

Dynamic Comprehensive Assessment of Power Development Based on Provincial Data

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Abstract—Dynamic comprehensive assessment of regional power industry development levels is of paramount importance for understanding the development characteristics and potential of the local power industry. A tri-level evaluation index system is established, describing five aspects of the local power industry development level, specifically, the coordination degree between the power industry and economy/energy, power generation, power consumption, power supply and development potential. A combination of information entropy and the analytic hierarchy process (AHP) is used to establish a static evaluation model, and a blend of subjective opinions and objective data information is then realized. By aggregating the static evaluation model for each time period based on a time-ordered weighting vector calculated using time-ordered information entropy, a dynamic comprehensive evaluation model of power industry development level is established. By considering provincial data from China recorded during 2007 to 2016 as the sample set, through synchronic and diachronic comparisons of the evaluation results, the differences, characteristics and potential of local power industry development in China are explored.

Index Terms—Analytic hierarchy process, development level of power electric industry, dynamic comprehensive assessment, information entropy.

I. INTRODUCTION

THE power industry is an important basic industry of any national economy. Power is the leading and supporting industry in any nation's energy development strategy. The level of electric power development is also an important index for measuring the degree of regional economic development, the efficiency of energy utilization and the potential for comprehensive development. The development of the power industry is affected by many factors. The economic, social and environmental conditions, as well as the availability of resources, vary by region, such that the development of electricity varies in terms of characteristics and levels among different areas.

Manuscript received September 11, 2018; revised February 3, 2019; accepted March 1, 2019. Date of online publication May 13, 2019; date of current version April 27, 2020. This work was supported by the National Natural Science Foundation of China under Grant No. 51777104, and the Science and Technology Project of State Grid Corporation of China.

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DOI: 10.17775/CSEEJPES.2018.00910

Because it is necessary to observe and compare a large amount of statistical data for a region, it is difficult to grasp the level of regional power development in its entirety, and it is also difficult to quantify the levels of power development in different regions and periods. Therefore, a quantitative and comprehensive evaluation of the level of electric power development is of considerable importance towards gaining an accurate understanding of the spatial and temporal characteristics of power development across different regions and at various times.

Conducting a comprehensive evaluation [1] entails aggregating information from multiple evaluation indicators in order to certain means to reflect the overall characteristics of the evaluation objects. The evaluation of a number of objects for a certain time section is called static evaluation, and a unified evaluation model for multiple time periods is called dynamic evaluation [2], [3]. The typical methods of comprehensive evaluation can be divided into subjective and objective weighting methods. The former determines the index weights according to the opinions of experts, whereas the latter establishes the evaluation model according to the objective characteristics of the data [4]. The evaluation of electric power development level is a typical dynamic comprehensive evaluation problem, which involves multiple evaluation objects, indices and time periods. Research into the field of comprehensive evaluations of the power industry has already been conducted [5]–[8]. From the perspective of sustainable development, an evaluation model was established using the analytic hierarchy process (AHP), and the Beijing power grid was taken as an example to evaluate the development of the power industry [5]. Power grid construction planning was evaluated from the perspective of low-carbon production [6] by using the G-1 method and entropy weight method to determine the subjective and objective weights, respectively, from which the comprehensive weight was derived. Then, an evaluation model was established for multiple grids based on a single grid and a single year. Another evaluation model of power grid security benefit using a fuzzy AHP was established [7]; this method analyses the operating level and development of a power grid in a certain area during the “12th Five-Year Plan”. The power balance scheme for a power grid was evaluated by using AHP-entropy weighted combinations of subjective and objective evaluations [8]. From the perspective of comprehensive energy system [9], the energy efficiency evaluation index of comprehensive energy system in the park is proposed, and the system equivalent model is established based on weighted directed graph. The information entropy

is used to determine the weight of each energy efficiency index. An evaluation index system was established from the perspective of power social coordination, energy efficiency, low-carbon benefits, power market operation and efficiency and smart grid construction [10]–[15]. However, the index system cannot be analyzed using actual data. In addition, a comprehensive evaluation of the actual operation of the power grid was also conducted by considering the real-time operation state evaluation of the power grid [16], the scheduling operation scheme evaluation [17], the daily dispatch operation evaluation [18] and the power supply service quality evaluation [19].

Upon our comprehensive review, with respect to power industry evaluation, we find that the existing research focuses only on certain aspects of the power industry and has failed to establish a system of comprehensive evaluation of the overall level of power development from multiple angles. In the field of evaluation, the existing research is mainly based on the analysis and evaluation of data specific to a certain area or year, and no unified modeling of time and space factors has been realized. The associated methods and conclusions cannot be applied to the evaluation of multiple space and time dimensions, and research on the evaluation of power development levels in different regions and at different times throughout a country is mostly in the preliminary qualitative analysis stage, which is relatively macroscale, empty and lacking data support. In view of the limitations of existing research, this study explores the comprehensive evaluation of the development level of the power industry in terms of space and time. First, a relatively complete and comprehensive evaluation index system is established to describe the level of electric power development using a three-level index system. Second, the combined subjective and objective evaluation method based on the combination of information entropy and AHP is used to determine the weight value of the comprehensive evaluation index to realize the combination of subjective evaluation and objective evaluation. Next, the time series information entropy is used to determine the sequential weighted vectors, thereby realizing the linear weighted aggregation of the time series weight and establishing the dynamic evaluation model of the electric power development level. Finally, the above models and methods are applied to an actual situation, and the characteristics, differences and potential of power development level in various regions of China are analyzed in combination with provincial time series data with the goal of providing a decision-making reference for the development of the domestic power industry.

II. METHODS

A. Construction of the Evaluation Index System for the Level of Electric Power Development

The index system is the basis of comprehensive evaluation research, and its rationality and comprehensiveness directly affect the results of evaluation studies. The development of the power industry has an objective difference in time and space. Its level is not only related to the power industry itself but also involves many other factors, such as the economy, society,

energy and the environment. Therefore, in the construction of an electric power development level evaluation index system, we should consider the situation of the power industry itself, in addition to the situation of the economy and energy production and consumption. The selected indices should not only reflect the overall situation of the power industry but also its local characteristics and differences.

In the latest global reports, energy development is described using six key indicators, such as energy consumption, carbon emissions and external dependence on energy. The development of electric power is described using six key indicators, which include, for example, power consumption, installation, power generation equipment utilization hours and network losses. This index system defines the close coupled relationship between energy and power development, but the evaluation of power development is relatively general and macroscopic. On the basis of this study, combined with the results of literature research and expert discussion, the evaluation index of the power industry will be further refined to three power system parts of power generation, power supply and electricity use in order to evaluate the level of electric power development in a more detailed and comprehensive manner.

The classic tri-level index system (target level- control level- index level) is used to describe the level of electricity development. By analyzing the key factors of electric power development and combining expert opinions and data acquisition, a comprehensive evaluation index system of electric power development level is constructed, as shown in Fig. 1. The index system describes five aspects of the regional power development level. These are power development coordination, power generation level, power supply level, power consumption level and power development potential. There are five categories of second-level indices and 31 third-level indices, covering power generation, power supply, electricity, power development potential, power industry and the economy, energy, environmental coordination and many other aspects.

B. Static Comprehensive Evaluation Method of Electric Power Development Level

The comprehensive evaluation method of the development level of electric power involves converting several evaluation indices into a single index that can reflect the comprehensive situation of power development and can provide more visual evaluation results for the analysis of the level of electric power development in a certain area. This study uses the combination of a subjective and objective AHP–information entropy method to calculate the weights of evaluation indices, which can realize the combination of the subjective opinions of experts and objective data information. This method is used to make a comprehensive evaluation of the level of power development.

1) Information Entropy Weighting Method

In information theory, entropy is a measure of the degree of disorder of a system and can be used to measure the effective information provided by the data. The entropy method, as an objective and practical weighting method, is a method to determine the weight of indices according to the amount of

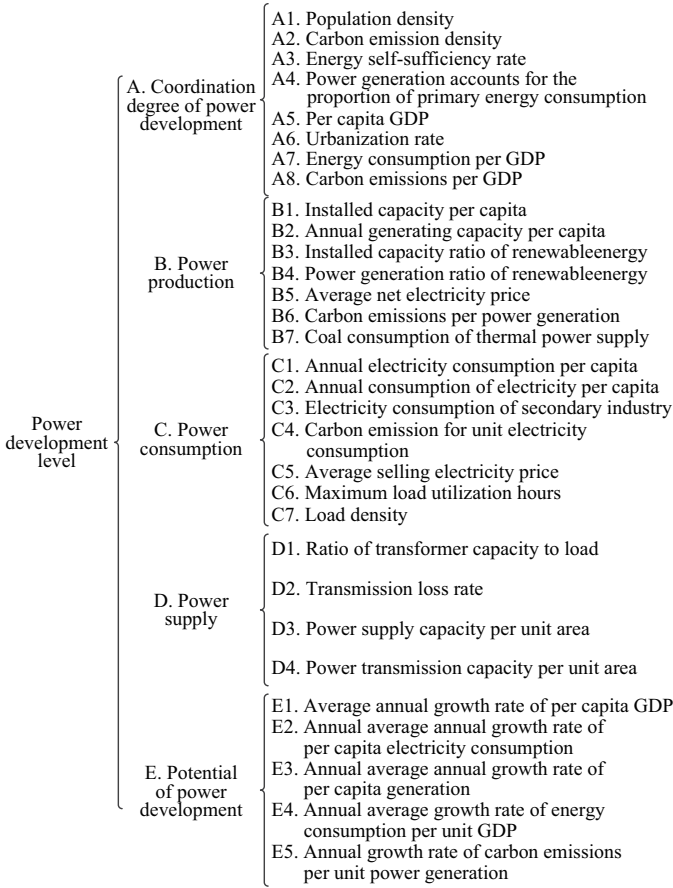


Fig. 1. General evaluation index system for power development level.

information contained in the entropy of different indices. The larger the difference of an evaluation index, the smaller the entropy value. The more information contained and transmitted, the higher the corresponding weight. The central idea of the entropy weight method is the weight coefficient, which should be measured with the degree of variation of each index on the whole and its influence on other indicators. The initial weighted information should be selected from the objective environment, and the corresponding weight coefficient can be judged by the information content contained in each index. The concrete steps are as follows.

The first step involves data standardization processing. To eliminate the dimensionless influence of each index, the original data set of the power development level should be normalized. The letter m indicates the number of evaluation objects, and n indicates the number of evaluation indicators. The index data set contains $m \times n$. The original data set is $\{x_{ij}^0 | i = 1, \dots, m; j = 1, \dots, n\}$, and the normalization data set is $\{x_{ij} | i = 1, \dots, m; j = 1, \dots, n\}$. Standardized processing for the positive indices:

$$x_{ij} = \frac{(x_{ij}^0 - \min_i x_{ij}^0)}{(\max_i x_{ij}^0 - \min_i x_{ij}^0)} \quad (1)$$

Standardized processing for the negative indices:

$$x_{ij} = \frac{(\max_i x_{ij}^0 - x_{ij}^0)}{(\max_i x_{ij}^0 - \min_i x_{ij}^0)} \quad (2)$$

After normalization, all indices are normalized as positive indices between $[0, 1]$, which facilitates a comparison between

the indicators and subsequent processing analysis.

The second step involves calculating the entropy value of the evaluation index. According to the definition of information entropy, the entropy of item j is e_j :

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^m x_{ij} \ln x_{ij} \quad (3)$$

Specified when $x_{ij} = 0$, $x_{ij} \cdot \ln x_{ij} = 0$.

In the third step, the weight of the evaluation index is calculated. If ω_j is the weight of evaluation index j , the entropy weight formula of the index is as follows:

$$\omega_j = (1 - e_j) / \left(m - \sum_{j=1}^m e_j \right) \quad (4)$$

In the formula, e_j is the entropy of the index j . The smaller the entropy value of the index is, the higher its entropy weight is, which indicates the greater importance of the index and the greater level of useful information it provides.

2) Analytic Hierarchy Process

The AHP is a decision-making method developed and used by the American operations research expert T. L. Saaty in the mid-1970 s. This study uses the AHP method to divide the general evaluation target according to the target layer, the index layer and the factor layer. The number of evaluation targets is m , the number of evaluation indices is n , and each evaluation index is subdivided into multiple evaluation factors. Using this method, we construct a standardized evaluation matrix, which takes the target layer as the row and the index layer as the column. The specific steps are described in the following.

The first step involves clarifying the problems and establishing a hierarchical structure. By gaining a deep understanding of the research objects, an evaluation index system is developed and stratified, forming a hierarchical structure chart.

The second step involves establishing the judgement matrix. Each pair of same-level indicators is compared with the indicators at the level above, and the judgement matrix is constructed. The 1–9 scale method proposed by T. L. Saaty is generally recommended, as shown in Table I.

TABLE I
MEANING OF THE SCALE

Scale	Meaning
1	The two factors are of equal importance.
3	The former factor is slightly more important than the latter.
5	The former factor is noticeably more important than the latter.
7	The former factor is significantly more important than the latter.
9	The former factor is of extremely high importance compared to the latter.
2, 4, 6, 8	The intermediate values of the above adjacent judgements.

In the third step, the consistency of the judgement matrix is checked.

The fourth step involves determining the hierarchical single order. According to the judgement matrix, the important order weights of all of the elements in this level are determined by taking a certain element of the above layer as the standard.

That is, the maximum eigenvalue and the corresponding eigenvectors of the judgement matrix are calculated, and the weights of each index of the level are formed after normalization of the feature vectors.

In the fifth step, the synthetic weight of each index to the system target is calculated and a general ranking is conducted to determine the importance of the lowest single index in the hierarchical structure diagram.

In this method, the subjective judgement of a group of experts is collated and integrated scientifically. The weights of the judges reflect the subjective value judgement of the evaluators, and the quantitative information is lower. However, the evaluators have a thorough grasp of the essence of the evaluation, the elements contained and the logical relationship between the elements. It is very practical to evaluate the index structure with complex data and a lack of necessary data. This can significantly improve the effectiveness, reliability and feasibility of the comprehensive evaluation.

3) Combinatorial Method of Information Entropy and AHP

The entropy weight method can fully utilize the data information in the index and reflect the objective weight value. However, using the entropy method to determine the weight of the index from the data itself may not reflect the actual importance and significance of the index. Therefore, the entropy weight method combined with the AHP method must be used to ensure that the weight not only contains information included in the data itself but also reflects the subjective judgement of the experts.

Assuming that ω_j represents the entropy weight calculated by the information entropy method and $\bar{\omega}_j$ represents the weights obtained by AHP, the combined weight can be obtained by combining the weights calculated by the information entropy and the AHP method, as follows:

$$\psi_j = \alpha\omega_j + (1 - \alpha)\bar{\omega}_j \quad (5)$$

In the formula, $0 \leq \alpha \leq 1$, the value α depends on the correlation between ω_j and $\bar{\omega}_j$. According to the Kendall correlation coefficient, this study assumes that $\alpha = 0.7$ [20].

C. Dynamic Comprehensive Evaluation Based on Time Series Information Entropy

In the second section, the static evaluation model of power development level is based on the index data of each evaluation object on a certain time section. Taking the time dimension into account, the index weight, index data and comprehensive evaluation value in the second section are rewritten as follows:

$$y_i(t) = \sum_{j=1}^n \omega_j(t)x_{ij}(t) \quad (6)$$

where $y_i(t)$ is the static evaluation value of evaluation object i in the time section t .

Static evaluation is only suitable for one evaluation at a time. In the static evaluation model of different time sections, the weight vectors of indices may vary. Integrating the weight information of each time index to establish an evaluation model suitable for multiple times is the problem to be solved in dynamic evaluation. In this paper, the concepts of time-ordered

information entropy [21] and time degree [21] are introduced to determine the sequential weighted vector. A multi-year dynamic comprehensive evaluation model is established by weighting the index weight of the static evaluation model of the power development level of each year according to the linear weighted aggregation based on a time series.

The total number of periods of participation in the evaluation is T . The sequential weighted vector is represented by $\bar{\rho} = (\rho_1, \dots, \rho_T)$, which reflects the contribution difference of different periods of information for dynamic comprehensive evaluation, with $\rho_t \in [0, 1]$ and $\sum_{t=1}^T \rho_t = 1$.

The amount of information contained in the time-ordered information entropy $\bar{\rho}$ is defined as:

$$I = - \sum_{t=1}^T \rho_t \ln \rho_t \quad (7)$$

The higher the time-ordered information entropy I is, the higher the uncertainty that $\bar{\rho}$ reflects. The difference between the degree of importance of the decision maker's long-term data and recent data is defined by the degree of time:

$$\lambda = \sum_{t=1}^T \frac{T-t}{T-1} \rho_t \quad (8)$$

The smaller the time λ is, the higher the degree of attention to recent data. The time degree is given in advance by the decision maker. Ideally, the sequential weighted vector can synthesize the information of the static evaluation model in every period as much as possible and take into account the difference of the time series. The mathematical model can then be expressed as follows:

$$\begin{aligned} \max \quad & I \\ \text{s.t.} \quad & \lambda = \sum_{t=1}^T \frac{T-t}{T-1} \rho_t \\ & \sum_{t=1}^T \rho_t = 1, \rho_t \in [0, 1] \end{aligned} \quad (9)$$

The upper formula is a conventional nonlinear constrained optimization problem. In this paper, the interior point method is used to solve it. Based on the sequential weighted vector, the weights of the static evaluation index of the electric power development level of each year are weighted linearly, and the dynamic comprehensive evaluation model of electric power development can be established to adapt to the multi-year evaluation.

$$\hat{y}_i(t) = \sum_{j=1}^n W_j x_{ij}(t) \quad (10)$$

where $W_j = \sum_{t=1}^T \rho_t \omega_j(t)$, $\hat{y}_i(t)$ is the evaluation value of object i in time period t in the dynamic comprehensive evaluation, which corresponds to the evaluation of the level of electric power development, that is, the evaluation value of province i in year t .

So far, the establishment of a dynamic comprehensive evaluation model for electric power development level has been completed. The steps involved in the entire method are shown in Fig. 2.

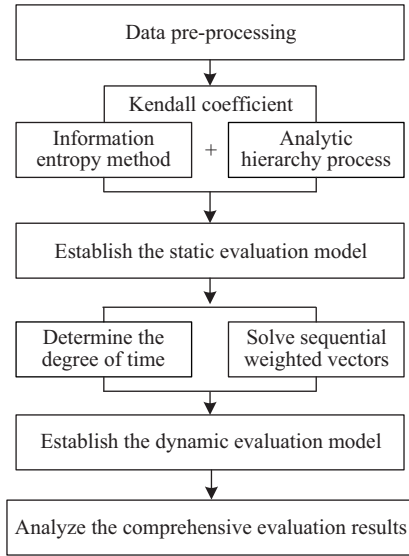


Fig. 2. Flowchart of the establishment of a dynamic comprehensive evaluation model.

1) Search the data: Collect the corresponding data according to the tri-level index system shown in Fig. 1, constitute the index data set, and normalize the data according to (1), (2).

2) Establish the static evaluation model: Based on the method in the second section, a static evaluation model for each year is established. The specific steps are as follows: a) Calculate the entropy weight value according to the method of information entropy weighting and obtain the weights of the objective evaluation of each index. b) Calculate the subjective weights of each index by using AHP. c) Based on the Kendall correlation coefficient, calculate the combined weights of each index and obtain the static evaluation models of each year.

3) Establish the dynamic evaluation model: Based on the method in the third section, a unified dynamic evaluation model is established. The specific steps are as follows: a) Determine the degree of time: determine the value of time degree according to the preferences of decision makers for timing differences. b) Solve sequential weighted vectors: the solution model is shown in (9). c) Establish the dynamic evaluation model: based on the static evaluation model of each year, the evaluation model is established according to (10). This is the final dynamic comprehensive evaluation model.

4) Obtain the output and analysis of the results of the comprehensive evaluation. The specific steps are as follows: a) Calculate the evaluation values of the second-level indices: based on the real data of the third-level indices, the dynamic comprehensive evaluation models of each of the second-level indices are used to calculate the evaluation values of each years' second-level indices. b) Calculate the evaluation values of the first-level indices: based on the evaluation values of the second-level indices, the first-level index evaluation model is used to calculate the evaluation values of the first-level index. This is the comprehensive level of electric power development. c) Based on the annual and provincial evaluation values of two-level indices, the development level and characteristics of electric power in different regions and different periods are analyzed.

III. RESULT AND DISCUSSION

A. Data Sources

In this study, 29 provinces, cities and autonomous regions in China are analyzed as samples from the period of 2007 to 2016 (owing to challenges in data acquisition, Tibet, Chongqing, Hong Kong, Macao and Taiwan are not included at present). The original data mainly come from China Statistical Yearbook, China Electric Power Yearbook, China Energy Statistics Yearbook and the new China's sixty-year statistical data compilation.

B. Dynamic Comprehensive Evaluation Model

1) Data Pre-processing

Before the comprehensive evaluation, the indices must be unanimous and dimensionless. After pre-processing, the difference in terms of nature and magnitude of the index data can be eliminated to prepare for the comprehensive evaluation of various indices in the later stage.

2) Calculation of the Weights of the Indices

A combination of entropy and AHP is used to determine the weights of the first and second levels of the power development level.

3) Determination of Sequential Weighted Vector Based on Time Series Information Entropy

Selecting the time degree $\lambda = 0.35$ indicates that the emphasis on recent data is slightly higher than that of long-term data. The model in (9) is solved, and the sequential weighted vector $\bar{\rho} = (\rho_{2004}, \dots, \rho_{2013})$ is obtained, as given in Table II.

TABLE II
SEQUENTIAL WEIGHTED VECTOR

Weight	Value	Weight	Value
ρ_{2007}	0.0644	ρ_{2012}	0.1012
ρ_{2008}	0.0706	ρ_{2013}	0.1108
ρ_{2009}	0.0772	ρ_{2014}	0.1212
ρ_{2010}	0.0845	ρ_{2015}	0.1327
ρ_{2011}	0.0925	ρ_{2016}	0.1452

4) Establishment of dynamic comprehensive evaluation model

Based on the method of the second and third sections, the dynamic evaluation model between the second and third level is established first (the index of each symbol is detailed in Fig. 1.).

$$\begin{cases}
 A = 0.25A_1 + 0.0362A_2 + 0.2452A_3 + 0.0979A_4 + \\
 \quad 0.2004A_5 + 0.097A_6 + 0.0377A_7 + 0.0357A_8 \\
 B = 0.183B_1 + 0.2128B_2 + 0.1663B_3 + 0.1845B_4 + \\
 \quad 0.0913B_5 + 0.1267B_6 + 0.0356B_7 \\
 C = 0.2356C_1 + 0.1557C_2 + 0.0368C_3 + 0.0461C_4 + \\
 \quad 0.0935C_5 + 0.0696C_6 + 0.363C_7 \\
 D = 0.0726D_1 + 0.0887D_2 + 0.5845D_3 + 0.2546D_4 \\
 E = 0.2406E_1 + 0.2247E_2 + 0.2342E_3 + 0.1019E_4 + \\
 \quad 0.1988E_5
 \end{cases}
 \quad (11)$$

Furthermore, a dynamic comprehensive evaluation model of the first-level index (i.e., the level of electric power development) is established.

$$P = 0.1301A + 0.2633B + 0.5078C + 0.0640D + 0.0348E \quad (12)$$

Based on the evaluation model of type (11) and type (12), the evaluation values of the second-level indices and the electric power development level of all provinces in China can be calculated by using the data of the third-level indices. Due to the limitations of space, this paper does not list the specific evaluation value of each index.

C. Analysis of Evaluation Results of the Second-level Index

The horizontal (spatial dimension) comparative analysis of the second-level evaluation indices of the power development level in different provinces of China is carried out. Fig. 3

shows the power development level histogram of several typical provinces in China's six power grids in 2016. It can be seen that there are similarities in the development of electric power in different provinces within the same region, as well as distinctive differences. The characteristics of power development in different provinces can be analysed using histograms. Inner Mongolia, Ningxia, Qinghai and other regions rely on abundant renewable energy (such as wind energy and solar energy) to generate electricity, which have a high level of power supply and have become an important power supply base.

A longitudinal (time dimension) comparative analysis of the second-level evaluation values of power development level is conducted. Let us consider Beijing, Shanghai, Shanxi and Ningxia as examples. Fig. 4 shows the second-level histograms of four provinces in 2008, 2010, 2012, 2014 and 2016.

It can be seen that the index B of Beijing and Shanghai is

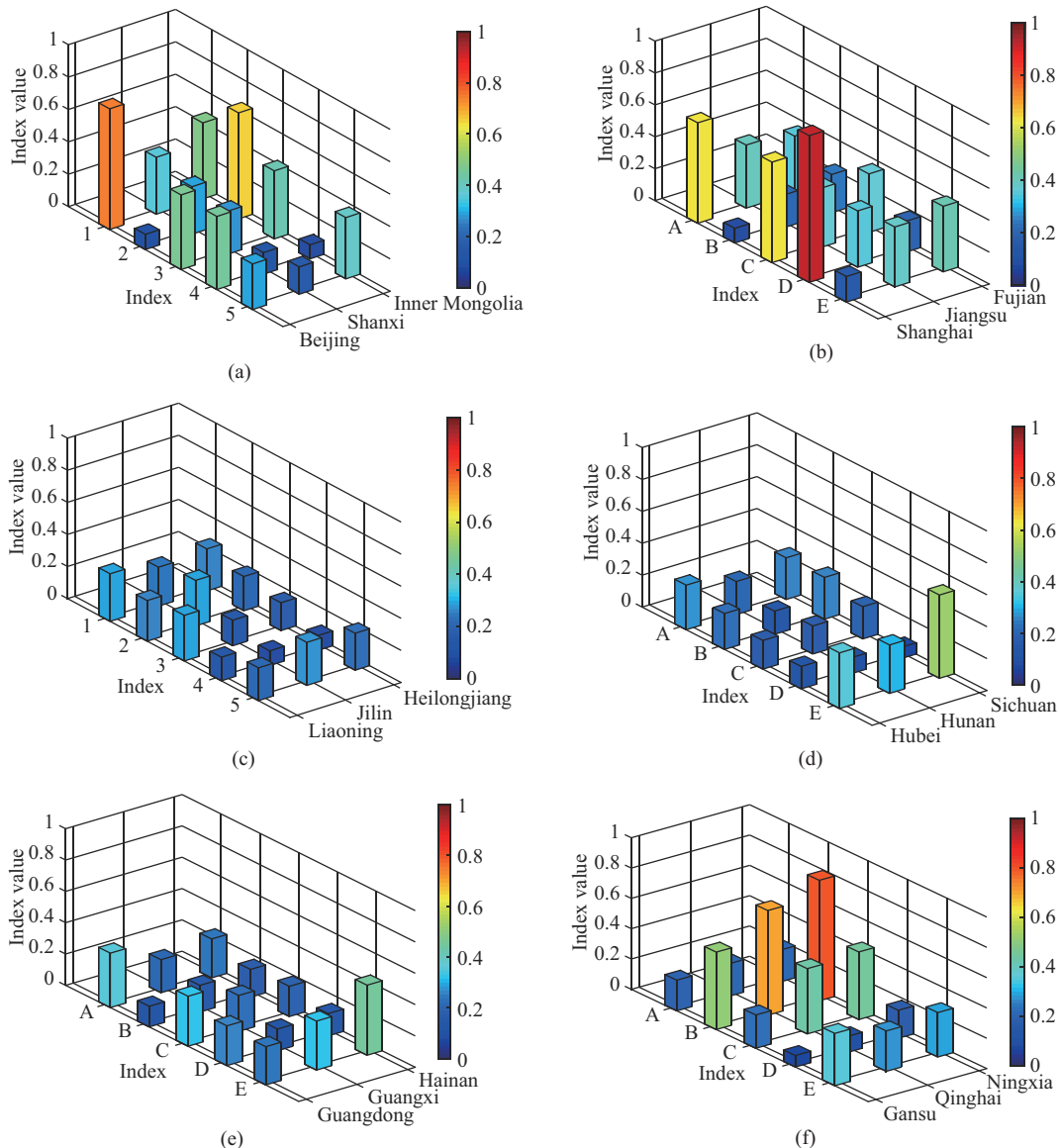


Fig. 3. Histograms for provincial development level of electric power industry in 2016. (a) Typical provinces in North China. (b) Typical provinces in East China. (c) Typical provinces in Northeast. (d) Typical provinces in Central China. (e) Typical provinces in southern China. (f) Typical provinces in Northwest.

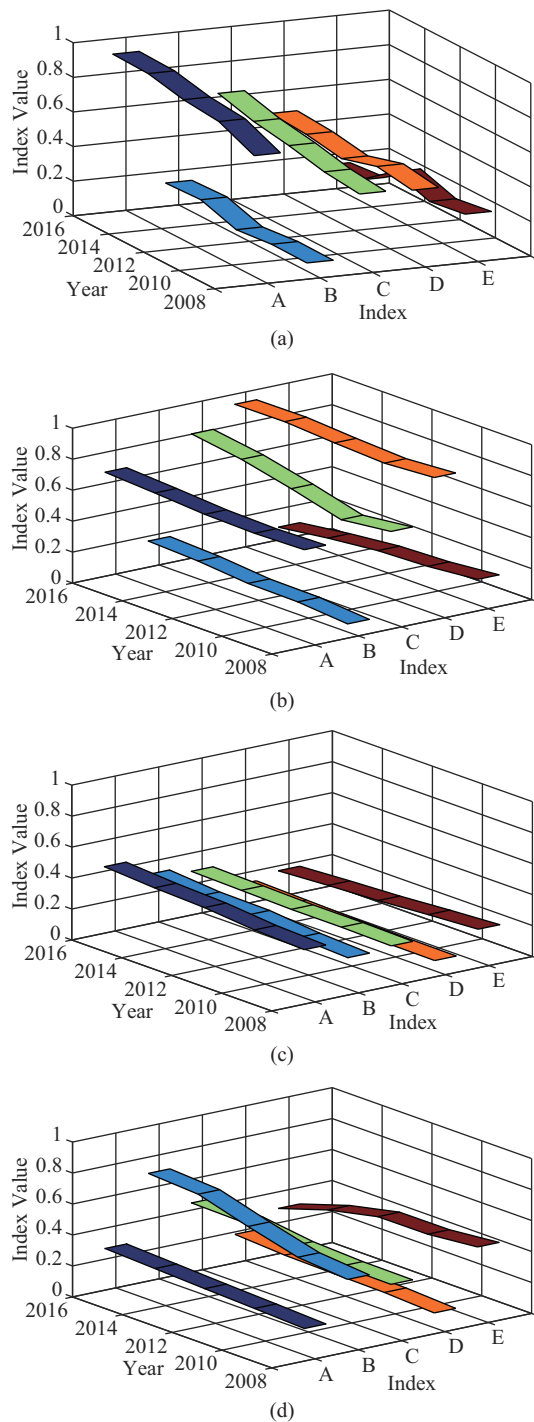


Fig. 4. Temporal histogram for the development level of the electric power industry of typical provinces. (a) Beijing. (b) Shanghai. (c) Shanxi. (d) Ningxia.

low while the index C is high, which reflects the high level of electricity consumption and low level of power generation. This pattern indicates that this is a typical area with regard to receiving electricity. The better power supply capability (index D) indicates that the power grid construction level is relatively high and that the power supply capability is strong. In the past 10 years, the level of economic development, energy utilization efficiency and power consumption demand (corresponding to indices A and C) in these two regions have been continuously

improved. However, owing to the constraints of resources and actual regional conditions, the power generation level has not been significantly improved, and the potential of the electric power development (index E) is also poor. Under the current development model, the level of electric power development has tended to be saturated. Shanxi and Ningxia are typical power supply areas (the index B is relatively high), especially where the power supply level has been increasing within the last ten years, but there are certain differences in the power development models of the two provinces. Shanxi is the largest thermal power base in China. Large energy consumption and environmental pollution have a negative impact on energy coordination efforts. The inherent characteristics of fossil resources have also reduced the development potential of the Shanxi power industry on a yearly basis (the index E is decreasing, and the speed of improvement of the index B gradually slows down). Ningxia is the largest wind power base in China. The availability of abundant wind and solar energy resources has increased the power supply capacity rapidly in recent years. The renewability and environmental friendliness of wind power and photovoltaic power also cause Ningxia to have a strong potential for development (the rapid improvement of indices B and E). In addition, the level of power transmission and transformation in various provinces shows a steady development trend, indicating that China's transmission and distribution level is constantly improving.

D. Results and Analysis of the Comprehensive Evaluation of Electric Power Development Level

The results of the comprehensive evaluation of the national power development level are further investigated. Table III gives a comprehensive evaluation of the average power development levels of China's six major power regions from 2007 to 2016, which can reflect the overall level of electric power development from a regional perspective and national perspective.

From the national perspective, Table III shows that the development level of electricity in various regions has been improving over the past 10 years. As can be seen clearly from Fig. 5, the level of power development in each province has gradually increased from "blue" representing a lower level to "yellow" or "red" representing a higher level. These indicate that the development level of China's electric power industry has been on the rise from 2007 to 2016, especially in the past five years.

From the regional perspective, according to the data in Table III, the comprehensive evaluation values of the electric power development level in North China and East China are always higher than those of other regions. Most provinces in the two regions are in leading positions with regard to electric power development. In fact, the economic levels, energy utilization levels and electricity consumption levels of these provinces are generally high, and the power grid construction is better. By contrast, the level of electricity development in Northeast China is at a medium level in the early years, although the development rate has declined in recent years. Because of the remote and backward economy in Northwest China, the overall level of electric power development was

TABLE III
COMPREHENSIVE EVALUATION VALUES OF THE REGIONAL DEVELOPMENT LEVEL OF THE POWER ELECTRIC INDUSTRY FROM 2007 TO 2016

Region	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
North China	0.406	0.425	0.461	0.500	0.552	0.594	0.631	0.677	0.723	0.758
Northeast	0.340	0.354	0.377	0.404	0.428	0.466	0.481	0.522	0.556	0.571
East China	0.465	0.488	0.520	0.565	0.603	0.639	0.669	0.723	0.768	0.808
Central China	0.297	0.305	0.323	0.345	0.369	0.377	0.406	0.432	0.463	0.484
Southern	0.318	0.326	0.358	0.384	0.413	0.436	0.468	0.505	0.544	0.587
Northwest	0.296	0.322	0.352	0.395	0.444	0.481	0.520	0.596	0.676	0.725
National average	0.354	0.370	0.399	0.432	0.468	0.499	0.529	0.576	0.622	0.655

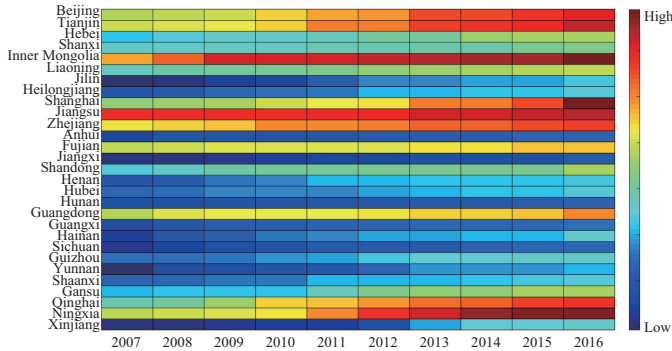


Fig. 5. Provincial development level of the electric power industry in 2007–2016.

relatively poor in the early years, although the electric power industry has developed rapidly in recent years.

Provinces such as Ningxia and Qinghai have become major power provinces. This is due to the rapid development of renewable energy power generations, such as wind power and photovoltaic power generation. Relying on abundant natural resources, the northwest has gradually become an important energy base in China and has significant potential for further development. There are considerable variations in the development level of electric power in the southern provinces. Guangdong has a developed economy, strong power demand and high level of electric power development. By contrast, the electric power development levels in Guangxi, Yunnan and Guizhou basically remain low in comparison to the rest of the country. Hainan has a small population and a low demand for electricity, so the size of the power industry is small. Therefore, the overall level of electricity development in the southern region is relatively low.

Finally, for Central China, based on the data of Table III, it can be seen that the development level of electric power has always been at a low level compared to the rest of the country. This is mainly due to the high energy consumption of thermal power and its general benefits in most areas of Central China. Although Sichuan and Hunan province are rich in water resources, there are many small hydropower stations, and management must be strengthened. However, the slow economic development in Central China has led to little boost in the demand for electricity. Therefore, in the present scenario, the outlook for the development level and potential of the power industry in central China is not optimistic.

IV. CONCLUSION

This paper reports a dynamic comprehensive evaluation of the electric power development levels across various regions

and time periods. A tri-level index system for the comprehensive evaluation of electric power development is constructed. The system comprehensively considers the influence of the coordination between the power industry and economic energy, the level of electricity generation, the level of electricity consumption, the level of power supply and the potential for electric power development in the future. By using a method that combines information entropy and AHP, a static evaluation model is established to fully utilize the advantages of subjective weighting that can reflect human expertise and objective weighting that can reflect the characteristics of the data. A dynamic comprehensive evaluation model to determine power development levels is established by aggregating the static models of each time section and by using sequential weighted vectors. With this model, the level of electric power development in 29 provinces, cities and autonomous regions of China from 2007 to 2016 was evaluated based on provincial data, and the results of the evaluation were compared and analyzed by using data and visualization.

The research results of this paper can lead to quantitative and comprehensive evaluations of the power development level of multiple time and space dimensions and can provide guidance for the future development of the power industry. Through the horizontal and vertical comparison analysis of the comprehensive level of electric power development and the evaluation value of all second-level indices in different regions, the advantages, defects, characteristics and developmental potential of power grids in each region can be clearly identified. The conclusion is conducive to understanding the overall situation, development speed and weak links of the development of electric power, allowing for more pertinent construction within the electric power industry.

REFERENCES

- [1] X. F. Yu and D. Fu, "Multi index comprehensive evaluation method," *Statistics and Decision*, no. 11, pp. 119–121, Nov. 2004.
- [2] Y. J. Guo, L. Hu, and Z. G. Wang, "Method of dynamic comprehensive evaluation based on three stage difference driving features," *Journal of Systems Engineering*, vol. 26, no. 4, pp. 546–550, Aug. 2011.
- [3] Y. J. Guo, Y. Yao, and P. T. Yi, "Method and application of dynamic comprehensive evaluation," *Systems Engineering—Theory & Practice*, vol. 27, no. 10, pp. 154–158, Oct. 2007.
- [4] Y. Yang, "Weighting method in multi index comprehensive evaluation," *Statistics and Decision*, no. 13, pp. 17–19, Jul. 2006.
- [5] L. Chen, "Research on indicators and assessment of sustainable development for Beijing power industry," M.S. thesis, Department of School of Economics and Management, North China Electric Power University, Baoding, 2004.
- [6] Y. L. Sun, C. Q. Kang, S. S. Chen, J. X. Meng, C. Lu, and J. S. Luo, "Low-carbon power grid index system and evaluation method," *Automation of Electric Power Systems*, vol. 38, no. 17, pp. 157–162, Sep. 2014.

- [7] Y. Z. Mu, Z. X. Lu, Y. Qiao, Y. Wang, H. Huang, Q. Y. Zhou, and J. H. Han, "A comprehensive evaluation index system of power grid security and benefit based on multi-operator fuzzy hierarchy evaluation method," *Power System Technology*, vol. 39, no. 1, pp. 23–28, Jan. 2015.
- [8] T. J. Pu, N. S. Chen, X. J. Ge, W. Wang, and G. Y. Liu, "Research on evaluation index system and synthetical evaluation method for balance of electric power and energy," *Power System Technology*, vol. 39, no. 1, pp. 250–256, Jan. 2015.
- [9] L. T. Tian, L. Cheng, R. Li, et al. "A Multi-scenario Energy Efficiency Evaluation Method for District Multi-energy Systems Based on Weighted Directed Graph," *Proceedings of the CSEE*, vol. 39, no. 22, pp. 6471–6483, Nov. 2019.
- [10] Y. J. Yang and J. C. Liu, "Research on the evaluation index system of power and social sustainable development," *Journal of North China Electric Power University (Social Science)*, no. S2, pp. 22–25, Dec. 2011.
- [11] Q. Y. Liu, "The study on comprehensive evaluation about energy-saving and emission reduction contribution effect of power grid enterprise," M.S. thesis, Department of School of Economics and Management, North China Electric Power University, Beijing, 2012.
- [12] W. J. Wang, "Research on smart grid low carbon benefit assessment and application," M.S. thesis, Department of School of Economics and Management, North China Electric Power University, Beijing, 2012.
- [13] Q. Wang, F. S. Wen, M. Liu, and S. Yi, "Combined use of fuzzy set theory and analytic hierarchy process for comprehensive assessment of electricity markets," *Automation of Electric Power Systems*, vol. 33, no. 7, pp. 32–37, Apr. 2009.
- [14] B. Wang, G. Y. He, S. W. Mei, Y. B. Chen, and W. Liu, "Construction method of smart grid's assessment index system," *Automation of Electric Power Systems*, vol. 35, no. 23, pp. 1–5, Dec. 2011.
- [15] W. Tan, G. Y. He, F. Liu, W. Y. Huang, Z. Y. Deng, and Y. Deng, "A preliminary investigation on smart grid's low-carbon index system," *Automation of Electric Power Systems*, vol. 34, no. 17, pp. 1–5, Sep. 2010.
- [16] S. Zhang, T. Wang, and X. P. Gu, "Synthetic evaluation of power grid operating states based on intuitionistic fuzzy analytic hierarchy process," *Automation of Electric Power Systems*, vol. 40, no. 4, pp. 41–49, Feb. 2016.
- [17] L. Yang, H. L. Wu, and K. Men, "An energy saving and economy operation evaluation method for China southern power grid," *Automation of Electric Power Systems*, vol. 38, no. 17, pp. 31–38, Sep. 2014.
- [18] Y. H. Dai, L. Chen, Y. Min, and T. Cheng, "Study on the daily operation assessment system of power grid," *Power System Technology*, vol. 39, no. 6, pp. 1611–1616, Jun. 2015.
- [19] Y. Y. Chi, D. X. Niu, X. Y. Li, G. Deng, and Z. Liu, "Research on evaluation of power supply service quality based on the matter-element analysis theory," *Automation of Electric Power Systems*, vol. 34, no. 13, pp. 33–37, Jul. 2010.
- [20] Y. F. Liu, "Practical application of Kender's harmonious coefficient in faithfulness in measurement and test results," *Journal of Xinxiang Education College*, vol. 19 no. 2, pp. 95–96, Jun. 2006.
- [21] R. R. Yager, "On ordered weighted averaging aggregation operators in multicriteria decision making," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 18, no. 1, pp. 183–190, Jan./Feb. 1988.



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