x_{i,J_{IK}} - \mu_k\right)^2} \tag{7}$$

Assign each data point $x_{i,J_{IK}}(i \in I)$ to the nearest cluster center.

If

$$min\left\{D_{x_{i,J_{IK}},\mu_m}, m = 1, 2, \ldots K.\right\} = D_{x_{i,j_{IK}},\mu_n} \tag{8}$$

Then $x_{i,J_{IK}} \in S_n$.

(c) Update cluster centers: For each cluster S_k, update its cluster center to the average value of all data points within the cluster.

$$\mu_k = \frac{1}{n_k} \sum_{x_{i,J_{IK}} \in S_k} x_{i,J_{IK}} \tag{9}$$

where n_k is the number of data points in cluster S_k.

Repeat steps 2 and 3 until the cluster centers no longer change or the maximum number of iterations is reached.

Select the cluster $S_{k_{min}}$ with the lowest mean. The set of regions $RP = \{i | x_{i,J_{IK}} \in S_{k_{min}}\}$ represents the regions with development potential for the key indicator J_{IK}.

4. Results and Analysis of Power System Regulation Capability Measurement

4.1. Results and Analysis of Weights of Indicators

Table 3 shows the weights of indexes corresponding to four dimensions, in which the power side regulation capability has the most prominent impact on the regulation capability of the whole power system. In 2018, 68.5% of China's energy consumption was coal and 71.9% of China's power production came from thermal power. Coal power will remain the main energy type for a long time. As such, in order to absorb more non-fossil energy and transform it from supplementary and alternative energy into main energy sources, coal power should offer greater flexibility and provide peak shaving support for the large-scale growth of renewable energy. As a result, to improve power system regulation capacity, attention should be paid to improving coal power flexibility and implementing of the coal power flexibility transformation project. At the same time, flexible peak-shaving resources, such as pumped storage and gas-fired power generation, should be constructed in resource-rich areas as an important supplement to coal power peak shaving. From the weight of 34 tertiary indexes, Uhv Acces, Power Ancillary Service Compensation Cost and Charging Points are relatively high, which shows that power system regulation capacity is systematic, and improvements cannot be solely focused on power production. The same amount of attention should be paid to transmission and distribution optimization on the grid side and flexible responses to demand on the load side, as well as the development of the system side.

Table 3. The weights of indicators.

Primary Index	Secondary Index	Tertiary Indicators
A: Supply Side (0.315)	A1: Thermal Power Flexibility (0.109)	A11: Retrofittable Capacity of Thermal Power Units (0.008)
		A12: Coal Mine Density (0.040)
		A13: Standard Coal Consumption for Power Supply (0.003)
		A14: Decommissioning Capacity of Thermal Power Units (0.057)
	A2: Flexible Regulation of Power Supply Construction (0.137)	A21: Pumped Storage Capacity (0.057)
		A22: Gas-Fired Power Generation Investment (0.080)
	A3: Power Capacity (0.068)	A31: Capacity-Load Ratio (0.013)
		A32: Unit Utilization Hours (0.008)
		A33: Power Purchase Cost (0.008)
		A34: Renewable Energy Power Capacity (0.009)
		A35: Ratio of Renewable Energy to Thermal Power (0.004)
		A36: Renewable Energy Power Consumption (0.023)

Table 3. *Cont.*

Primary Index	Secondary Index	Tertiary Indicators
B: Grid Side (0.298)	B1: Coordination Between the Source and The Power Grid (0.008)	B11: Power Generation Per Unit Transmission Line Length (0.008)
	B2: Grid Construction (0.246)	B21: Purchase and Sale Price Difference (0.007)
		B22: Power Distribution Capacity (0.052)
		B23: Power Distribution Capacity (0.015)
		B24: Transmission Network Loss (0.008)
		B25: Reliability of Power Supply (0.006)
		B26: Shut-Down Time (0.006)
		B27: Inter-provincial power output (0.023)
		B28: Inter-provincial power input (0.002)
		B29: Uhv Access (0.123)
	B3: Intelligent Scheduling (0.008)	B31: Industrial Power Consumption (0.004)
		B32: Abandoned Wind Rate (0.004)
	B4: Grid Regulation (0.034)	B41: Remaining Utilization Hours of Thermal Power (0.034)
C: Load Side (0.213)	C1: Flexible Power Load (0.016)	C11: Electricity Consumption (0.007)
		C12: Maximum Load Utilization Hours (0.008)
	C2: Electric Vehicle Energy Storage (0.196)	C21: Electric Vehicle Quantity (0.059)
		C22: Charging Points (0.100)
		C23: Internet Development (0.035)
D: Support Side (0.172)	D1: Power Equipment Industry (0.043)	D11: Electrical Machinery And Equipment Innovation (0.018)
		D12: Electrical Machinery And Equipment Scale (0.023)
	D2: Power Ancillary Service Compensation (0.116)	D21: Power Ancillary Service Compensation Cost (0.116)
	D3: Power Market (0.013)	D22: Power Market Scale (0.013)

According to the definition of the entropy weight method, the entropy of the index reflects the information uncertainty of the index; that is, the smaller the entropy, the greater the amount of information contained in the index and the higher the degree of variation of the index. Entropy does not reflect the subjective importance of the index; rather, it objectively describes the amount of information contained in the index. For example, the weight ω of index A12: Coal Mine Density was 0.04, ranking ninth among all of the indexes, which means that there was a certain degree of variation in the regional coal mine density data of each province, and the information contained therein may indicate that the resource endowments of each province are different. Due to the limitations associated with resource endowment, although the weight of the regional coal mine density index was high, it was very difficult or expensive for provinces with low index scores to improve the power system regulation capacity by increasing coal mine density. On the other hand, the weights of indicators such as A32: Unit Utilization Hours, A35: Ratio Of Renewable Energy To Thermal Power, B25: Reliability Of Power Supply, B31: Industrial Power Consumption were less than 0.01, which did not mean that they played a small role in improving the regulation capacity of the power system; rather, the indexes of most provinces were at a relatively high or low level. Therefore, the degree of variation observed among these indexes was low, and their weights were small. It cannot be ignored that some areas in most provinces have not been vigorously developed, and the data of most provinces are at a low level, which means that their corresponding indexes are associated with a small weight in the evaluation system: This may be an opportunity for some of these provinces to achieve corner-overtaking and quickly improve the power system regulation capacity. For example, the index D22: Power Market Scale reflects the quality of power market construction. From the data, most provinces are still in the initial stage of power market construction, which plays an important role in improving power system regulation capacity by releasing system flexibility through the flexible electricity price mechanism, thereby reflecting the capacity value of the regulated power supply. Therefore, some provinces with backward resource endowment and power network infrastructure can release the potential of flexible regulation by prioritizing the development of the power market.

4.2. Power System Regulation Capability Scores and Analysis

Figure 2 shows the distribution of power system regulation capability scores across different regions in China. As indicated by the legend, regions closer to red indicate higher scores, while regions closer to green indicate lower scores. It is evident that there is a clear distribution pattern among the regions in China. The northwest regions have a higher prevalence of green areas, while the southeast regions gradually shift towards yellow, indicating higher scores. Generally, the coastal regions in the southeast have higher scores. It can be observed that the overall power system regulation capability in China is not high, with most regions scoring relatively low. Additionally, there are regional disparities in development, with some regions scoring significantly higher than others. Further analysis will be conducted to examine the differences in scores among regions.

Figure 2. Power system regulation capability score distribution chart.

Table 4 shows the scores and ranking of the power system regulation capacity of each province during the statistical period, as well as the mean value and standard deviation. Referring to the practices of Zongbing Deng [5], the short board limit was taken as the mean value of the power system regulation capacity score minus 0.5 standard deviations. The nine provinces and regions with scores higher than the average included Shanghai, Beijing, Jiangsu, Tianjin, Guangdong, Zhejiang, Shaanxi, Guangxi, and Henan, as well as six areas in the eastern region, one in the central region, and two in the western region. The 10 provinces and regions with scores lower than the short board limit included Inner Mongolia, Jiangxi, Chongqing, Liaoning, Heilongjiang, Gansu, Jilin, Qinghai, Hainan, and

Xinjiang, as well as one area in the eastern region, four in the central region, and five in the western region. There was obvious regional heterogeneity in the power system regulation capacity of each province. The power system regulation capacity of the eastern region was strong, that of the central region was weak, and the western region was identified as the most backward.

Table 4. Scores and Gap Analysis of Power system regulation capability of China.

Rank	Province	Score	Rank	Province	Score	Rank	Province	Score
1	Shanghai	0.560	11	Fujian	0.171	21	Inner Mongolia	0.134
2	Beijing	0.343	12	Shanxi	0.167	22	Jiangxi	0.133
3	Jiangsu	0.299	13	Anhui	0.160	23	Chongqing	0.130
4	Tianjin	0.282	14	Yunnan	0.158	24	Liaoning	0.127
5	Guangdong	0.246	15	Hunan	0.150	25	Heilongjiang	0.115
6	Zhejiang	0.222	16	Guizhou	0.149	26	Gansu	0.113
7	Shanxi	0.207	17	Sichuan	0.147	27	Jilin	0.110
8	Guangxi	0.199	18	Hebei	0.142	28	Qinghai	0.108
9	Henan	0.184	19	Hubei	0.138	29	Hainan	0.107
10	Shandong	0.171	20	Ningxia	0.137	30	Xinjiang	0.102
Mean	0.180		Std.	0.092		Short-board limit	0.135	

5. Key Indicators, Regional Potential Areas, and Enhancement Strategies

5.1. Key Indicators Identification

Considering that the entropy weight method completely ignores the subjective judgements associated with the index weight, all indexes are divided into two categories according to development potential with the actual situation. The judgment principles mainly included: (1) whether development was significantly affected by resource endowment. Indexes such as Gas-Fired Power Generation Investment, Pumped Storage Capacity, and Coal Mine Density are difficult to develop in areas with poor resource endowment, even with high economic and human costs; and (2) whether the economic utility of further investment is low. With the vigorous development of China's power infrastructure, some indexes have reached a high level in most provinces (e.g., Power Purchase Cost, Reliability of Power Supply), and income from further development of these indexes is relatively low. In addition, it is important to consider whether the index represents the new development direction of power system regulation capacity. Fields like electric vehicle energy storage and the power market are developing rapidly and show obvious differences among regions, which means that backward areas have substantial catch-up space. According to the above principles, the indexes were determined based on whether or not they had development potential. They were then separated by the median weight to obtain the four-quadrant diagram shown in Figure 3.

The indexes located in the first quadrant, which have a high weight and great development potential, indicate key areas in which the regulation capacity of the power system can be improved. All provinces, particularly those that are rich in resources, should pay attention to these areas. The indexes located in the second quadrant have a low weight but high development potential, which indicates that these fields may represent foundations for further improving power system regulation capacity. Although the indexes in the fourth quadrant have a high weight, they are subject to resource endowment. Provinces with rich natural resources can focus on flexible peak shaving power supply, while provinces with poor resources should prioritize other areas. The indexes in the third quadrant have low weights and offer little development potential. Most of them reflect the level of power supply infrastructure and offer little potential in terms of improvement because of high costs and low marginal incomes; therefore, development is not a high priority.

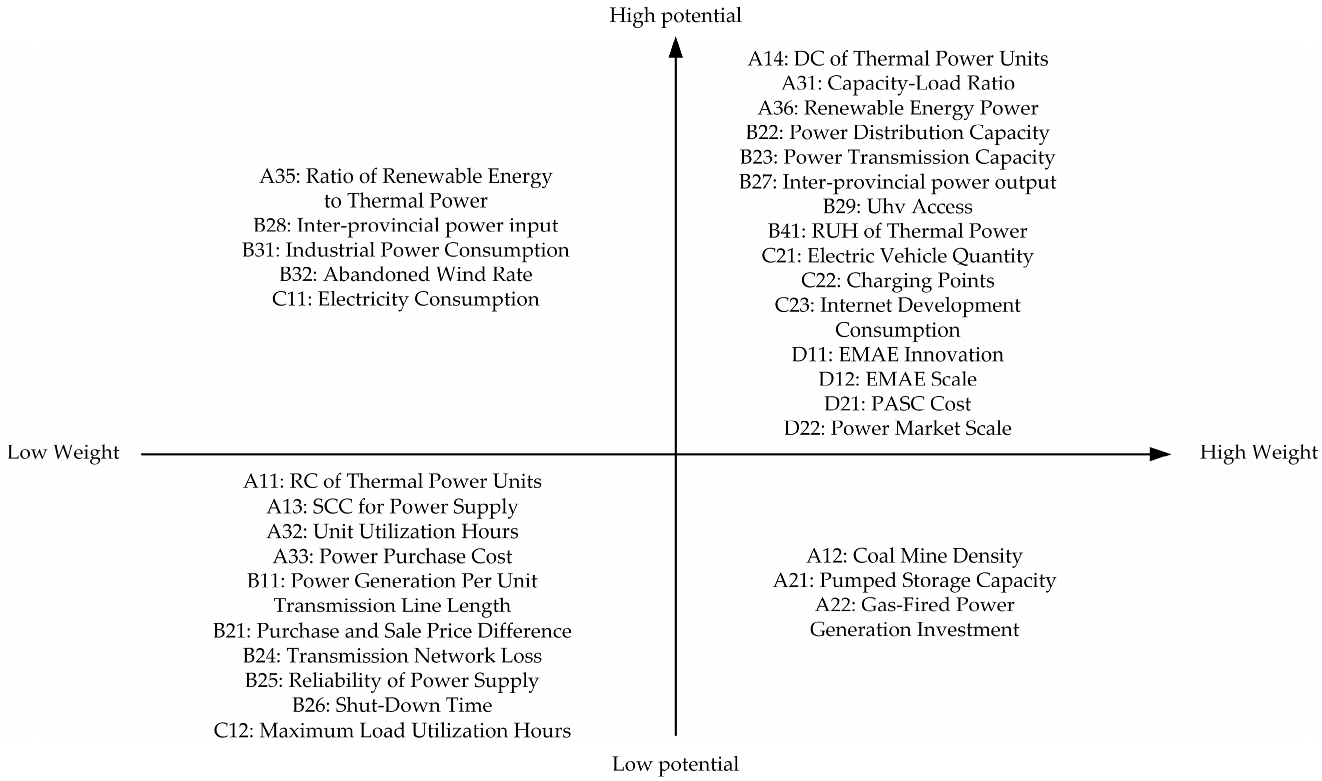

Figure 3. Weight development potential quadrant chart.

5.2. Identification of Potential Areas for Regional Power System Regulation Capability

As mentioned above, from the connotation of the entropy weight method, the weight reflects the information variation of data, and indexes with high weights are generally discrete. Therefore, the scores of provinces and regions on each index can be classified by means of cluster analysis, which allows for the identification of potentially weak areas in each province, so as to propose targeted improvement strategies. Because the three indexes in the fourth quadrant (Gas-Fired Power Generation Investment, Pumped Storage Capacity, and Coal Mine Density) are subject to resource endowment and offer little development potential, the indexes in the first quadrant with higher weights and greater development potential were selected. A cluster analysis was carried out to assess 30 regions, and each index was classified into three categories. To identify areas with development potential, the indicators that fall into the lower range of the third category in each region's score are summarized and consolidated.

Table 5 shows the index of each province that had the lowest score in the cluster analysis. It can be seen that first, the number of provinces in the third category comprising five indexes (Charging Points, Decommissioning Capacity Of Thermal Power Units, Remaining Utilization Hours Of Thermal Power, Electric Vehicle Quantity, and Power Distribution Capacity) exceeded 25. Less than five provinces rank at the top of these indexes and a significant gap can be observed between the remaining provinces and provinces with higher scores. This shows that there is substantial room for improvement countrywide with respect to the five areas of power system regulation capacity construction reflected by these market and grid indexes (i.e., electric vehicle energy storage, thermal power flexibility, regional power grid regulation, electric vehicle construction). Second, more than half of the provinces fall into the third category composed of seven indexes (i.e., Uhv Access, Power Ancillary Service Compensation Cost, Electrical Machinery and Equipment Innovation, Internet Development, Renewable Energy Power Consumption, Inter-provincial power output and Electrical Machinery and Equipment Scale). This shows that some development has been undertaken in these fields, but the development potential of about half of the provinces has yet to be tapped. Less than half of the provinces fall into the third category which is composed of three indexes, including Power Distribution Capacity, Capacity-Load Ratio, and Power Market Scale. This shows that many provinces have made some progress in these fields, but there is still room for development in some provinces, which could be addressed by investing resources to compensate for shortcomings and narrow the gap relative to other provinces.

Table 5. Weaknesses of provinces.

Province	A14	A31	A36	B22	B23	B27	B29	B41	C21	C22	C23	D11	D12	D21	D22
Beijing	√	√	√			√	√	√				√	√		√
Tianjin		√	√			√	√	√		√		√			
Hebei	√	√	√	√			√	√	√	√	√	√		√	
Shanxi	√		√	√			√	√	√	√	√	√	√	√	
Inner Mongolia	√		√	√	√		√	√	√	√	√	√	√	√	
Liaoning	√	√	√	√			√	√	√	√			√		
Jilin	√		√	√	√		√	√	√	√	√	√	√	√	
Heilongjiang	√		√	√	√	√	√	√	√	√	√	√	√		√
Shanghai	√	√				√		√						√	√
Jiangsu	√	√	√			√		√	√	√				√	
Zhejiang	√	√	√	√		√		√	√	√				√	
Anhui	√		√	√			√	√	√	√	√			√	
Fujian	√	√		√		√	√	√	√	√				√	
Jiangxi	√	√	√	√	√	√	√	√	√	√	√			√	
Shandong	√	√	√	√		√	√	√	√	√				√	
Henan	√	√	√	√		√		√	√	√				√	
Hubei	√			√			√	√	√	√	√	√		√	√
Hunan		√		√	√	√	√	√	√	√	√	√		√	
Guangdong	√	√		√		√		√	√	√				√	
Guangxi	√			√	√	√	√		√	√	√	√		√	
Hainan	√		√	√	√	√	√	√		√	√	√	√	√	√
Chongqing	√	√		√		√	√	√	√	√	√	√		√	
Sichuan	√			√	√		√		√	√		√	√	√	√
Guizhou	√			√	√		√	√	√	√	√	√	√	√	
Yunnan	√			√	√		√		√	√	√	√	√	√	
Shaanxi	√		√	√	√		√	√	√	√	√	√	√		√
Gansu	√			√	√		√	√	√	√	√	√	√	√	√
Qinghai	√			√	√	√	√	√	√	√	√	√	√	√	
Ningxia	√		√	√	√		√	√	√	√	√	√	√		√
Xinjiang			√	√	√		√	√	√	√	√	√	√		

Note: The checkmark √ indicates that the indicator is a key area for the province.

5.3. Enhancement Strategies for Power System Regulation Capability

Based on the identification of potential areas for each region as mentioned above, this paper presents specific enhancement strategies for each indicator.

Power side: Some provinces are weak in thermal power flexibility. Provinces with low scores in Decommissioning Capacity of Thermal Power Units should accelerate efforts to eliminate backward production capacity and promote the flexible transformation of thermal power units. They should also close and retire some old 300,000 kW thermal power units and focus on launching 600,000 kW and above supercritical and ultra-supercritical units. On the other hand, other provinces are weak in power capacity. Compared with other regions, the installed capacity of the power supply in these provinces still lags; therefore, these provinces should focus on accelerating power construction to improve overall capacity. In terms of construction planning, an emphasis should be placed on the development of renewable energy, and the self-use coal power planning and the coal power capacity scales should be strictly controlled.

Grid side: There are two kinds of provinces that need to improve their grid side ability. The first kind of provinces are weak in grid construction. UHV Access had the highest weight and is key to improving both grid construction and the overall power system regulation capacity. In most of the relatively backward provinces, the construction of the UHV power grid has not been carried out. To plan smart grid use, the UHV grid is necessary as it acts as the backbone grid. It is also important to coordinate the development of power grids at all levels so as to promote the cross-regional consumption of surplus renewable power. The other three indexes of grid construction reflect the construction of the basic regional power grid (except the UHV grid). Provinces that lag behind should strengthen their efforts to plan and build the main grid of the regional transmission network and coordinate power grids of various voltage levels. The second kind of provinces are weak in grid regulation. In terms of peak shaving with renewable energy, these provinces show weak potential. On the basis of controlling the total installed capacity of thermal power, the flexible transformation of thermal power units and the construction of new peak shaving power stations should be promoted to improve the regulation capacity of the regional power grid.

Load side: Provinces that need to improve their load side ability are weak in electric vehicle energy storage. These provinces can lower the threshold of the electric vehicle charging service market, reform the electric vehicle charging price mechanism, implement policies such as green certificates and carbon credits to encourage orderly charging and discharging, carry out pilot operations of electric vehicle energy storage, and explore the interaction mechanism between electric vehicles and the power grid, so as to take full advantage of the energy storage potential of electric vehicles.

Support side: There are three kinds of provinces that need to improve their support side ability. The first kind of provinces are weak in power equipment industry development. These provinces should actively promote supply side structural reform, improve industrial technology competitiveness, promote the coordinated development of power generation, transmission, and distribution equipment, and transform the power equipment industry from follower to leader. The second kind of provinces are weak in power ancillary service compensation. These provinces should promote the establishment and improvement of the provincial frequency modulation ancillary service market and the inter-provincial standby ancillary service market and continuously optimize the transaction varieties of ancillary services, so as to consume more renewable energy. The third kind of provinces are weak in power market. In the development of power trading in these provinces, there are often some problems, such as a lack of marketization confidence, working mechanisms that fail to satisfy the requirements of power trading, a conflict between trading and renewable energy consumption, inter-provincial barriers, and contract transfer barriers. Therefore, these provinces should deepen their understanding of the resource allocation aspect of market-oriented transactions, perfect the medium-and-long-term power transaction price mechanism, strengthen the coupling of transaction information and promote the competition among trading institutions, to achieve a high proportion of medium-and-long-term power contracts.

6. Conclusions and Policy Implications

Improving the power system regulation capacity is critical to resolving the problem of renewable energy consumption. Accurate analysis and measurement of the power system regulation capacity and its regional differences and shortcomings are of great practical significance for promoting and improving power system regulation capacity. Based on defining the connotation of power system regulation capacity, this paper constructed an evaluation index system that took into account four factors; that is, the power supply, power grid, power load, and support system, which facilitated a quantitative investigation of China's power system regulation capacity, and produced the following main conclusions: (1) the national average power system regulation capacity score was 0.18, which is at a low level. Less than one third of provinces scored higher than the average. (2) The contribution of each dimension to the power system regulation capacity is obviously different. In terms of the weight of each dimension, the results were as follows: the power side (0.315), the grid side (0.298), the load side (0.213), and the support side (0.172). (3) Obvious regional heterogeneity was observed in the development of power system regulation capacity, which is stronger in the east, weaker in central China, and the most backward in the west. This weakness may be explained by the lack of development in areas corresponding to the key indexes.

The main policy implications of the above conclusions are as follows: First, on the whole, policy makers should focus on improving load side and support side regulation capacity, while consolidating and improving the regulation capacity of the power side and grid side. Second, policy makers should improve power system regulation capacity according to local conditions. For the power side, backward thermal power production capacity should be gradually eliminated, and thermal power units should be flexibly transformed. Pumping storage peak shaving and gas peak shaving power stations should be planned and constructed to develop flexible regulation power reserves. For the grid side, the construction of smart grids with a UHV grid as the backbone grid should be promoted, along with the coordination of power grids at all levels. Shared peak shaving and standby resources in regional power grids should be developed to enhance the space for renewable energy power generation. For the load side, policy makers should promote the construction of electric vehicles, charging piles, and vehicle networking, explore electric vehicle energy storage, build the charging intelligent service platform through the "Internet plus charging infrastructure", and promote a two-way interaction between energy and information in relation to electric vehicles and the smart grid. For the support side, policy makers should promote supply side structural reform, improve industrial technology, and establish an innovative application system in which enterprises, research institutions, and universities can participate. The compensation mechanism should be improved in the case of power auxiliary services and the direct cost and opportunity cost of flexible thermal power operations, pumped storage power and new energy storage power. The construction of the power market should be accelerated to increase the power market-oriented trading volume and establish a market-oriented system.

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Nomenclature

N	Number of tertiary indicators
M	Number of tertiary indicators
I	Index for the *i*-th region
J	Index for the *j*-th indicator
R	Matrix of raw evaluation data
r_{ij}	Raw data for the *j*-th indicator. In the *i*-th region
x_{ij}	Normalized value of r_{ij}
p_{ij}	The weight of x_{ij} in the *j*-th indicator.
E_j	Entropy value of indicator *j*
ω_j	Entropy value of indicator *j*
T_i	Score of power system regulation capability for region *i*
IP_h	Set of indicators with high potential
IP_l	Set of indicators with low potential

IW_h	Set of indicators with high weight
IW_l	Set of indicators with low weight
M_ω	Median of weights
IK	Set of key indicators
j_{IK}	Key indicator
K	Number of clusters in K-means algorithm
S_k	The k-th cluster
μ_k	Centroid of the k-th cluster
$X_{i,j_{IK}}$	Indicator data of region i in key indicator set IK
$D_{X_{i,J_{IK}},\mu_k}$	Euclidean distance between data point $X_{i,j_{IK}}$ and centroid μ_k
n_k	Number of data points in cluster k
$S_{k_{min}}$	Cluster with the lowest mean
RP	Set of regions with development potential

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