The Evaluation System of Power Market Monitoring Based on AHP and the Entropy Method

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Abstract. China's new round of power system reform requires enhanced supervision of the power market. As power market monitoring is an important link of power market supervision, its necessity and importance has been further highlighted under the new reform. This paper constructs an evaluation index system of power market monitoring based on the industrial organization theory. Moreover, we combine the analytic hierarchy process (AHP) and the entropy method to obtain weights of different indices. Finally, a comprehensive evaluation of the power market monitoring is obtained. This paper has practical value for the risk warning of the power market.

1. Introduction
China's power industry is undergoing market-oriented reform. In 2015, China issued the No.9 document on new power system reform, which required the orderly release of electricity prices in competitive links except the transmission and the distribution. The No.9 document also required the orderly release of electricity distribution business to social capital, the orderly release of public welfare, non-regulatory power generation, consumption plans, as well as a further release of market vitality. Meanwhile, the No.9 document also requires a deep strengthening of government supervision, thus the importance and necessity of power market monitoring is further highlighted.

Power market monitoring refers to a series of activities including carrying out the real-time monitoring, investigating and rectifying violations of the rules, identifying market design defects and putting forward suggestions based on the defects found. It can effectively identify the conditions that hinder the market efficiency, such as the abuse of market power and market manipulation, playing an important role in finding risks and correcting market failures. Therefore, power market monitoring has an important function of early risk warning. Its main works include scientifically establishing a monitoring index system which reflects the operation and fluctuation of the power market and making a comprehensive evaluation. Based on the industrial organization theory, this paper constructs an evaluation index system of power market monitoring to study the issues of power market monitoring. Moreover, the hierarchy process (AHP) and the entropy method are applied to obtain the weights of different indices. Ultimately, a comprehensive evaluation is obtained. This paper has practical value for the risk warning of the power market.
2. Literature review
Currently, some scholars have carried out researches on issues related to power market monitoring. Some established a market power monitoring system or framework for the power market (Liu et al., 2004; Guler and Gross, 2005)[1,2]. Garcia and Reitzes (2007) reviewed different market regulation and market power mitigation policies in the world electricity market[3]. Hellmer and Warell (2009) used the HHI index to study different measures of concentration and dominance in the power market[4]. Liu et al. (2014) constructed a comprehensive risk evaluation index system for self-regulation according to the characteristics of the current power market in China[5]. Helman (2014) studied the market power of power generators[6]. Zogolli (2015) analyzed the characteristics, market design and regulatory framework of the electricity trading in the European electricity market[7]. Pinczynski and Kasperowicz (2016) introduced the content of power market monitoring and focused on the monitoring of economic parameters[8]. Kasperowicz et al. (2017), taking the Spanish electricity market as an example, constructed an evaluation system of the power market monitoring system[9]. Chen et al. (2018) proposed an evaluation system of regulatory indicators in the power market based on order relation analysis [10]. Guo et al. (2020) analyzed the short-term regulatory policies of the power market, and introduced the regulatory mechanism of power transmission and transformation companies in foreign power markets[11].

As can be seen from the above literature review, there are few studies on the monitoring and evaluation system of the power market. Most of the studies focus on a certain type of monitoring objects, such as market power and power trading, etc., or the supervision of the power market which focus on the entire power market.

3. The construction of power market monitoring index system
Industrial organization theory is the theoretical basis of market monitoring which constitutes an important branch of microeconomics, studying the behavior of enterprises and market structure under the condition of imperfect competition. The basic system of industrial organization theory consists of three categories: market structure, market behavior and market performance, namely SCP model. In this part, we build a power market monitoring index system based on the SCP model.

3.1 The indices of power market monitoring

3.1.1 Market structure
Market structure refers to the factors and characteristics of the relationship between sellers, buyers, sellers and buyer groups. Market concentration, key suppliers, residual supply rate, marginal unit formation rate, must-run rate and market supply-demand ratio are selected as monitoring indices of power market structure in this part.

(1) Market concentration
Market concentration is often measured by the market static index HHI.

\[ HHI = \sum_{i=1}^{n} G_i^2 \]  

Where \( G_i \) represents the market share of power generation enterprise i. The higher the HHI value, the higher the market concentration.

(2) Key suppliers
The key supplier index is a 0-1 variable, is a measure of how "critical" a target power plant is. Specifically, the index detects whether the sum of the capacities of other power plants can meet the load demand after deducting the capacity of the target power plant. If so, the value is 0. If not, the value is 1.

(3) Residual supply rate
The residual supply rate is the sum of the market share of a given generator over a given period. The quantity declared by generator i is \( q_i \), where N is the number of power generators, D is the total market demand, and the residual supply rate is expressed as follows:

\[ RS = \frac{\sum_{i=1}^{N} q_i}{D} \]  

(2)
If the residual supply rate of generator i is less than 100%, it indicates that the generator has the ability to control the market price.

(4) Marginal unit formation rate

\[
M_i = \frac{T_i}{T_b}
\]  

In the formula, \(M_i\) is the marginal unit formation rate of generator i, \(T_i\) is the number of time periods for generator i to form marginal units, and \(T_b\) is the total number of bidding time periods. When the marginal unit formation rate of generator i is much higher than the proportion of its annual generating capacity in the annual generating capacity of all the competing generators, the market power level of the generator can be preliminarily judged.

(5) Must-run rate

\[
MR_i = \max \left[ \frac{D - \sum_{j=1}^{N} q_j}{C_i} \right] 
\]  

The must-run rate is the percentage of generating capacity that a generator must operate as a percentage of generating capacity. Where \(MR_i\) is the must-run rate of generator i, \(D\) is the total market demand, \(q_j\) is the declared electric quantity of the jth generator, and \(C_i\) is the generating capacity of generator i. The higher the required operating rate, the greater the market power.

(6) Market supply-demand ratio

\[
SD = \frac{\sum_{i=1}^{N} S_i}{\sum_{j=1}^{M} D_j} \times 100\%
\]  

\(S_i\) is the power supply of the ith power generating enterprise in the market, and \(D_j\) is the power demand of the jth power purchasing enterprise in the market.

### 3.1.2 Market behavior

Market behavior refers to the strategic behavior taken by enterprises in order to obtain greater profits and higher market share. Market behavior in the electricity market mainly includes the price strategy and supply strategy of power generator.

(1) Highest market price index

\[
CP_i = \frac{q_{al}}{Q_a} \times 100\%
\]  

In the formula, \(CP_i\) is the market maximum price index of the power generation enterprise i, \(q_{al}\) is the electricity quantity reported by the power generation enterprise i that is close to the highest price, and \(Q_a\) is all declared electricity quantity.

(2) Maximum price arrival rate

\[
CR = \frac{T_{hi}}{T_b}
\]  

In the formula, \(T_{hi}\) is the number of periods in which the market clearing price is equal to the maximum price.

(3) Price markup index

\[
PA_i = \frac{P_{mi} - MC_i}{MC_i}
\]  

In the formula, \(PA_i\), \(P_{mi}\) and \(MC_i\) are the price markup index, quotation and marginal cost of power generation enterprise i respectively.

(4) Declared capacity retention

\[
AH_i = \frac{Q_{cl} - Q_{bi}}{Q_{cl}}
\]  

The declared capacity retention reflects the power supply control degree of the generator. In the formula, \(AH_i\) is the declared capacity retention of the generator i, \(Q_{cl}\) is the generating capacity of the generator i, and \(Q_{bi}\) is the actual declared capacity.

### 3.1.3 Market performance

Market performance refers to the realistic state achieved by an industry in terms of price, output, cost, profit, product quality and technological progress through certain market behavior under a certain
market structure. Market performance is restricted by market structure and market behavior. It is the ultimate symbol of whether the market relationship or resource allocation is reasonable or not, reflecting the efficiency of market operation.

(1) Excess return
Excess earnings of power generator can be reflected through high bid winning rate, low bid winning rate and successful bid degree.

1) The winning rate of high bid
\[ H_i = \frac{S_{hi}}{S_i} \times 100\% \]  
In the formula, \( S_{hi} \) is the electric quantity that the bidding price of power generation enterprise \( i \) is higher than the highest value of the previous year's historical clearing price and the winning bid. \( S_i \) is the total bidding quantity of power generation enterprise \( i \).

2) The winning rate of low bid
\[ L_i = \frac{S_{li}}{S_i} \times 100\% \]  
In order to improve the winning rate, some power generator will be free riders, that is, to offer a low price to improve the winning rate. In the formula, \( S_{li} \) is the amount of electric quantity that the bidding price of power generation enterprise \( i \) is lower than the lowest value of the previous year's historical clearing price and the winning bid. \( S_i \) is the total bidding quantity of power generation enterprise \( i \).

3) Successful bid degree
\[ BS_i = \frac{S_{di}}{S_a} \times 100\% \]  
In the formula, \( BS_i \) is the quotation success degree of the power generation enterprise \( i \), \( S_{di} \) is the percentage of declared and transacted electric quantity of the power generation enterprise \( i \), and \( S_a \) is the percentage of the market average declared and transacted electric quantity.

(2) Lerner index (LI)
\[ LI = \frac{P - MC}{P} \]  
In the equation, \( P \) is the market price of the power market, which is the ideal competitive price calculated based on the marginal cost of the generator set. The greater the value of LI indicator, the greater the behavioral market power in the market.

(3) Degree of market competition
\[ CD = \frac{P_l - MC}{P_l} \times 100\% \]  
The degree of market competition can be calculated from the upper limit of market price and the marginal price of market, where \( P_l \) is the upper limit of market price and MC is the marginal price of market.

3.2 The calculation method of monitoring results
This paper combines the analytic hierarchy process (AHP) and the entropy method with the multiplication and synthesis method of the minimum information entropy principle to get the combined weight of each index.

3.2.1 Analytic hierarchy process
Analytic hierarchy process (AHP) combines the evaluation methods of qualitative and quantitative analysis. Its basic steps are: establishing the hierarchical structure model, constructing the judgment matrix, consistency test, calculating the weight of each layer, and overall consistency test.

(1) Construction of judgment matrix
The construction of judgment matrix is based on the comparison of the relative importance of all factors of the layer to a factor of the upper layer, generally using the 1-9 scale method. The details are shown in Table 1.
### Table 1. Value and implication of judgment matrix

| Value | Implication                                      |
|-------|--------------------------------------------------|
| 1     | $I_i$ and $I_j$ are equally important            |
| 3     | $I_i$ is slightly more important than $I_j$      |
| 5     | $I_i$ is obviously more important than $I_j$     |
| 7     | $I_i$ is more important than $I_j$               |
| 9     | $I_i$ is extremely important than $I_j$         |
| 2, 4, 6, 8 | The median of the two adjacent judgments |

Inverse Comparison result of $I_j$ and $I_i$

According to the judgment matrix $A$, the maximum eigenvalue $\lambda_{\text{max}}$ and the normalized eigenvector $W$ are calculated. The calculation formula is as follows:

$$AW = \lambda_{\text{max}} W$$  \hspace{1cm} (15)

In the formula, $W = (w_1, w_2, \ldots, w_n)$ is the corresponding weight of each index, and $n$ is the order of the judgment matrix $A$.

(2) Matrix consistency test

The judgment matrix may have some inconsistencies due to the complexity of the judgment. In order to solve this problem, it is necessary to check the consistency of the judgment matrix.

$$\varepsilon_{ci} = \frac{\lambda_{\text{max}} - n}{n - 1}$$  \hspace{1cm} (16)

$$\varepsilon_{cr} = \frac{\varepsilon_{ci}}{\varepsilon_r} < 0.1$$  \hspace{1cm} (17)

Where $n$ is the order of the judgment matrix, $\lambda_{\text{max}}$ is the maximum eigenvalue of the judgment matrix, and $\varepsilon_r$ is the average random consistency index with values shown in Table 2. If $\varepsilon_{ci}$ is 0, the matrix has complete consistency; the larger the value of $\varepsilon_{ci}$, the worse the consistency of the judgment matrix. And when $\varepsilon_{cr} < 0.1$, the consistency test is passed.

### Table 2. Average random consistency index

| $n$ | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|    | 0.58| 0.89| 1.12| 1.26| 1.36| 1.41| 1.46| 1.49|

#### 3.2.2 Entropy method

Entropy method is based on the principle of information entropy. The smaller the information entropy of the evaluation index is, the greater the information provided by the index and the greater the weight value given to it should be. Let $m$ be the number of evaluation objects, $n$ the number of evaluation indices, and $x_{ij}$ be the evaluation score of the $j$th evaluation index of the evaluation object $i$. The steps to determine the weight of indices by entropy method are as follows:

(1) Index normalization processing

Since the units of each evaluation index are not consistent, it is necessary to conduct dimensionless processing on the original data of positive and negative indices, and the specific operations are as follows:

$$x'_{ij} = \frac{x_{ij} - \min[x_{1j}, x_{2j}, \ldots, x_{mj}]}{\max[x_{1j}, x_{2j}, \ldots, x_{mj}] - \min[x_{1j}, x_{2j}, \ldots, x_{mj}]}$$  \hspace{1cm} (18)

$$x_{ij} = \frac{x_{ij} - \min[x_{1j}, x_{2j}, \ldots, x_{mj}]}{\max[x_{1j}, x_{2j}, \ldots, x_{mj}] - \min[x_{1j}, x_{2j}, \ldots, x_{mj}]}$$  \hspace{1cm} (19)

(2) Computing Information Entropy

The entropy of the $j$th evaluation index, $H_j$, is calculated according to the following formula:

$$H_j = -\beta \sum_{i=1}^{n} f_{ij} \ln(f_{ij})$$  \hspace{1cm} (20)

$$f_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}}$$

$$\beta = \frac{1}{\ln(n)}$$  \hspace{1cm} (21)
This paper makes the following assumption: in the calculation of $H_j$, it may appear that $f_{ij} = 0$, so $\ln(f_{mk})$ is not mathematically meaningful, so if $x_{ij} = 0$, then $f_{ij} = 0$, and $f_{ij}/\ln(f_{ij}) = 0$.

### 3. Calculate entropy weights

The traditional entropy method is used to calculate the entropy weight $w_j$, it adopts the standardized processing method, as shown in the following formula:

$$ w_j = \frac{|1-H_j|}{\sum_{j=1}^{n}|1-H_j|} $$

In the formula, $1 - H_j$ is the redundancy of information entropy.

#### 3.2.3 Combined weighting method

In the paper, we combines analytic hierarchy process (AHP) and the entropy method to calculate the weights of indices. The commonly used methods to construct the comprehensive weight include the multiplication method, the weighted linear method and the additive and multiplicative mixed method. However, these methods often contain the artificial subjective tendency. This article selects the multiplicative synthesis under the principle of minimum information entropy. The subjective weight $w_j$ and objective weight $w'_j$ are combined. The combined weight value can be obtained by using Lagrange multiplier method optimization:

$$ W_j = \left(\frac{w_j w'_j}{\prod_{j=1}^{n} w_j w'_j}\right)^{0.5} $$

#### 3.2.4 Monitoring and evaluation results

Based on the power market monitoring and evaluation index system and its combined weight value, the power market monitoring and evaluation results can be obtained. The specific calculation formula is as follows:

$$ R_T = \sum_{j=1}^{n} W_j x_{ij} $$

In the formula, $R_T$ is the monitoring result of the power market, and the operation situation of the power market can be judged according to its value. Consequently, the early risk warning and response measures can be taken with reference to $R_T$.

### 4. Empirical study

This part adopts random number simulation for empirical study. Firstly, each index is given a maximum score of 10 points according to the AHP. Randomly generate the evaluation index value of 100 evaluation subjects distributed between 0 and 10. Secondly, the judgment matrix is constructed according to AHP and the consistency test is carried out. Thirdly, the entropy method is used for objective assignment. Lastly, based on the principle of minimum information entropy, we combined the subjective weight and the objective weight, and the Lagrange multiplier method is used to optimize the combined weight.

The determination of the warning levels of the monitoring results is based on the comprehensive evaluation from experts in the power industry. The warning level is divided into different types, namely: yellow warning, orange warning, red warning. Based on a weighted score and expert opinion, a yellow alert is given for points above a certain level, an orange alert for points between some certain levels, and a red alert for points below a certain level.

#### 4.1 Market structure

Market structure indicators mainly include six first-level indicators whose weights are listed in Table 3.
Table 3. Market structure indicators

| First-level indicators         | AHP     | Entropy weight | Combined weight |
|--------------------------------|---------|----------------|-----------------|
| Market concentration          | 0.1574  | 0.1411         | 0.1531          |
| Key suppliers                 | 0.1871  | 0.1823         | 0.1897          |
| Residual supply rate          | 0.1889  | 0.1622         | 0.1798          |
| Marginal unit formation rate  | 0.0492  | 0.1518         | 0.0888          |
| Must-run rate                 | 0.1221  | 0.1893         | 0.1562          |
| Market supply-demand ratio    | 0.2953  | 0.1734         | 0.2324          |

4.2 Market behavior

Market behavior indicators mainly include four first-level indicators whose weights are listed in Table 4.

Table 4. Market behavior indicator

| First-level indicators                  | AHP     | Entropy weight | Combined weight |
|----------------------------------------|---------|----------------|-----------------|
| Highest market price index             | 0.2678  | 0.2351         | 0.2577          |
| Maximum price arrival rate             | 0.3699  | 0.2819         | 0.3317          |
| Price markup index                     | 0.2871  | 0.2480         | 0.2741          |
| Declared capacity retention            | 0.0752  | 0.2349         | 0.1365          |

4.3 Market performance

Market performance indicators mainly include three first-level indicators whose weights are listed in Table 5.

With the weights obtained above, we can calculate the power market monitoring result and provide suggestions for risk warning.

Table 5. Market performance indicator

| First-level indicators         | Second-level indicators         | AHP     | Entropy weight | Combined weight |
|-------------------------------|--------------------------------|---------|----------------|-----------------|
| Excess return                 | The winning rate of high bid    | 0.2765  | 0.2063         | 0.2435          |
|                               | The winning rate of low bid     | 0.2449  | 0.2305         | 0.2422          |
|                               | Successful bid degree           | 0.1994  | 0.1982         | 0.2026          |
| Lerner index(LI)              |                                 | 0.0759  | 0.2024         | 0.1264          |
| Degree of market competition  |                                 | 0.2033  | 0.1626         | 0.1853          |

5. Conclusion

In this paper, we construct an evaluation index system of power market monitoring. Moreover, we combine analytic hierarchy process (AHP) and the entropy method to obtain the index weight. Finally, the comprehensive evaluation of power market monitoring is obtained to provide effective support for the risk warning of the power market. According to our results, we draw the following conclusions.

Both the subjective weighting method and the objective weighting method assigned different weights to different indices with objective weights distributed more evenly. Most of the combined weights lie between the AHP and the entropy weights with few of them larger than both of the AHP and the entropy weights. For the market structure, the market supply-demand ratio is assigned largest weight. For the market behavior, the maximum price arrival rate is assigned largest weight. For the market performance, the winning rate of high bid is assigned largest weight. Our findings carry certain implications for the early warning function of power market monitoring.
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