INTRODUCTION

In July 2019, the General Office of the State Council issued the “Guidance on Accelerating the Construction of a Social Credit System and Building a New Credit-Based Regulatory Mechanism,” which emphasized the fundamental role of a credit system in the innovation of the regulatory mechanism and improvement of the regulatory capacity and level. Currently, the construction of a credit system in the market-oriented reform of the electricity system of China is still not completely established, making it challenging to match the existing electricity market mechanism. A scientific and effective credit evaluation method needs to be quickly defined to maintain safe and stable electricity market operations.

Credit evaluation method of generating companies considering the market behavior in China electricity market

Jingdong Xie | Shiyao Wang | Xuemei Zhou | Bo Sun | Xin Sun

Shanghai University of Electric Power, Shanghai, China

Correspondence
Shiyao Wang, Shanghai University of Electric Power, Shanghai 200090, China.
Email: 19106020@mail.shiep.edu.cn

Funding information
Data Center of Management Science, National Natural Science Foundation of China - Peking University, Grant/Award Number: 71972127

Abstract
Since the reformation of the electricity market of China is increasing and the modernization of the national governance system is being promoted, the electricity market management system needs to be gradually improved. Credit evaluation is an essential part of the electricity market management system. Therefore, a complete credit evaluation system plays a fundamental role in ensuring that the electricity market can operate safely, stably, efficiently, and reliably. The traditional credit evaluation methods focus on the financial situation and credit records of the generating companies. With the gradual development of the electricity market transactions, the market behavior needs to be included in the credit evaluation indicator system to standardize the behavior of the generating companies and reduce the risks of the market transactions. This study establishes a complete credit evaluation system from three perspectives: market behavior, financial situation, and social responsibility. In addition, to determine the weight of indicators in the credit evaluation, the analytic hierarchy process (AHP) algorithm, fuzzy theory, and the non-dominated sorted genetic algorithm II (NSGA-II) algorithm are combined. The variance of the evaluation results and the deviation degree of the indicator weight are considered the objective functions of the NSGA-II algorithm to optimize the indicator weight. Finally, comparing as an example the results of the credit evaluation before and after the optimization of an electricity market shows that the credit evaluation method can effectively distinguish the generating companies that adopt different market behaviors and has a high practical significance.

KEYWORDS
credit evaluation, electricity market, NSGA-II algorithm, weight optimization
The current research on the credit evaluation methods of the electricity market is insufficient. In addition, in each country, the evaluation methods focus on different aspects, and a recognized evaluation system has not yet been determined. The PJM will conduct the credit scoring based on the audit reports provided by the market members. The main indicators include a multiple interest guarantee, debt repayment rate, total liabilities, tangible net assets ratio, total liabilities, tax depreciation, earnings before sales, and the ratio between short-term debt and total assets. Its evaluation indicators mainly investigate the debt-paying ability of the generating companies. The credit rating of CAISO mainly adopts the equivalent credit rating results of Moody. Its evaluation system is composed of qualitative and quantitative indicators, and it includes five aspects: the long-term electricity supply contracts, pricing flexibility, the capital structure of the members, financial status, and company size. In addition, it gives a higher weight to the indicators, such as whether market members can sign long-term electricity contracts and their financial situation for approximately three years. The credit rating of Australia is usually assessed by the Australian Securities and Investments Commission (ASIC). Its credit rating considers factors such as company and capital structures, company management, operating capacity, investment process, risk management, past performance, economic circle, and capital cycle. Usually, the mature foreign electricity market evaluation systems mentioned above analyze the credits of the market members by calculating the quantitative financial indicators. The credit evaluation indicators in China are mainly based on making the behavior of market members' standard and maintaining the operations of the market safe and stable. Reference indicates the credit evaluation indicator system of the Yunnan electricity market based on seven factors: basic management, contract management, transaction process, transaction results, market order, solvency, and credit record. Reference includes the financial indicators into the credit evaluation indicator system of the Guangdong electricity market to consider the operation ability, profitability, growth ability, and debt-paying ability of the market members. Reference introduces the credit evaluation indicator system of the electricity supply companies based on six aspects: basic conditions, trustworthiness ability, trustworthiness willingness, trustworthiness performance, financial situation, and credit record; it also uses the kernel principal component analysis to determine the indicator weight.

Although the above credit evaluation methods covered many aspects, they never included the violation transaction behaviors in the transaction process. Reference introduced a game theory model and conducted an IEEE9-bus test, which proved that the generating companies have a strong motive for collusion in the Canadian wholesale electricity market. Reference shows that the possibility of a collusive behavior among the members cannot be excluded after using the market electricity price and corporate power generation capacity data to perform the revealed preference test to the retail electricity market in Japan. The development of the electricity market of China is in its primary stage. In the electricity market, the market power abuse cannot be ignored, which refers to the ability of the market participants to influence the market prices with their predominant market shares and to make price deviate from that in full competition. It mainly contains collusive bidding, extreme quotations, and capacity withholding. However, the existing credit evaluation methods cannot reflect these violation transaction behaviors of the generating companies on their credit scores. Furthermore, they cannot restrict and punish the generating companies that violate the regulations. Consequently, the healthy and stable development of the markets is limited. The recognition methods of the violation transaction behaviors are continuously improving. This paper proposes that the credit evaluation agencies refer to the violation behavior recognition results and quantity them with the credit evaluation indicator system. As a result, the credit evaluation can be combined with the market transaction risk prevention, and the credit rating results can be used for decision-making and the supervision of risk prevention. Recently, to improve the renewable energy consumption capacity, the government has introduced the renewable portfolio standard policy (at least 9% of the total power generation of the generating companies must come from non-hydro renewable energy sources). However, the existing evaluation methods have not considered environmental protection, so the corresponding indicators are added to the evaluation indicator system in this paper.

Based on this idea, this paper will establish a broader and more comprehensive credit evaluation method for the generating companies in the electricity market based on the traditional evaluation method. The analytic hierarchy process (AHP) lacks objectivity in determining the weight of the indicators and cannot quantify the advantages and disadvantages of the evaluation results. For this reason, the fuzzy theory, AHP algorithm, and NSGA-II genetic algorithm are combined in this paper to design an optimization method for the weights of the indicators, which is applied in the calculation of the credit evaluation results of the generating companies in the electricity market.

2 CREDIT EVALUATION INDICATOR SYSTEM FOR GENERATING COMPANIES IN THE ELECTRICITY MARKET OF CHINA

2.1 Establishment of the indicator system

The construction of the credit evaluation indicator system of an electricity market is a systematic project. The setting of
indicators can reflect the orientation of the market operation rules and distinguish between the good and bad members of the market. Considering that China's system is different from that of other countries, the indicator should be focused on the market transaction behavior and pay attention to the illegal behaviors, such as the abuse of market power, to standardize the behavior of market members and reduce transaction risks. In addition, when setting up the credit evaluation system of China's electricity market, we should follow the important principles, such as law of market economy, safe operation of the system, “three public policies,” and environmental protection so that a scientific and effective credit evaluation indicator system can be constructed.

2.2 Framework of the indicator system

This paper follows the basic design principles and establishes a three-level credit evaluation indicator system and a two-stage evaluation process for the generating companies in the electricity market. The credit evaluation indicator system consists of 29 indicators listed in Table 1, including market behavior, financial situation, and social responsibility. In the first stage, we score the credit evaluation indicators and calculate the total score. In the second stage, the generating companies with certified irregularities or excellent performance will receive or lose points based on the total score of the evaluation process, shown in Figure 1.

2.3 Description of the indicator system

1. Description of the market behavior indicators

The indicator system considered in this paper mainly focuses on the market behavior considering four aspects: the registration information, violation transaction behavior, settlement management, and information disclosure. The score of violation transaction behavior indicators is an essential manifestation of whether the generating companies have abused their market power.

The completeness and timeliness of the registration information are the most basic indicators to qualify the market members.

The violation transaction behaviors mainly include collusive bidding, extreme quotation, and capacity withholding. Currently, the identification of the irregularities in the trading process is inefficient and difficult to identify. It primarily relies on the decisions of the experts after complaints and reportings. The definition of the indicators should consider the intelligent recognition results of the violation transaction behavior to enable the credit evaluation results standardize the market transaction behavior. The results of the collusive bidding evaluation model in Reference 11 provide the probability that each generating company adopts a collusive quotation strategy to raise the market prices for their profits. Identifying violations in the electricity market through the cloud model and fuzzy Petri network in Reference 14 can provide the probability that each generating company uses an extreme quotation to obtain extra profits. The monitoring method of the capacity withholding in Reference 15 can provide the probability that each generating company obtains additional profits by reducing its power declaration. This paper proposes three indicators: the suspicion of collusive bidding, suspicion of extreme quotation, and suspicion of capacity withholding. These indicators show the probability of three types of transaction behavior violations: collusive bidding, extreme quotation, and capacity withholding. The credit evaluation agencies can refer to the probability of various violation behaviors, and the thresholds provided by the experts.

The generating companies are classified according to three types of suspicion intervals: low suspicion, medium suspicion, and high suspicion. The generating companies in the low suspicion interval should be regarded as non-violators, while those in the medium suspicion interval should be notified, and the score of their corresponding indicators lowered. Finally, the generating companies in the high suspicion interval should be penalized by setting the score of their corresponding indicators to zero.

The settlement management mainly considers the completion rate of the contract and the settlement, and the punctuality rate of settlement, reflecting the generating companies' performance willingness of contract and credit status of settlement.

The information disclosure includes standardization and timeliness of disclosure, reflecting the information disclosure of the generating companies.

2. Description of financial status indicators

The financial status is mainly considered under five aspects: profitability, operational capacity, performance guarantee, solvency, and growth capacity. The profitability considers the return on equity, the ratio of profits to cost, and the return on assets, which reflects the assets and profits use. The operational capacity considers the market shares in the provinces, the accounts receivable turnover, and the utilization of total assets, which reflects the operating turnover situation. The performance guarantee considers the timeliness of the submission and the payment of the guarantee amount. In addition, the guarantee amount is associated with the annual electricity sales scale, and the part beyond the expected electricity sales needs to be supplemented. The solvency considers the asset-liability ratio, current ratio, and quick ratio, reflecting the debt situation and repayment ability. The
| First-level indicators | Second-level indicators | Third-level indicators | Indicator content/calculation formula | Indicator number |
|------------------------|-------------------------|------------------------|--------------------------------------|-----------------|
| Market behavior        | Registration information| Integrity of the registration information | Whether the registration information of the generating companies is complete according to the management measures of the electricity market access | 1               |
|                        |                         | Timeliness of the registration information variation | Whether the generating companies apply for change within the specified time due to variations in the registration information | 2               |
| Violation transaction behavior | Suspicion of collusive bidding | | Whether the generating companies collude with the prices to disrupt market prices | 3               |
|                        | Suspicion of extreme quotation | | Whether the generating companies use extreme quotations to own the market power and earn extra profits | 4               |
|                        | Suspicion of capacity withholding | | Whether the generating companies deliberately report less power generation capacity and reduce the market supply to evade supervision | 5               |
| Settlement management  | Completion rate of transaction contract | | Ratio of the number of the electric contracts offered by the generating companies to those signed. It indicates the contract performance of the generating companies | 6               |
|                        | Completion rate of transaction settlement | | Ratio of the number of the electric contracts settled by the generating companies to those signed. It indicates the contract settlement situation of the generating companies | 7               |
|                        | Punctuality rate of transaction settlement | | Ratio of the number of transactions completed on time by the generating companies to the total number of transactions. It indicates the settlement of the market transactions basic situation | 8               |
| Information disclosure | Normalization of information disclosure | | Whether the generating companies reveal information in a standard and accurate manner following the management measures of information disclosure | 9               |
|                        | Timeliness of information disclosure | | Whether the generating companies reveal information in a timely manner following the management measures of information disclosure | 10              |
| Financial situation    | Profitability           | Return on equity       | Net profit/net assets × 100%. It indicates the net profit of an enterprise by operating its assets | 11              |
|                        |                         | Ratio of profits to cost | Total profit/total cost × 100%. It indicates the operating results brought about by the expenses | 12              |
|                        |                         | Return on assets        | Net profit/average total assets × 100%. It indicates the efficiency of the asset utilization | 13              |
| Operational capacity   | Local market shares     | Electricity of the cumulative market of the generating companies/total market electricity × 100% | | 14 |
|                        | Accounts receivable turnover | | Net credit sales/average balance of the accounts receivable × 100%. It indicates the turnover speed and management efficiency | 15              |
|                        | Utilization of total assets | | Net operating income/average total assets × 100%. It represents the operation efficiency of the assets | 16              |
| Performance guarantee  | Timeliness of submission | | Whether the generating companies submit the performance guarantee on time | 17              |
|                        | Payment of the guarantee amount | | Whether the guarantee amount paid by the generating companies meets the declared annual electricity sales range | 18              |
growth capacity considers the total assets and operating profit growth rates, reflecting the future development.

3. Description of the social responsibility indicators

Social responsibility is considered under two aspects: security management and environmental protection. Security management includes the equipment failure rate, continuous safe operation days, and safety awareness, which reflects the image and reputation of the generating companies. Environmental protection includes the environmental assessment score, the completion rate of the renewable and non-hydro renewable energy quotas. Suppose the country attributes high importance to energy conservation and environmental protection. In that case, generating companies’ social image and market recognition will improve as the environmental assessment score and the completion rate of the clean energy quota increase.

4. Description of the addition and deduction of points in the second stage

The “deduction of points” indicators include transaction violations and bad credit records. The transaction violations are considered under three aspects: the number of registration failures, contract performance failures, and market transaction violations. The number of registration failures represents the times that generating companies submit false registration information to the trading agencies. The number of contract performance failures represents the times that the generating companies miss the deadlines for delivering electricity. The bad credit records are an assessment of the companies’ payment behavior.

TABLE 1 (Continued)

| First-level indicators | Second-level indicators | Third-level indicators | Indicator content/calculation formula | Indicator number |
|------------------------|-------------------------|------------------------|--------------------------------------|-----------------|
| Solvency               | Asset–liability ratio   | Total liabilities/total assets × 100%. It indicates the liabilities and solvency | 19 |
|                        | Current ratio           | Current assets/current liabilities × 100%. It indicates the short-term solvency | 20 |
|                        | Quick ratio             | Quick assets/current liabilities × 100% It indicates whether the existing assets can pay debts | 21 |
| Growth capacity        | Growth rate of total assets | Total assets growth of the current year/total assets of the previous year × 100%. It indicates the capability to accumulate capital | 22 |
|                        | Growth rate of operating profit | Operating profit growth of the current year/operating profit growth of the previous year × 100%. It indicates the increase and decrease of the profits and provides a reference for future development | 23 |
| Social responsibility  | Security management     | Equipment failure rate  | (Downtime + maintenance time)/total time × 100%. It indicates the equipment management level and production safety level | 24 |
|                        |                         | Continuous safe operation days | Start counting from the second day of the last accident, and add one to the number of safe days after each day (without accident) passes. It represents the management level of the safety production of the generating companies | 25 |
|                        |                         | Safety awareness         | The recognition degree of hazard sources and risks in production, and whether the means of preventing major risks are perfect. It reflects the completeness of generating companies' emergency plans for potential accidents and emergencies | 26 |
| Environmental protection | Environmental assessment score | The environmental credit score was provided by the environmental protection department. It represents the environmental behavior of the generating companies | 27 |
|                        |                         | Completion rate of renewable energy quota | Purchasing electricity of renewable energy/renewable energy electricity quota × 100%. It reflects the completion of the renewable energy quota | 28 |
|                        |                         | Completion rate of non-hydro renewable energy quota | Electricity purchasing of non-hydro renewable energy/ non-hydro renewable energy electricity quota × 100%. It represents the total non-hydro renewable energy quota used | 29 |
companies fail to satisfy the contract without a specific reason once the transaction contract is signed and uploaded in the electricity market system. The number of market transaction violations represents the times that the generating companies show collusion behavior, violent pricing, market manipulation, and other violations identified by the trading center. Bad credit records are considered under three aspects: administrative penalty records, blacklist records, and contract breach records. The administrative law enforcement department issues the administrative penalty records. The blacklist records represent the records where the generating companies have been listed in dishonest enterprises and production safety blacklist, or where the enterprise legal persons are listed as people subjected to enforcement for trust-breaking. The contract breach records represent the judgment document records of the generating companies who lose the trials due to contract breach.

The “addition of points” indicators include the excellent behaviors within and outside the industry, suggestions, and reports. Excellent behaviors within the industry refer to the enterprise awards in the electricity industry assigned by the national, provincial, and municipal departments in the past three years. Excellent behaviors outside the industry refer to the awards assigned by the commercial, judicial, taxation, charity, and other departments in the past three years. Suggestions and reports refer to the behaviors that the companies discover and report loopholes in the trading rules (eventually their advice is adopted) or report illegal transactions.

There is no limit to the deduction of points. However, the limit for the addition of points shall be set according to the total score of the evaluation.

3 | WEIGHT OF THE CREDIT EVALUATION INDICATOR

3.1 | Calculation of the indicator weight

Currently, the methods to evaluate the weights of the evaluation indicators can be classified into two categories: (a) In
the first, the experts estimate the relative importance of each indicator according to previous experiences and then calculate the indicator weight through a scoring matrix, such as the expert investigation method and the AHP. In the second, the weight is determined according to the data characteristics of each indicator, such as the coefficient of variation method and the entropy weight method. Because of limited data samples and several qualitative indicators, the first category, which requires less data volume, is discussed in this paper. In addition, since the expert investigation method can be subjective and unreliable when the data samples are not sufficient, the AHP method is selected in this paper as the calculation method for a preliminary weight determination. The main steps of the AHP method are as follows: organize the elements related to the decision into several levels, define a judgment matrix for a pairwise comparison, and finally carry out a consistency test. The initial weights of the indicators calculated through the AHP algorithm are listed in the second column of Table 3.

### 3.2 Optimization of the indicator weight

1. The optimization process of an indicator weight

The evaluation indicator system defined in this paper contains several qualitative indicators. The AHP method can be subjective in the definition of the judgment matrix, resulting in subjective weight calculation results. Combining the fuzzy theory and AHP can produce more accurate and objective results through a negative feedback mechanism that optimizes the weight with a genetic algorithm.

The basic idea of a negative feedback adjustment of the indicator weight based on the evaluation result is that if the evaluation results do not vary significantly, the indicator weight should be zero. Meanwhile, if the evaluation results show significant differences, the indicator should have a higher weight. The variance is an important figure that reflects the degree of difference in statistics. The idea of variance maximization can be adopted in this paper, the total variance of the corresponding evaluation results can be maximized through a set of weights. Consequently, the evaluation results have broader coverage and are more sensitive to the scoring variations. In addition, although the AHP has several disadvantages, the relevant experience of experts should not be underestimated. We can combine the method of minimum deviation degree to optimize the weight with multiple objectives. The weight optimization process is shown in Figure 2.

2. The interval of the weight variation

In this paper, the fuzzy theory is used to determine the interval of the weight variation, which is considered the search space of the optimization algorithm.

The fuzzy sets A1, A2, A3, A4, and A5 were adopted to represent 5 levels of weight: tiny, small, moderate, large, and huge and to generate the corresponding membership functions. This paper adopts a Gaussian membership function, which better represents these conditions:

\[
\mu_{A_i} = e^{-\frac{c_i - x^2}{2\sigma^2}}, \quad x \in (0, 1), \quad i = 1, 2, 3, 4, 5
\]  

In Equation (1), \( c_i \) represents the mean value, and \( \sigma \) the variance. The variance of the standard membership function can be determined from the interval of the initial weight to subdivide the indicator weight. To generalize the method, the five membership functions in this paper have the same variance. To determine the position of the membership function and cover the interval of the weight variation more precisely, the mean values of the five normal membership functions are the minimum, the first quartile, the median, the third quartile, and the maximum values of the initial weight set. The parameter settings and the image of the membership functions are listed in Table 2 and shown in Figure 3, respectively.

Through Equation (1), the weight corresponding to the abscissas of the intersection points of the five membership functions in the figure can be calculated as 0.016, 0.02, 0.03, and 0.078, and the fuzzy set interval of the indicator weight can be obtained. By the principle of maximum membership, it is possible to determine the fuzzy set interval of 29 initial indicator weights as shown in Table 3.

### 4 Optimization algorithm of indicator weight based on NSGA-II

#### 4.1 Generation of random scores

By analyzing the preprocessed expert scoring data, it was found that most of the data follow a normal distribution. Other indicators include seven indicators: the timeliness of the registration information change, information disclosure, and performance guarantee submission, payment of the guarantee amount, suspicion of collusive bidding, extreme quotation, and capacity withholding. Since the scoring mechanism deducts points after each violation behavior, the score is segmented and follows multiple distributions. This paper generates 29 sets of random numbers based on 29 credit evaluation indicators to simulate the evaluation process. Each set of data contains 5000 random integers ranging from 0 to 100, which are the initial scoring data of each indicator.

The indicator data following the normal distribution law are generated based on the central limit theorem of Lindberg–Levy as shown in Equation (2) to represent the case under discussion better. They are mutually independent random
series with standard distributions and have the same mean value and variance of the data obtained from the survey. The indicator data that satisfy the law of multiple distributions are all generated based on the probability formula shown in Equation (3). The random series are mutually independent and have the same occurrence probability of the data obtained from the survey.

$$\lim_{n \to \infty} P \left( \frac{\sum_{i=1}^{n} x_i - n\mu}{\sqrt{ns^2}} \leq x \right) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt \quad (2)$$

Let \(\{x_i\}\) be a series of random variables with independent and identical distributions and \(E(x_i) = \mu, D(x_i) = \sigma^2, i = 1,\).
Equation (2) is satisfied if \( x \in R \). Therefore, let \( x_i \) be a random variable with a uniform distribution, the random variable \( \sum_{i=1}^{n} x_i \) has a normal distribution if \( n \) is sufficiently large.

\[
P(X_1 = n_1, \ldots, X_k = n_k) = \begin{cases} 
\frac{n!}{n_1! \cdots n_k!} p_1^{n_1} \cdots p_k^{n_k}, & \text{when } \sum_{i=1}^{k} n_i = n \\
0, & \text{otherwise}
\end{cases}
\]

(3)

Suppose a random experiment has \( k \) possible outcomes: \( A_1, A_2, \ldots, A_k \); let the random variable \( X_1, X_2, \ldots, X_k \) be their occurrence times, and \( p_1, p_2, \ldots, p_k \), their probability distributions. The event probability \( P \) of \( A_1, A_2, \ldots, A_k \) occurring \( n_1, n_2, \ldots, n_k \) times, respectively, obeys to multiple distributions of \( n \) samples.
Figure 4 shows the distribution curve of 22 groups of random indicator data that obey normal distributions. Figure 5 shows the probability bar chart of 7 groups of random indicator data corresponding to multiple distributions.

### 4.2 Optimization model based on the NSGA-II genetic algorithm

Based on the initial weights of the evaluation indicators obtained by the AHP algorithm and the randomly generated scoring data, 5000 times credit evaluations can be simulated using a set of evaluation results containing 5000 data. Based on the same random score, different weight combinations produce different evaluation results. The maximization of the variance is performed in the weight optimization process to maximize the dispersion of the evaluation results,
and in a mathematical sense, it is to maximize the sum of the score squared deviations. Furthermore, the minimum deviation method is to minimize the difference between the indicator weight and the initial weight of the AHP algorithm. According to the principle of maximum variance and minimum deviation, a multi-objective weight optimization model was defined. The objective function and restrictions of the optimization model are expressed by Equations (4)-(6) and Equations (7)-(9), respectively.

Objective function:

\[
F_1 = \max \left[ \sum_{j=1}^{m} \left( \sum_{i=1}^{n} w_i \cdot r_{ij} - M \right)^2 \right] \tag{4}
\]

\[
F_2 = \min \left[ \sum_{i=1}^{n} |w_i - w_i^0| \right] \tag{5}
\]

**TABLE 4** Weight optimization results

| Indicator number | Initial weight | First optimization | Second optimization | Third optimization | Fourth optimization | Fifth optimization | Normalized mean value | Change range |
|------------------|----------------|--------------------|---------------------|--------------------|---------------------|--------------------|----------------------|--------------|
| 1                | 0.036          | 0.037              | 0.035               | 0.046              | 0.039               | 0.034              | 0.038                | 5.56%        |
| 2                | 0.054          | 0.034              | 0.037               | 0.046              | 0.043               | 0.032              | 0.038                | −29.63%       |
| 3                | 0.13           | 0.121              | 0.132               | 0.117              | 0.123               | 0.124              | 0.123                | −5.38%        |
| 4                | 0.098          | 0.14               | 0.142               | 0.139              | 0.127               | 0.142              | 0.138                | 40.82%        |
| 5                | 0.098          | 0.142              | 0.127               | 0.12               | 0.119               | 0.131              | 0.128                | 30.61%        |
| 6                | 0.057          | 0.052              | 0.054               | 0.063              | 0.07                | 0.068              | 0.061                | 7.02%         |
| 7                | 0.044          | 0.035              | 0.032               | 0.034              | 0.036              | 0.032              | 0.034                | −22.73%       |
| 8                | 0.024          | 0.01               | 0.008               | 0.012              | 0.01               | 0.015              | 0.011                | −54.17%       |
| 9                | 0.037          | 0.043              | 0.033               | 0.034              | 0.033              | 0.042              | 0.037                | 0.00%         |
| 10               | 0.025          | 0.024              | 0.024               | 0.027              | 0.025              | 0.028              | 0.026                | 4.00%         |
| 11               | 0.029          | 0.029              | 0.025               | 0.026              | 0.023              | 0.022              | 0.025                | −13.8%        |
| 12               | 0.023          | 0.025              | 0.03               | 0.022              | 0.024              | 0.027              | 0.026                | 13.04%        |
| 13               | 0.023          | 0.027              | 0.025               | 0.028              | 0.024              | 0.023              | 0.025                | 8.70%         |
| 14               | 0.007          | 0.008              | 0.014               | 0.01               | 0.013              | 0.009              | 0.011                | 57.14%        |
| 15               | 0.026          | 0.026              | 0.026               | 0.027              | 0.025              | 0.022              | 0.025                | −3.85%        |
| 16               | 0.015          | 0.003              | 0.01                | 0.009              | 0.003              | 0.01               | 0.007                | −53.33%       |
| 17               | 0.027          | 0.025              | 0.022               | 0.024              | 0.024              | 0.022              | 0.023                | −14.81%       |
| 18               | 0.04           | 0.04               | 0.034               | 0.034              | 0.059              | 0.038              | 0.041                | 2.50%         |
| 19               | 0.035          | 0.037              | 0.041               | 0.041              | 0.032              | 0.032              | 0.037                | 5.71%         |
| 20               | 0.012          | 0.004              | 0.006               | 0.004              | 0.007              | 0.013              | 0.007                | −41.67%       |
| 21               | 0.012          | 0.014              | 0.009               | 0.009              | 0.007              | 0.005              | 0.009                | −25.00%       |
| 22               | 0.027          | 0.026              | 0.028               | 0.026              | 0.026              | 0.026              | 0.026                | −3.70%        |
| 23               | 0.018          | 0.018              | 0.018               | 0.027              | 0.028              | 0.017              | 0.017                | 7.02%         |
| 24               | 0.025          | 0.023              | 0.022               | 0.021              | 0.022              | 0.024              | 0.022                | −12.00%       |
| 25               | 0.014          | 0.003              | 0.004               | 0.002              | 0.01               | 0.007              | 0.005                | −64.29%       |
| 26               | 0.007          | 0.011              | 0.008               | 0.007              | 0.009              | 0.003              | 0.008                | 14.29%        |
| 27               | 0.03           | 0.022              | 0.026               | 0.025              | 0.025              | 0.024              | 0.024                | −20.00%       |
| 28               | 0.008          | 0.008              | 0.009               | 0.013              | 0.006              | 0.007              | 0.009                | 12.50%        |
| 29               | 0.017          | 0.017              | 0.019               | 0.017              | 0.018              | 0.02               | 0.018                | 5.88%         |
where $M$ represents the average of the total scores calculated by using 5000 groups of random scores, $r_{ij}$ the randomly generated scoring data, $w_i$ the indicator weight, $w^0_i$ the initial weight of the $i$th indicator calculated through the AHP algorithm, and $w_{i}^{\text{min}}, w_{i}^{\text{max}}$ the upper and lower limits of the $i$th indicator, respectively, corresponding to the fuzzy set interval.

The NSGA-II algorithm is a fast non-dominated multi-objective optimization algorithm with an elite retention strategy that can solve the multi-objective optimization problem described in this paper. The NSGA-II is an upgraded version of the NSGA. The idea is to significantly reduce the time complexity and maintain the elite solutions in the population to the greatest extent to find the optimal solution of the objective function. The NSGA-II adds a non-dominant fast sorting strategy, reduces the complexity of the NSGA algorithm, and improves computational efficiency. It puts forward the congestion degree and the corresponding comparison operator, providing a successful strategy for the same level comparison after promptly sorting and maintaining the diversity of the population. Furthermore, the NSGA-II introduces an elite strategy, merges the parent and children, and selects the best individuals for the next-generation population after a fast sorting to maintain the excellent individuals in the parent. The algorithm flowchart of this paper is shown in Figure 6.

### 4.3 Analysis of the results

The algorithm program described in this paper was iterated five times, and the weights were optimized using each time different random scores. The population size, the crossover probability, and the maximum number of iterations are 20, 0.9, and 500, respectively. The Pareto optimal solution for a single run is shown in Figure 7.

As the Pareto solution is not unique, the average of the optimal chromosomes is considered as the optimization result of a single run. The normalized mean values obtained from the 5 runs were used as the final indicator weights to calculate the evaluation results, as shown in Table 4.

The data listed in the table show that the optimized weights of the 32 indicators vary randomly. However, the weights of the 9th and 23rd indicators did not change, suggesting that the initial weights of these indicators were more accurate. The most significant variation occurs in indicator 25 (continuous safe operation days), whose weight was reduced by 64.29% after the optimization process. This suggests that the initial weight of the indicator is overestimated.

To verify the rationality of the weight optimization algorithm proposed in this paper, experts were hired to obtain 29 credit indicators of five generating companies A, B, C, D, E.
and E in a specific electricity market and calculate the credit scores before and after the weight optimization (see Table 5).

“Result 1” and “Result 2” are obtained considering the initial weight calculated through the AHP and the optimized weight calculated through the NSGA-II algorithm, respectively. The data analysis shows that the variances of the credit evaluation results of the five power generators range from 80.4 to 96.4. This result proves that the method used in this paper to optimize the weight is efficient and that the credit scores are more scattered after the optimization process. Consequently, the advantages and disadvantages of the power generators can be better identified.

5 | CASE STUDY

We conducted a credit evaluation of five generating companies: A, B, C, D, and E in a specific electricity market. In the first stage, we hired experts to obtain 29 relevant indicators and calculated the weighted total score. “Result 2” in Table 5 is the evaluation result of the first stage. In the second stage, the credit evaluation agency collected the information of the five generating companies regarding the addition and deduction of points, as shown in Table 6.

According to the second-stage evaluation process principle, there is no limit to the deduction of points and, if the indicators of the deduction of points occur once, 5 points will be subtracted from the total score. On the other hand, a maximum of 10 points can be added, and 3 points will be added if the indicators of the addition of points occur once. The scoring grade comparisons and the final credit evaluation results are shown in Tables 7 and 8, respectively.

The results of this case show that:

1. C is the generating company that shows the best credit score. The scores of its market behavior indicators is above 90, while the scores of the financial and social responsibility indicators are average. There is no deduction of points record, and it has won awards both within and outside the industry. E is the generating company that shows the worst credit score. The scores of its market behavior indicators are low, and the scores of the financial and social responsibility indicators are lower than the average. There is a punishment record associated with it as well.

2. Even if the credit score is high in the first stage, the bad credit records in the second stage will still cause a reduction in the credit ratings of the generating company.

3. The scores of the market behavior indicators have a significant impact on the final credit evaluation results. Suppose the score of 3th indicator of generating company 3 varies from 100 to 50, the final credit score and its credit rating drop from 95.4 to 89.2 and from AAA to A, respectively. When the scores of the violation transaction behavior indicators of other generating companies are modified, their

| TABLE 6 | Scorings of the evaluation indicators in the second stage |
|------------------|--------------|--------------|--------------|--------------|--------------|
| Deduction of points | A | B | C | D | E |
| The number of registration failures | 0 | 0 | 0 | 0 | 0 |
| The number of contract performance failures | 0 | 0 | 0 | 1 | 0 |
| The number of market transaction violations | 0 | 0 | 0 | 0 | 0 |
| Administrative penalty records | 0 | 0 | 0 | 0 | 1 |
| Blacklist records | 0 | 0 | 0 | 0 | 0 |
| Contract breach records | 0 | 0 | 0 | 0 | 0 |
| Addition of points | A | B | C | D | E |
| Excellent behaviors in the industry | 1 | 1 | 1 | 0 | 0 |
| Excellent behaviors outside the industry | 0 | 0 | 0 | 0 | 0 |
| Suggestions and reports | 0 | 1 | 0 | 0 | 0 |

| TABLE 7 | Grade comparison table |
|-----------------|------------------|------------------|------------------|------------------|------------------|
| Final score     | AAA              | AA               | A                | A                | B                |
| Credit rating   | [95-110]         | [90-95)          | [85-90)          | [80-85)          | [75-70)          | [60-65)          |

| TABLE 8 | Final credit evaluation results |
|------------------|--------------|--------------|--------------|--------------|--------------|
| Generating companies | A | B | C | D | E |
| Final score      | 78.9         | 90.0         | 95.4         | 84.0         | 55.1         |
| credit rating    | A-           | AA           | AAA          | A-           | C            |

| Generating companies | A | B | C | D | E |
|------------------|--|--|--|--|--|
| Final score      | 78.9         | 90.0         | 95.4         | 84.0         | 55.1         |
| credit rating    | A-           | AA           | AAA          | A-           | C            |
credit ratings have also declined. It can be seen that the credit evaluation system defined in this paper can better distinguish between the generating companies that respect or violate the market transaction rules.

6 CONCLUSIONS

Based on the principles of the indicator system development and electricity market transaction rules, this paper defines a set of credit evaluation methods for the generating companies by considering the market behavior to identify and penalize the industry violation transaction behavior. This paper proposes a method to optimize the credit indicator weight and verifies the feasibility of the credit evaluation system and weight optimization method. Since, in this study, the indicator weight is based on the random scores generated several times, the weights of the final indicators obtained through this method are random and accidental. In future works, improvements can be made to the algorithm, which can be revised using more data. At the same time, with the continuous improvement of the market mechanism, credit evaluation indicators should be constantly revised. Finally, the credit evaluation results can limit violation transaction behaviors and promote the healthy and stable development of the electricity market.

ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (71972127).

ORCID
Shiyao Wang https://orcid.org/0000-0002-1500-3429

REFERENCES

1. Guidance on accelerating the construction of a social credit system and building a new credit-based regulatory mechanism [EB/OL]. (2019-07-16) [2020-10-15]. http://www.gov.cn/zhenget/content/2019-07/16/content_5410120.htm
2. PJM. Credit policy updates-draft tariff attachment Q revisions [EB/OL]. (2016-07-12) [2020-10-17]. https://www.pjm.com/-/media/committees-groups/committees/mrc/20161027/20161027-item-04-credit-policy-updates-draft-tariff-attachment-q-revisions.ashx
3. CAISO business practice manual for credit management & market clearing, version 11 [EB/OL]. (2016-12-31) [2020-10-20]. https://bpmcm.caiso.com/BPM%20Document%20Library/Credit%20Management%20and%20Market%20Clearing/Credit%20Management%20and%20Market%20Clearing%20V11_clean.doc
4. Australia Ratings. Investment rating methodology [EB/OL]. Methodology. 2017-11-12: [2020-10-20]. https://www.australiaratings.com/investmentratings
5. Yan MH, Zhou CD, Yang YJ. Research on credit risk management of Yunnan electric power market. In: The third Smart Grid Conference Proceedings; 2018:7.
6. Tian L, Gan BY, Sun Q, et al. The analysis of credit risk management in Guangdong electricity market. In: International Conference on Power System Technology (POWERCON), November 6-8, 2018, Guangzhou, China. New York: IEEE; 2018:740-746.
7. Zhang L, Duan Z, Yu X. Study on credit evaluation of Power Supply Company in power market based on KPCA-MEE. Electric Power. 2018;51(07):128-135.
8. Emami IT, Abyaneh HA, Zareipour H. A novel simulation-based method for assessment of collusion potential in wholesale electricity markets. Sustain Energy Grids Networks. 2020;24:100405.
9. Matsukawa I. Detecting collusion in retail electricity markets: results from Japan for 2005 to 2010. Utilities Policy. 2019;57:16-23.
10. Sun B, Deng RL, Xie JD. Collusion bidding identification of cartel-type generators based on ordered logit model [J/OL]. Automat Electric Power Syst. 2020:1-8. http://kns.cnki.net/kcms/detail/32.1180.TP.20200903.1716.018.html
11. Sun B, Li ZH, Xie JD. Research on collusion bidding of power generators in spot market—simulation analysis of constructing a collusion bidding evaluation model of power generators based on cloud model. Price: Theory Pract. 2020;01:57-61.
12. Zhang HS, Cao Z, Yang CH. Collusive behavior recognition in electricity market based on AdaBoost-DT algorithm. Electric Power Eng Technol. 2020;39(02):152-158.
13. Ge R, Chen LX, Wang YY, et al. Optimization and design of construction route for electricity market in China. Automat Electric Power Syst. 2017;41(24):10-15.
14. Liu DN, Zhang Q, Li XT. Identification of potential harmful behaviors in electricity market based on cloud model and fuzzy Petri net. Automat Electric Power Syst. 2019;43(02):25-33.
15. Yu ZZ, Yang XW, Zhang DL. Capacity retention monitoring method based on power - reserve joint optimization. Electrotech Appl. 2018;37(11):60-64.
16. Zhou CD, Yang YJ, Wang BC. Design and application of electric power market evaluation indicator system—a comprehensive evaluation of Yunnan power market based on fuzzy analytic hierarchy process. Price: Theory Pract. 2019;07:112-115.
17. Wang K, Song HZ. Comparative analysis of three objective weighting methods. Technoecon Manage Res. 2003;06:48-49.
18. Deng X, Li JM, Zeng HJ. Research on computer methods of AHP Wight vector and its applications. Math Practi Theory. 2012;42(07):93-100.
19. Wu J, Chen ZD, Jia YH. Application of fuzzy theory to weight optimization algorithm of railway passenger transport safety indicator. J Beijing Jiaotong Univ. 2018;42(03):37-43 + 52.
20. Yu SW. Construction of a fuzzy membership function based on interval number. J Shandong Univ. 2010;40(6):32-35.
21. Sun Y, Bao XZ. A method of combination Weighting valuation based on variance maximization and its application. China J Manage Sci. 2011;19(6):141-148.
22. Pereira LA, Hoffner S, Nicol G, Dias TF. Multiobjective optimization of five-phase induction machines based on NSGA-II. IEEE Trans Ind Electron. 2017;64(12):9844-9853.

How to cite this article: Xie J, Wang S, Zhou X, Sun B, Sun X. Credit evaluation method of generating companies considering the market behavior in China electricity market. Energy Sci Eng. 2021;00:1–14. https://doi.org/10.1002/ese3.929