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Multi-Criteria Decision-Making for Power Grid Construction Project Investment Ranking Based on the Prospect Theory Improved by Rewarding Good and Punishing Bad Linear Transformation

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ABSTRACT

Using the improved prospect theory with the linear transformations of rewarding good and punishing bad (RGPBIT), a new investment ranking model for power grid construction projects (PGCPs) is proposed. Given the uncertainty of each index value under the market environment, fuzzy numbers are used to describe qualitative indicators and interval numbers are used to describe quantitative ones. Taking into account decision-maker's subjective risk attitudes, a multi-criteria decision-making (MCDM) method based on improved prospect theory is proposed. First, the $[-1, 1]$ RGPBIT operator is proposed to normalize the original data, to obtain the best and worst schemes of PGCPs. Furthermore, the correlation coefficients between interval/fuzzy numbers and the best/worst schemes are defined and introduced to the prospect theory to improve its value function and loss function, and the positive and negative prospect value matrices of the project are obtained. Then, the optimization model with the maximum comprehensive prospect value is constructed, the optimal attribute weight is determined, and the PGCPs are ranked accordingly. Taking four PGCPs of the IEEE RTS-79 node system as examples, an illustration of the feasibility and effectiveness of the proposed method is provided.

KEYWORDS

Power grid construction project; investment ranking; RGPBIT operator; MCDM; optimal weight

1 Introduction

The planning, investment, and construction of power grids are the basis for ensuring the safe and stable operation of power systems. The power grid construction has the characteristics of large investments and long periods [1]. In such a way that the cash flow of power grid companies can operate stably and maximize the economic and social benefits of investing in the power grid, it is an urgent problem that must be solved now [2]. In the electricity market environment, the traditional mode of investment has a lot of inconsistencies, resulting that it being difficult to accurately estimate PGCP income, and thus has a high investment risk [3]. Hence, developing investment ranking methods that comply with the market rules and enterprises' actual situations is crucial.

The comprehensive evaluation index system is generally adopted for the investment ranking of PGCPs [4–6]. Its advantage is that it can not only consider subjective and objective factors like technical and economic benefit but also consider the operability of the project. However, when using



the comprehensive indicator system for evaluation, the difficulties lie in 1) the quantification of quantitative indicators and qualitative indicators [7–9]; 2) how to analyze and compare indicators with different attributes and dimensions under the same scale; 3) how to consider the decision-makers risk appetite when evaluating the project.

The power market environment is characterized by uncertainties like on-grid price, electricity sales, power supply cost, power sales price, etc. [10]. For quantitative indicators in the comprehensive indicator system, uncertainty methods are often used to describe them, such as the interval number method [11], the fuzzy method [12], the probability method [13], and multi-scenario method [14]. The attribute values of quantitative indicators are described in this paper using the interval number method. For qualitative indicators, this paper uses expert evaluation and the triangular fuzzy number method [15] to quantify.

In the comprehensive evaluation index system of PGCPs investment ranking, there are not only technical indicators such as coordination, security, and reliability [16,17], but also economic indicators such as investment cost and investment income [18], as well as objective indicators such as project maturity [7]. In terms of indicator attributes, benefit indicators, cost indicators, and moderate indicators (the closer the indicator value is to a specific value, the better it is) are involved. Because the dimensions and attributes of each indicator are different, the data needs to be initialized for analysis and comparison. The commonly used initialization methods include normalization transformation, range maximization transformation, interval transformation, averaging transformation, and percentage transformation [19–21]. At the time of initialization, most of the literature has reduced all indicators to the interval [0, 1]. The disadvantage of this method is that it only rewards but not punishes the indicator data, which has certain limitations. In response to this problem, Reference [22] first proposed the liner transformation of rewarding good and punishing bad (RGPBIT), expanding the index interval to $[-1, 1]$, and giving negative punishment to indicators below the mean value. References [23,24] proved that the resolution accuracy can be improved based on the principle of RGPBIT. Therefore, this paper proposes to use the RGPBIT to normalize all index data.

When evaluating and making decisions on PGCPs, the current common methods include dynamic programming [25], the best matching degree method of the project library [26], and optimization methods aiming at minimizing investment risk [27] or optimizing a certain index [28,29]. For instance, Reference [30] built a multi-objective decision-making optimization model for smart grid investment and proposed a solution method based on the hybrid cuckoo algorithm, which provided a reference for grid enterprises to develop grid business. Reference [31] established a multi-stage investment decision-making model to achieve the highest return on power grid projects. The effectiveness of the model and its advantages in improving investment efficiency were verified by case simulation and analysis. Reference [32] aimed for the maximum comprehensive benefit, introduced the investment feedback mechanism and established the PGCP's investment timing optimization model.

In line with the above discussion, some gaps should be noted. On the one hand, the above methods all focus on objective indicators and fail to take into account the subjective preferences of decision-makers. In fact, under uncertainty, the risk preference of decision-makers is crucial to the decision results. Prospect theory [33,34] organically combined psychology and economics, and it believes that when facing gains, decision-makers are risk averse, but when facing losses, they are risk preference, and they are more sensitive to losses, which is suitable for dealing with their subjective preference in the PGCP investment decision-making in this paper. On the other hand, although the principle of RGPBIT has been proven to have high resolution, it has not been effectively applied in the research of PGCP investment decision-making. Therefore, this paper applies the prospect theory to ranking

the PGCPs' investment and introduces RGPBIT to improve the conventional prospect theory. In this way, an optimization model for maximizing the comprehensive prospect value is developed, and the PGCPs are ranked according to the comprehensive prospect value.

Overall, the main contribution of this paper is twofold. Firstly, under the framework of technical and economic analysis of PGCPs, this paper introduces the management factors of PGCPs and constructs a comprehensive performance evaluation index system with 4 dimensions of technology, efficiency, importance, and maturity, which expands the dimensions of investment decision evaluation of PGCPs. Secondly, the multi-criteria decision-making (MCDM) model for PGCP investment is constructed by combining prospect theory with the RGPBIT technique. The model can fully consider decision makers' subjective preferences, and the RGPBIT overcomes the limitations of traditional initialization methods of reward without punishment, which can improve the resolution accuracy of indicators, thus making the results more reliable.

The rest of this paper is as follows: [Section 2](#) constructs the indicator system for evaluating the comprehensive performance of PGCPs. [Section 3](#) introduces the method of the decision-making matrix based on RGPBIT. [Section 4](#) represents the MCDM model based on improved prospect theory. [Section 5](#) reports the results of the case study and [Section 6](#) summarizes this paper.

2 Comprehensive Indicator System for Investment Ranking of PGCPs

The focus of PGCP investment decision-making should mainly include two aspects: the technical level of the project and the investment benefit of the project. The former ensures the feasibility of project construction, and the latter ensures the economy of project investment. However, for power grid enterprises, there may be a large number of PGCPs that can meet the feasibility and economy. Therefore, it is necessary to further consider the project management factors when making investment decisions. The main management factors include two aspects. One is the importance of the project, that is, the supporting role of the proposed project for the operation of the power system, such as reducing the system overload ratio; The second is the management level of the whole process of the project, which reflects whether the proposed project can be completed with high quality as planned.

To sum up, drawing on relevant research [5,8,18], the comprehensive indicator system for investment ranking is mainly divided into 4 dimensions: technology, benefit, project importance, and maturity. Each dimension is subdivided into indicators, as shown in [Fig. 1](#). When establishing the indicator system, the evaluation indicators are divided into 3 layers, namely target, dimension, and indicator layers. The indicators included in various levels are as follows:

Technology indicators. It mainly includes network coordination, technical innovation level, power supply reliability, and investment risk level.

Benefit indicators. It mainly considers the economic and social benefits, including the reduction of line loss, the increase in investment income ratio, as well as the increase in electricity sales.

Project importance indicators. Different PGCPs have different degrees of importance. Here, it mainly considers the reduction number of heavy load main transformers and heavy load lines after the project construction.

Project maturity indicators. Such indicators refer to the ability to control the early planning and implementation of the project, the ability to complete the project, and the ability to achieve the expected objectives of the project. It includes PGCP early planning ability, PGCP participation team management and control ability, and PGCP bidding control ability.

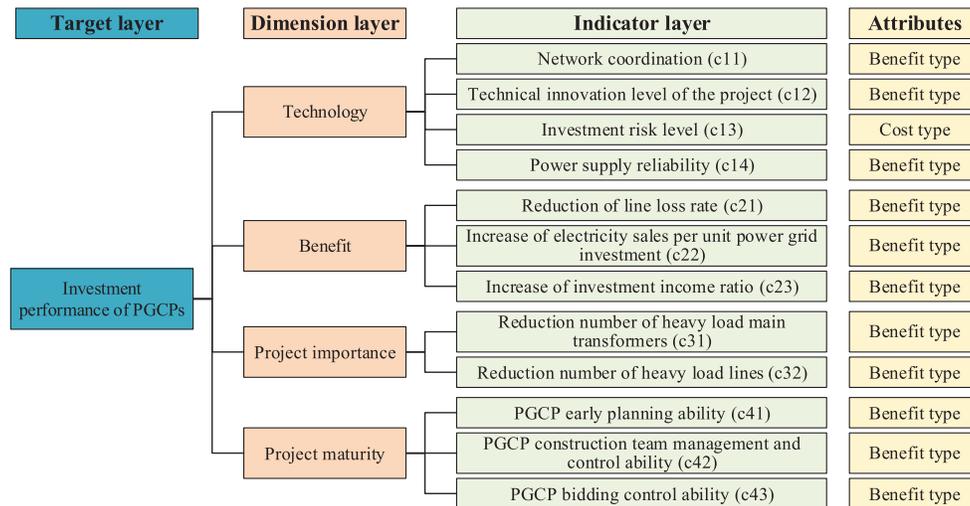


Figure 1: Comprehensive indicator system for investment ranking of PGCPs

3 Equations and Mathematical Expressions

Let $S = \{s_1, s_2, \dots, s_m\}$ be m PGCPs, and $U = \{u_1, u_2, \dots, u_n\}$ be n evaluation indicators. Let x be the indicator value, and i and j represent the j -th indicator of the i -th PGCP, respectively.

3.1 Indicator Uncertainty Characterization

(1) Characterization of quantitative indicator

Uncertainties exist in the market environment like on-grid price, electricity sales, power supply cost, power sales price, etc., so each indicator is also uncertain. The uncertainty of each quantitative indicator is described in this paper using the interval number method. Set the interval of x_{ij} is $[t_{ij}^L, t_{ij}^U]$, where t_{ij}^L and t_{ij}^U are lower and upper limits of x_{ij} .

(2) Characterization of qualitative indicators

This paper quantifies qualitative indicators using triangular fuzzy numbers [14,35]. Table 1 shows the fuzzy language and numbers.

Table 1: Fuzzy language and its corresponding triangular fuzzy number

Fuzzy language	Triangular fuzzy number
Extremely high	(0.9, 1.0, 1.0)
Very high	(0.8, 0.9, 1.0)
High	(0.7, 0.8, 0.9)
Relatively high	(0.6, 0.7, 0.8)
Slightly high	(0.5, 0.6, 0.7)
General	(0.4, 0.5, 0.6)
Slightly low	(0.3, 0.4, 0.5)
Relatively low	(0.2, 0.3, 0.4)
Low	(0.1, 0.2, 0.3)

(Continued)

Table 1 (continued)

Fuzzy language	Triangular fuzzy number
Very low	(0, 0.1, 0.2)
Extremely low	(0, 0, 0.1)

Suppose that K experts are assigned to participate in scoring. The final evaluation results of all experts on the j -th index of the i -th project are as follows:

$$\begin{cases} b_{ij}^L = \frac{1}{K} \sum_{k=1}^K b_{ij}^{Lk} \\ b_{ij}^M = \frac{1}{K} \sum_{k=1}^K b_{ij}^{Mk} \\ b_{ij}^U = \frac{1}{K} \sum_{k=1}^K b_{ij}^{Uk} \end{cases} \tag{1}$$

where b_{ij}^L , b_{ij}^M and b_{ij}^U are respectively the fuzzy attribute values of the j -th indicator of the i -th project, and the superscript k indicates the k -th expert.

3.2 The Normalized Decision-Making Matrix Based on RGPBIT

This section transforms the above indicator values to $[-1, 1]$ interval based on the RGPBIT operator. The main method is: when the indicator value is better than the average level, assign the index value as $[0, 1]$; When the index value is less than the average value, assign the index value as $[-1, 0]$.

(1) RGPBIT of quantitative indicators

Let:

$$\bar{T}_j = \frac{1}{2m} \sum_{i=1}^m (t_{ij}^L + t_{ij}^U), i = 1, 2, \dots, m; j = 1, 2, \dots, n \tag{2}$$

Among them, for benefit type indicators, it is:

$$\begin{cases} y_{ij}^L = \frac{t_{ij}^L - \bar{T}_j}{|\bar{T}_j|} \\ y_{ij}^U = \frac{t_{ij}^U - \bar{T}_j}{|\bar{T}_j|} \end{cases} \tag{3}$$

For cost type indicators, it is:

$$\begin{cases} y_{ij}^L = \frac{\bar{T}_j - t_{ij}^U}{|\bar{T}_j|} \\ y_{ij}^U = \frac{\bar{T}_j - t_{ij}^L}{|\bar{T}_j|} \end{cases} \tag{4}$$

where y_{ij}^L and y_{ij}^U are the lower limit and upper limit of the j -th indicator of the i -th PGCP after linear transformation respectively. Since the values of y_{ij}^L and y_{ij}^U may be greater than 1 or less than -1 , to

keep their values in the interval $[-1, 1]$, the following normalization formula is adopted:

$$\begin{cases} e_{ij}^L = \frac{y_{ij}^L}{\max_j \{|y_{ij}^L|, |y_{ij}^U|\}} \\ e_{ij}^U = \frac{y_{ij}^U}{\max_j \{|y_{ij}^L|, |y_{ij}^U|\}} \end{cases} \tag{5}$$

where e_{ij}^L and e_{ij}^U are upper and lower limits of the j -th indicator of the i -th PGCP after RGPBIT.

(2) RGPBIT of qualitative indicators

Let:

$$v_j = \frac{1}{3m} \sum_{i=1}^m (b_{ij}^L + b_{ij}^M + t_{ij}^U), i = 1, 2, \dots, m; j = 1, 2, \dots, n \tag{6}$$

Among them, for benefit type indicators, it is:

$$\begin{cases} e_{ij}^L = \frac{b_{ij}^L - v_j}{\max_j \{b_{ij}^{U*} - v_j, v_j - b_{ij}^{L*}\}} \\ e_{ij}^M = \frac{b_{ij}^M - v_j}{\max_j \{b_{ij}^{U*} - v_j, v_j - b_{ij}^{L*}\}} \\ e_{ij}^U = \frac{b_{ij}^U - v_j}{\max_j \{b_{ij}^{U*} - v_j, v_j - b_{ij}^{L*}\}} \end{cases} \tag{7}$$

For cost type indicators, it is:

$$\begin{cases} e_{ij}^L = \frac{v_j - b_{ij}^U}{\max_j \{b_{ij}^{U*} - v_j, v_j - b_{ij}^{L*}\}} \\ e_{ij}^M = \frac{b_{ij}^M - v_j}{\max_j \{b_{ij}^{U*} - v_j, v_j - b_{ij}^{L*}\}} \\ e_{ij}^U = \frac{v_j - b_{ij}^L}{\max_j \{b_{ij}^{U*} - v_j, v_j - b_{ij}^{L*}\}} \end{cases} \tag{8}$$

where $b_{ij}^{U*} = \max_{1 \leq i \leq m} \{b_{ij}^U\}$, $b_{ij}^{L*} = \max_{1 \leq i \leq m} \{b_{ij}^L\}$, $j = 1, 2, \dots, n$.

Through the RGPBIT operator, the evaluation matrix $A = (x_{ij})_{m \times n}$ composed of original data is normalized to a normalized matrix $E = (e_{ij})_{m \times n}$ with an indicator interval of $[-1, 1]$.

3.3 Determination of the Best and Worst Schemes

The best and worst schemes are given below for quantitative and qualitative indicators, respectively.

(1) The best and worst schemes of quantitative indicators (interval indicator)

Define:

$$e_j^+ = \max \left\{ \frac{e_{ij}^L + e_{ij}^U}{2}, 1 \leq i \leq m \right\}, j = 1, 2, \dots, n \tag{9}$$

The corresponding attribute value is recorded as $[e_{ij}^{L(+)}, e_{ij}^{U(+)}]$, and e_j^+ is the best scheme point of interval indicator.

Define:

$$e_j^- = \min \left\{ \frac{e_{ij}^L + e_{ij}^U}{2}, 1 \leq i \leq m \right\}, j = 1, 2, \dots, n \tag{10}$$

The corresponding attribute value is recorded as $[e_{ij}^{L(-)}, e_{ij}^{U(-)}]$, and e_j^- is the worst scheme point of the interval indicator.

(2) The best and worst schemes of qualitative indicators (fuzzy indicator)

Define:

$$\begin{cases} e_{ij}^{L(+)} = \max_{1 \leq i \leq m} \{e_{ij}^L\} \\ e_{ij}^{M(+)} = \max_{1 \leq i \leq m} \{e_{ij}^M\}, j = 1, 2, \dots, n \\ e_{ij}^{U(+)} = \max_{1 \leq i \leq m} \{e_{ij}^U\} \end{cases} \tag{11}$$

The corresponding fuzzy attribute value is recorded as $(e_{ij}^{L(+)}, e_{ij}^{M(+)}, e_{ij}^{U(+)})$, and e_j^+ is the best scheme point of fuzzy indicator.

Define:

$$\begin{cases} e_{ij}^{L(-)} = \min_{1 \leq i \leq m} \{e_{ij}^L\} \\ e_{ij}^{M(-)} = \min_{1 \leq i \leq m} \{e_{ij}^M\}, j = 1, 2, \dots, n \\ e_{ij}^{U(-)} = \min_{1 \leq i \leq m} \{e_{ij}^U\} \end{cases} \tag{12}$$

The corresponding fuzzy attribute value is recorded as $(e_{ij}^{L(-)}, e_{ij}^{M(-)}, e_{ij}^{U(-)})$, and e_j^- is the worst scheme point of fuzzy indicator.

The best scheme point set and the worst scheme point set of each indicator constitute the attribute values of the best scheme and the worst scheme respectively. The vectors composed of the best attribute values and the worst attribute values are as follows:

The best attribute value vector:

$$e^+ = (e_1^+, e_2^+, \dots, e_n^+) \tag{13}$$

In the formula, if e_j^+ is the interval indicator, $e_j^+ = [e_{ij}^{L(+)}, e_{ij}^{U(+)}]$, and if e_j^+ is the fuzzy indicator, $e_j^+ = (e_{ij}^{L(+)}, e_{ij}^{M(+)}, e_{ij}^{U(+)})$.

The worst attribute value vector:

$$e^- = (e_1^-, e_2^-, \dots, e_n^-) \tag{14}$$

In the formula, if e_j^- is the interval indicator, $e_j^- = [e_{ij}^{L(-)}, e_{ij}^{U(-)}]$ and if e_j^- is the fuzzy indicator, $e_j^- = (e_{ij}^{L(-)}, e_{ij}^{M(-)}, e_{ij}^{U(-)})$.

3.4 Construction of Decision-Making Matrix Based on the Grey Correlation Coefficient

The closeness of each indicator to the best and worst scheme points reflects the advantages and disadvantages of the indicator. Based on this, this paper uses the gray correlation method [36,37] to

characterize the closeness of each indicator to the best and worst scheme points, and constructs the decision-making matrix of alternatives.

If the index set of the i -th PGCP is $s_i = (e_{i1}, e_{i2}, \dots, e_{in})$, $e^+ = (e_1^+, e_2^+, \dots, e_n^+)$ and $e^- = (e_1^-, e_2^-, \dots, e_n^-)$ are the best scheme and the worst scheme, respectively, then the correlation coefficients ξ of the project indicator set with the best and worst scheme points are:

$$\left\{ \begin{aligned} \xi_{ij}^+ &= \frac{\min_i \min_j |e_{ij} - e_j^+| + \rho \max_i \max_j |e_{ij} - e_j^+|}{|e_{ij} - e_j^+| + \rho \max_i \max_j |e_{ij} - e_j^+|} \\ \xi_{ij}^- &= \frac{\min_i \min_j |e_{ij} - e_j^-| + \rho \max_i \max_j |e_{ij} - e_j^-|}{|e_{ij} - e_j^-| + \rho \max_i \max_j |e_{ij} - e_j^-|} \end{aligned} \right., i = 1, 2, \dots, m; j = 1, 2, \dots, n \tag{15}$$

where ρ is the resolution coefficient, and $\rho \in (0, 1)$. In this paper, $\rho = 0.5$.

If e_{ij} is a quantitative indicator, then

$$\left\{ \begin{aligned} |e_{ij} - e_j^+| &= \frac{1}{\sqrt{2}} \sqrt{(e_{ij}^L - e_{ij}^{L(+)})^2 + (e_{ij}^U - e_{ij}^{U(+)})^2} \\ |e_{ij} - e_j^-| &= \frac{1}{\sqrt{2}} \sqrt{(e_{ij}^L - e_{ij}^{L(-)})^2 + (e_{ij}^U - e_{ij}^{U(-)})^2} \end{aligned} \right. \tag{16}$$

If e_{ij} is a qualitative indicator, then

$$\left\{ \begin{aligned} |e_{ij} - e_j^+| &= \frac{1}{\sqrt{3}} \sqrt{(e_{ij}^L - e_{ij}^{L(+)})^2 + (e_{ij}^M - e_{ij}^{M(+)})^2 + (e_{ij}^U - e_{ij}^{U(+)})^2} \\ |e_{ij} - e_j^-| &= \frac{1}{\sqrt{3}} \sqrt{(e_{ij}^L - e_{ij}^{L(-)})^2 + (e_{ij}^M - e_{ij}^{M(-)})^2 + (e_{ij}^U - e_{ij}^{U(-)})^2} \end{aligned} \right. \tag{17}$$

The positive correlation coefficient matrix $\xi^+ = (\xi_{ij}^+)_{m \times n}$ and negative correlation coefficient matrix $\xi^- = (\xi_{ij}^-)_{m \times n}$ can be obtained accordingly.

4 PGCP Investment Ranking Method Based on Prospect Theory

Prospect theory [38] is a method taking into account the subjective feelings of decision-makers, that is, when facing gains, decision-makers are risk averse, and when facing losses, they are risk preference.

Calculating the prospect value of each PGCP is based on prospect theory. By combining the value function and decision-making weight, the prospect value is determined, and it is calculated as follows:

$$V = \sum_{j=1}^n w(p_j) v(x_j) \tag{18}$$

where V means prospect value, $w(p_j)$ means decision-making weight, $v(x_j)$ means value function, p is indicator weight, and x is indicator value.

4.1 Value Function and Decision-Making Weight

In decision-making, the value function [39] is the value formed by subjective feelings. The commonly used value function is as follows:

$$v(x) = \begin{cases} x^\alpha, & x \geq 0 \\ -\theta (-x)^\beta, & x < 0 \end{cases} \tag{19}$$

where parameter α and β respectively represent the concavity and convexity of the regional value power function of benefits and losses [40], reflecting the sensitivity of decision-makers to benefits and losses, and generally $\alpha, \beta \leq 1$. θ reflects the degree of the decision-makers aversion to loss, and generally $\theta > 1$.

Generally, the decision-making weight [41] is determined according to Eq. (20):

$$w(p) = \frac{p^\gamma}{(p^\gamma + (1 - p)^\gamma)^{1/\gamma}} \tag{20}$$

where γ represents the decision-maker's risk attitudes towards benefits and losses.

4.2 Improved Benefit and Loss Function

The prospect theory shows that when facing the decision, the decision-maker will judge the benefits and losses of the decision according to the reference point value, so selecting the reference point is crucial to the results of the decision. In this paper, the best scheme and the worst scheme based on RGPBIT are used as reference points to judge the benefits and losses of decision results. Specifically, when the best scheme is taken as a reference point, the indicator values of the alternative are inferior to the best scheme, so the decision-maker is faced with losses, and at this time the decision-maker pursues risks. When the worst scheme is taken as a reference point, the indicator values of the alternative are superior to the worst scheme, so the decision-maker is faced with benefits, and the decision-maker is risk-averse at this point.

Therefore, using the prospect theory and the correlation coefficient of every indicator with the best/worst scheme, the prospect value of each indicator will be calculated.

The attribute value of the j -th indicator of the i -th PGCP is e_{ij} . If the reference point is e_j^- , the decision-maker is faced with benefits. If the reference point is e_j^+ , the decision-maker will face losses. So the benefits and losses value function of e_{ij} is:

$$\begin{cases} v^+(e_{ij}) = (1 - \xi_{ij}^-), e_{ij} \geq e_j^- \\ v^-(e_{ij}) = -\theta [-(\xi_{ij}^+ - 1)]^\beta, e_{ij} < e_j^+ \end{cases} \tag{21}$$

In the formula, $v^+(e_{ij})$ and $v^-(e_{ij})$ are respectively the positive and negative prospect values brought by benefits and losses.

The positive and negative prospect value matrices of the project indicators can be obtained from the benefits and losses value functions, which are $v^+ = (v_{ij}^+)_{m \times n}$ and $v^- = (v_{ij}^-)_{m \times n}$, respectively.

4.3 Comprehensive Prospect Value of PGCP

According to Eq. (20), the indicator decision-making weights of the scheme benefits and losses are:

$$\begin{cases} w^+(p_j) = \frac{p_j^{\gamma^+}}{[p_j^{\gamma^+} + (1 - p_j)^{\gamma^+}]^{1/\gamma^+}} \\ w^-(p_j) = \frac{p_j^{\gamma^-}}{[p_j^{\gamma^-} + (1 - p_j)^{\gamma^-}]^{1/\gamma^-}} \end{cases} \tag{22}$$

where γ^+ and γ^- respectively represent the risk attitude of decision-makers towards benefits and losses, and also reflect the bending degree of decision-making weight function.

The comprehensive prospect value V_i of the project s_i is the sum of positive and negative prospect values and their corresponding decision-making weights, that is:

$$V_i = \sum_{j=1}^n v^+(e_{ij}) w^+(p_j) + \sum_{j=1}^n v^-(e_{ij}) w^-(p_j) \quad (23)$$

When performing MCDM issues, in order to make each alternative's comprehensive prospect value larger, the optimal weight of each index is obtained through optimization methods. The optimization model is as follows:

$$\max V = \sum_{i=1}^m \sum_{j=1}^n v^+(e_{ij}) w^+(p_j) + \sum_{i=1}^m \sum_{j=1}^n v^-(e_{ij}) w^-(p_j) \quad (24a)$$

$$\text{s.t.} \begin{cases} \sum_{j=1}^n p_j = 1 \\ p_j \geq 0 \\ a_j \leq p_j \leq b_j \leq 1 \\ i = 1, 2, \dots, m; j = 1, 2, \dots, n \end{cases} \quad (24b)$$

In the formula, a and b are lower and upper limits for each indicator weight. The optimal weight $p^* = [p_1^*, p_2^*, \dots, p_n^*]$ can be obtained through the optimization method, then the comprehensive optimal prospect value of s_i is:

$$V_i = \sum_{j=1}^n v^+(e_{ij}) w^+(p_j^*) + \sum_{j=1}^n v^-(e_{ij}) w^-(p_j^*) \quad (25)$$

The comprehensive optimal prospect values of various PGCPs are gained from Eq. (25), and the projects can be ranked from large to small based on the comprehensive optimal prospect values.

5 Case study

5.1 Case Introduction

In this section, the typical IEEE-RTS79 node system [42] is applied for a case study to verify the applicability of the developed model. As a result of regional load growth, transmission lines and transformers need to be planned. The information on planned PGCPs (1, 2, 3, 4) is as follows. The marketization rate is set to be 0.3. Then, the project cost of the transmission line for one km is 1.4 million yuan and the project cost of the transformer is 400000 yuan/MVA [43]. The service life of the equipment is 18 years.

PGCP 1: There is an increased load of 136 MW on the bus 6. Therefore, it is proposed to construct a new 25.76 km transmission line, which connects node 6 and node 10. Besides, an 80 MVA transformer is added at the same time. The investment fee is 68.06 million yuan and the operation cost for the project is 5 million yuan/year.

PGCP 2: There is a changed load at bus 4, increasing from 74 to 285 MW. A new 44 km transmission line is proposed to be built from node 4 to node 9, and the transformer capacity is increased from 240 to 300 MVA. Then, the investment fee is 85.6 million yuan and the operation cost for the project is 5.9 million yuan/year.

PGCP 3: There is a changed load at bus 5, increasing from 71 to 300 MW. A new 36 km transmission line is proposed to be built from node 1 to node 5, and the transformer capacity is

increased from 120 to 320 MVA. Then, the investment fee is 130.4 million yuan and the operation cost for the project is 5.2 million yuan/year.

PGCP 4: There is a changed load at bus 8, increasing from 171 to 270 MV, a new 26 km transmission line is proposed to be built between nodes 7 and 8, and the transformer capacity is increased from 200 to 300 MVA. The investment fee is 76.4 million yuan and the operation cost for the project is 5 million yuan/year.

5.2 Indicator Calculation

In the indicator system in Fig. 1, PGCP early planning ability, PGCP participation team management and control ability, PGCP bidding control ability, technical innovation level of the project, and investment risk level are qualitative indicators, which are quantified by fuzzy methods according to expert scoring. For the rest quantitative indicators, the calculation of the network coordination indicator is the same as that in reference [44], and calculating the load loss rate is used to determine the reliability of the power supply. For indicators such as reduction of line loss rate, the power flow with/without the planning project is calculated in a given system, and then the indicator values are obtained accordingly. For the increase in electricity sales, based on the economic development situation, the gray prediction model is employed to predict the electricity demand, and the increased electricity amount is the increased electricity sold. For the investment income ratio index, the investment amount and income are calculated respectively by combining the life-cycle and uncertainty methods [45], and the ratio of the two is the investment income ratio. The calculation process and results of each indicator are shown in Appendix A, and the results of each indicator for investment ranking of PGCPs are obtained, as shown in Table 2.

Table 2: Calculation results of alternative indicators

Indicator	PGCP 1	PGCP 2	PGCP 3	PGCP 4
<i>c</i> 11	[0.1604, 0.1731]	[0.1583, 0.1625]	[0.1590, 0.1673]	[0.1618, 0.1724]
<i>c</i> 12	(0.5625, 0.6625, 0.76255)	(0.225, 0.325, 0.425)	(0.375, 0.475, 0.575)	(0.475, 0.575, 0.675)
<i>c</i> 13	(0.2125, 0.3125, 0.4125)	(0.4, 0.5, 0.6)	(0.525, 0.625, 0.725)	(0.25, 0.35, 0.45)
<i>c</i> 14	[0.91504, 0.92378]	[0.91502, 0.91849]	[0.91497, 0.91723]	[0.91559, 0.91938]
<i>c</i> 21	[0.114, 0.123]	[0.219, 0.232]	[0.158, 0.193]	[0.099, 0.112]
<i>c</i> 22	[11.8, 13.0]	[10.6, 11.7]	[11.5, 12.6]	[11.2, 12.4]
<i>c</i> 23	[1.1856, 1.2035]	[1.0924, 1.1763]	[1.0982, 1.1321]	[1.13, 1.17]
<i>c</i> 31	[4, 6]	[3, 5]	[6, 7]	[4, 7]
<i>c</i> 32	[7, 9]	[6, 8]	[8, 10]	[5, 8]
<i>c</i> 41	(0.4, 0.5, 0.6)	(0.275, 0.375, 0.475)	(0.6625, 0.7625, 0.8625)	(0.4375, 0.5375, 0.6375)
<i>c</i> 42	(0.4875, 0.5875, 0.6875)	(0.325, 0.425, 0.525)	(0.3, 0.4, 0.5)	(0.25, 0.35, 0.45)
<i>c</i> 43	(0.3375, 0.4375, 0.5375)	(0.275, 0.375, 0.475)	(0.475, 0.575, 0.675)	(0.5125, 0.6125, 0.7125)

5.3 Investment Ranking Results of Alternatives

(1) Results of RGPBIT

In the indicator system in Fig. 1, only the investment risk level is the cost type indicator, and other indicators are benefit type indicators. Firstly, the RGPBIT operator is carried out for the indicators, and the normalized matrix of the transformed indicator value belonging to $[-1, 1]$ is obtained. The best and worst scheme points are obtained accordingly, and the correlation coefficient matrices of the project indicators and the ideal points are obtained. The results are shown in Table 3.

Table 3: Correlation coefficient matrices between the project and the best and worst schemes

Indicator	Correlation coefficient with the best scheme				Correlation coefficient with the worst scheme			
	PGCP 1	PGCP 2	PGCP 3	PGCP 4	PGCP 1	PGCP 2	PGCP 3	PGCP 4
<i>c</i> 11	1.0000	0.5713	0.4566	0.6151	0.4566	0.6944	1.0000	0.6344
<i>c</i> 12	1.0000	0.4003	0.5457	0.7202	0.4004	0.9985	0.6006	0.4742
<i>c</i> 13	1.0000	0.5402	0.4487	0.8546	0.4423	0.6820	0.9242	0.4773
<i>c</i> 14	0.8628	0.4824	0.6267	1.0000	0.4754	1.0000	0.6689	0.4824
<i>c</i> 21	0.3592	1.0000	0.5396	0.3333	0.8202	0.3333	0.4585	1.0000
<i>c</i> 22	1.0000	0.4261	0.7605	0.5453	0.4261	1.0000	0.4425	0.6505
<i>c</i> 23	1.0000	0.3705	0.3579	0.4922	0.3579	0.7581	1.0000	0.5597
<i>c</i> 31	0.4835	0.3849	0.8345	1.0000	0.6411	1.0000	0.4116	0.3849
<i>c</i> 32	0.6744	0.5097	1.0000	0.4492	0.5688	0.7462	0.4492	1.0000
<i>c</i> 41	0.4903	0.3945	1.0000	0.5288	0.6689	1.0000	0.3945	0.6084
<i>c</i> 42	1.0000	0.5537	0.5172	0.4568	0.4568	0.7229	0.7965	1.0000
<i>c</i> 43	0.5046	0.4287	0.8262	1.0000	0.7403	1.0000	0.4712	0.4287

(2) Positive and negative prospect value matrices

The value function and decision-making weight parameters used in the prospect theory calculation are [40]: $\alpha = 0.88$, $\beta = 0.88$, $\gamma^+ = 0.61$, $\gamma^- = 0.68$. Substitute the correlation coefficient into the loss function and value function, to obtain the positive and negative prospect value matrices of all PGCPs, as shown in Table 4.

Table 4: Positive and negative prospect value matrices of all PGCPs

Indicator	Positive prospect value matrix				Negative prospect value matrix			
	PGCP 1	PGCP 2	PGCP 3	PGCP 4	PGCP 1	PGCP 2	PGCP 3	PGCP 4
<i>c</i> 11	0.5847	0.3523	0.0000	0.4125	0.0000	-1.0678	-1.3156	-0.9713
<i>c</i> 12	0.6376	0.0032	0.4459	0.5680	0.0000	-1.4348	-1.1236	-0.7335
<i>c</i> 13	0.5982	0.3649	0.1033	0.5651	0.0000	-1.1356	-1.3322	-0.4124
<i>c</i> 14	0.5668	0.0000	0.3781	0.5602	-0.3918	-1.2604	-0.9452	0.0000
<i>c</i> 21	0.2209	0.6999	0.5829	0.0000	-1.5208	0.0000	-1.1370	-1.5748
<i>c</i> 22	0.6134	0.0000	0.5979	0.3965	0.0000	-1.3802	-0.6397	-1.1245
<i>c</i> 23	0.6772	0.2868	0.0000	0.4858	0.0000	-1.4973	-1.5237	-1.3862
<i>c</i> 31	0.4059	0.0000	0.6270	0.6521	-1.2438	-1.4672	-0.4620	0.0000

(Continued)

Table 4 (continued)

Indicator	Positive prospect value matrix				Negative prospect value matrix			
	PGCP 1	PGCP 2	PGCP 3	PGCP 4	PGCP 1	PGCP 2	PGCP 3	PGCP 4
<i>c</i> 32	0.4770	0.2992	0.5917	0.0000	-0.8383	-1.2016	0.0000	-1.3312
<i>c</i> 41	0.3781	0.0000	0.6431	0.4382	-1.2435	-1.4469	0.0000	-1.1604
<i>c</i> 42	0.5844	0.3232	0.2464	0.0000	0.0000	-1.1062	-1.1855	-1.3150
<i>c</i> 43	0.3053	0.0000	0.5708	0.6110	-1.2127	-1.3747	-0.4825	0.0000

(3) Optimal decision-making weight and comprehensive prospect value

The optimal decision-making weight is calculated using Eq. (24), as shown in Table 5.

Table 5: Optimal decision-making weight for investment ranking

Indicator	The lower limit of the weight value	The upper limit of the weight value	Optimal weight value
<i>c</i> 11	0.035	0.095	0.095
<i>c</i> 12	0.060	0.090	0.090
<i>c</i> 13	0.045	0.100	0.100
<i>c</i> 14	0.045	0.105	0.105
<i>c</i> 21	0.040	0.100	0.040
<i>c</i> 22	0.025	0.130	0.130
<i>c</i> 23	0.045	0.140	0.045
<i>c</i> 31	0.045	0.090	0.090
<i>c</i> 32	0.050	0.085	0.085
<i>c</i> 41	0.050	0.070	0.050
<i>c</i> 42	0.060	0.110	0.080
<i>c</i> 43	0.055	0.090	0.090

Further, according to Eq. (25), the comprehensive prospect values of PGCPs 1 to 4 are respectively 0.1554, -1.8594, -0.7078, and -0.5704, so the investment ranking of the four PGCPs should be $V_1 > V_4 > V_3 > V_2$. Among the 4 indicators with the highest optimal weights shown in Table 5, V_1 performs best in *c*13, *c*14 and *c*22, and is only slightly lower than V_4 in *c*11. That is, V_1 has better network coordination, the lowest investment risk level, the highest power supply reliability, and the largest increase of electricity sales per unit power grid investment. On the contrary, V_2 performs the worst in *c*11 and *c*22, and the second worst in *c*13 and *c*14. According to the ranking results, it can be found that the technical and benefits indicators, as the intuitive expression of the technical feasibility and economic sustainability of the PGCP, are the key considerations in the investment decision-making of PGCP. At the same time, management factors such as project importance and project maturity will play an important role in supporting decision-making for PGCPs' investment ranking.

5.4 Comparative Analysis of Models

To further verify the effectiveness of the proposed model, three comparison models are designed in this section. The model information and corresponding evaluation results are shown in Table 6.

Table 6: Comparison of model information and evaluation results

Model	Model description	PGCP 1	PGCP 2	PGCP 3	PGCP 4
Model 1	Prospect theory with RGPBIT	0.1554	-1.8594	-0.7078	-0.5704
Model 2	Prospect theory	-0.0336	-1.2958	-0.3152	-0.6253
Model 3	Utility theory	0.5915	0.1039	0.3827	0.4129
Model 4	TOPSIS	0.6378	0.2830	0.5374	0.5382

Based on the calculation results in Table 6, this section further tests the robustness and effectiveness of the proposed model. Among them, the robustness is analyzed by the ranking consistency test [46,47], and the effectiveness of the model is analyzed by the sample separation test [9,48]. The following indicators are constructed:

$$r_s = 1 - \frac{6 \times \sum_{i=1}^N (x_i - y_i)^2}{N \times (N^2 - 1)} \quad (26)$$

$$r_w = 1 - \frac{6 \times \sum_{i=1}^N (x_i - y_i)^2 [(N - x_i + 1) + (N - y_i + 1)]}{N \times (N^3 + N^2 - N - 1)} \quad (27)$$

$$WS = 1 - \sum_{i=1}^N \left(2^{-x_i} \frac{|x_i - y_i|}{\max\{|x_i - 1|, |x_i - N|\}} \right) \quad (28)$$

where r_s , r_w and WS are the Spearman ranking correlation coefficient, weighted Spearman ranking correlation coefficient, and WS ranking correlation coefficient. x_i and y_i are two ranking results, and N is the alternatives' total number. These three indicators reflect the similarity between the two ranking results. Larger indicator value reveals higher similarity between the ranking results. In this paper, if the rankings of the constructed model and the comparison model have high similarity, it indicates that the model in this paper is robust.

$$\sigma = \sqrt{\frac{\sum_{i=1}^m (V_i - \bar{V})^2}{m}} \quad (29)$$

$$\theta = \frac{V_{i,\max} - V_{i,\min}}{\bar{V}} \times 100\% \quad (30)$$

$$\vartheta = \frac{\sigma}{\bar{V}} \quad (31)$$

where σ , θ and ϑ are standard deviation, relative range, and coefficient of variation respectively, reflecting the degree of sample separation of the model. \bar{V} is the mean value of the comprehensive

prospect value of the scheme, and $V_{i,max}$ and $V_{i,min}$ are maximum and minimum values of comprehensive prospect values. The larger the three indicators, the greater the difference between the comprehensive prospect values of different schemes, that is, the better the sample separation ability of the model.

According to the calculation results of the four models, the ranking consistency and sample separation index of each model can be calculated, as shown in [Tables 7 and 8](#).

Table 7: Ranking consistency test results of four models

		Model 1	Model 2	Model 3	Model 4
Ranking results	Case 1	1	1	1	1
	Case 2	4	4	4	4
	Case 3	3	2	3	3
	Case 4	2	3	2	2
Consistency indicators	r_s	1.0000	0.8000	1.0000	1.0000
	r_w	1.0000	0.7600	1.0000	1.0000
	WS	1.0000	0.8750	1.0000	1.0000

Table 8: Calculation results of sample separation indicators of four models

Model	Sample separation test index		
	σ	θ	ϑ
Model 1	0.8336	-2.7024	-1.1180
Model 2	0.5424	-2.2242	-0.9557
Model 3	0.2015	1.3081	0.5407
Model 4	0.1516	0.7109	0.3037

According to [Tables 7 and 8](#), on the one hand, the ranking consistency test results show that the ranking results of Model 3 and Model 4 are identical to that of Model 1, and the ranking consistency coefficients are all 1. The ranking results of Model 2 and Model 1 are different, but the best and worst schemes are the same. Therefore, the ranking results of the three comparison models are highly consistent with those of Model 1, indicating that the constructed model is robust. On the other hand, the sample separation test results show that the three separation index values (or the absolute values of the index) of Model 1 are significantly greater than the values of the three contrast models, indicating that the constructed model can more clearly distinguish the sample differences, thus improving the decision-making efficiency. Next, this section further compares and analyzes the results of the four models.

(1) Comparison and analysis with traditional prospect theory model

This paper adopts the prospect theory method improved by RGPBIT operator. Compared with the traditional prospect theory method, RGPBIT combines reward and punishment, overcoming the shortcomings of the existing method of “only rewarding but not punishing”.

The results based solely on prospect theory are shown in the second row of [Table 6](#). It can be seen that the ranking result based on the comprehensive prospect value of the traditional prospect theory model is $V_1 > V_3 > V_4 > V_2$. The difference from the proposed RGPBIT prospect theory model lies in PGCPs 3 and 4, and the numerical range of the comprehensive prospect value based solely on prospect theory is smaller than the proposed method in this paper.

[Table 9](#) represents the prospect values of each PGCP indicator for the two methods (Model 1 and Model 2). It can be seen that under the effect of “punishing the good”, the prospect values of network coordination, power supply reliability, and investment income ratio of PGCP 3 are obviously smaller than those based on traditional prospect theory. However, only one indicator named power supply reliability of PGCP 4 is significantly less than the result based on traditional prospect theory. Therefore, it can be seen that the proposed RGPBIT prospect theory model in this paper not only considers the “rewarding the good”, but also takes into account the “punishing the bad”. Compared with the traditional prospect theory results based on “rewarding the good”, the investment ranking results of PGCPs may be different.

Table 9: Prospect values of PGCP investment ranking indicators under Model 1 and Model 2

Indicator	Model 1				Model 2			
	PGCP 1	PGCP 2	PGCP 3	PGCP 4	PGCP 1	PGCP 2	PGCP 3	PGCP 4
c_{11}	0.1062	-0.1122	-0.2170	-0.0853	0.0034	-0.0052	-0.0069	-0.0036
c_{12}	0.1128	-0.2285	-0.1005	-0.0166	0.1033	-0.2094	-0.1125	-0.0280
c_{13}	0.1114	-0.1252	-0.2074	0.0351	0.1244	-0.1806	-0.2679	-0.0204
c_{14}	0.0395	-0.2208	-0.0935	0.1069	0.0144	-0.0475	-0.0169	0.0231
c_{21}	-0.1215	0.0821	-0.0419	-0.1527	-0.1162	0.0775	-0.0355	-0.1440
c_{22}	0.1299	-0.2747	-0.0007	-0.1399	0.0585	-0.1234	0.0140	-0.0596
c_{23}	0.0844	-0.1205	-0.1590	-0.0688	0.0207	-0.0243	-0.0388	-0.0142
c_{31}	-0.1291	-0.2343	0.0371	0.1153	-0.0903	-0.1970	0.0972	-0.0500
c_{32}	-0.0473	-0.1339	0.1017	-0.2054	-0.0346	-0.1120	0.0789	-0.1589
c_{41}	-0.0888	-0.1612	0.0846	-0.0716	-0.0882	-0.1603	0.0843	-0.0710
c_{42}	0.0975	-0.1105	-0.1352	-0.1955	0.0987	-0.1131	-0.1374	-0.1976
c_{43}	-0.1397	-0.2195	0.0239	0.1081	-0.1277	-0.2004	0.0264	0.0989

(2) Comparative analysis with utility theory model

The investment ranking results of PGCPs based on utility theory are further given in this paper, as shown in the third row of [Table 6](#). The utility theory takes the decision-maker as a rational person to make rational judgments on various risks in decision-making problems, and then make decisions [49,50]. The common point of this method with the proposed RGPBIT prospect theory is that decision-makers risk preference is taken into account when making investment decisions. The difference is that in RGPBIT prospect theory, decision-makers have different risk attitudes towards benefits and losses, while the utility theory judges whether the decision-maker is risk-seeking, risk aversion, or risk neutral according to the expected value calculated from the utility function. Generally, in most cases, the results of prospect theory are consistent with those of utility theory [51,52]. It can be seen from [Table 6](#) that the ranking of four PGCPs based on comprehensive utility values is $V_1 > V_4 > V_3 > V_2$, which is

consistent with the results of the RGPBIT prospect theory, which shows the feasibility of the methods proposed in this paper.

(3) Comparison and analysis with TOPSIS model

According to TOPSIS, the positive ideal solution is the optimal solution, and its attribute values all reach the optimal value. The negative ideal solution is the worst solution with all indicator values reaching the worst. This method compares each alternative with the positive and the negative ideal solutions, and the alternative closest to the positive one and farthest from the negative one is the optimal solution [53,54].

The idea of the TOPSIS method is the same as that of the prospect theory method. The difference is that the prospect theory uses the value function and decision-making weight to reflect the decision-maker's risk attitude towards benefits and losses, to determine the comprehensive prospect value. The ranking method of TOPSIS uses the distance degree from the ideal solution. It is noted from Table 6 that the rankings of TOPSIS are consistent with that of the proposed RGPBIT prospect theory model in this paper, both of which are $V_1 > V_4 > V_3 > V_2$.

6 Conclusion

The planning, investment, and construction of the power grid are the basis for ensuring the safe and stable operation of the power system. Power grid construction is characterized by many projects, large investments and long cycles, so it is necessary to develop targeted investment ranking methods. Based on the technology and economic analysis framework of investment decision-making of PGCPs, this paper introduces project management factors and constructs a comprehensive performance evaluation index system for PGCPs. On this basis, taking into account the subjective preferences of decision-makers in the process of PGCP investment decision-making, an MCDM model based on prospect theory is proposed, and the RGPBIT operator is used to improve conventional prospect theory.

Based on the IEEE-RTS79 node example, the investment ranking of four PGCPs to be built is evaluated. The results show that V_1 is the best and V_2 is the worst. This is because V_1 performs well in important indicators such as network coordination, investment risk, power supply reliability, and increased sales of electricity, while performing poorly. The ranking results further verify that the technology and benefits indicators, as the intuitive expression of PGCP's technical feasibility and economic sustainability, are the key considerations of PGCP's investment decisions. At the same time, management factors such as project importance and project maturity will play an important role in supporting the decision-making of PGCP investment ranking.

Compared with the three ranking methods called conventional prospect theory, utility theory, and TOPSIS, the ranking consistency index of the model built in this paper is high, indicating that the proposed model has strong robustness. At the same time, the sample separation index of the model in this paper is significantly greater than those of the comparison models, indicating that the decision-making efficiency is higher. According to the comparison results, it can be verified that the proposed MCDM method based on RGPBIT improved prospect theory can improve the decision-making efficiency on the premise of ensuring robustness, which can provide a new solution for MCDM of PGCPs with considering the subjective performance of decision makers.

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Appendix A

Taking the IEEE-RTS79 system as an example, the basic operation data is referred to [42], and the calculation process and results of each indicator are as follows:

(1) Quantitative index calculation

1) Network coordination

Reference [44] gave the calculation method of network coordination, mainly considering line coordination. The line coordination D_L is measured by the standard deviation of different line load rates of the power grid, specifically as

$$D_L = \sqrt{\frac{1}{N_L} \sum_{i=1}^{N_L} (L_i - \bar{L}_i)^2} \quad (\text{A1})$$

where L_i is the load rate of the i -th line, \bar{L}_i is the average load rate of the line, and N_L is the number of lines.

Due to the uncertainty of load, the system power flow is uncertain. The maximum load and minimum load are used to calculate the system coordination, as shown in Table A1.

Table A1: Results of network coordination indicator

PGCP	Coordination under minimum load	Coordination under maximum load	Network coordination
1	0.1604	0.1731	[0.1604, 0.1731]
2	0.1583	0.1625	[0.1583, 0.1625]
3	0.1590	0.1673	[0.1590, 0.1673]
4	0.1618	0.1724	[0.1618, 0.1724]

2) Power supply reliability

Load loss rates are used to calculate the power supply reliability index, as shown in Eq. (A2). Based on Monte Carlo simulation [55], the load loss rate of the system after constructing the project is calculated, then by subtracting the load loss rate from 1, it can determine the reliability of the power supply.

$$P_{LOLP} = \frac{1}{N} \sum_{\kappa=1}^N F_{LOLP}(t_i) \quad (\text{A2})$$

where N is the total number of samples, and $F_{LOLP}(t_i)$ is the load shedding state of the system under state t_i , where 1 indicates load shedding and 0 indicates no load shedding. Using the failure rate of previously constructed projects, assume that the value range of the failure rate of PGCP 1 is [0.0002673, 0.0003583], and take the lower limit and upper limit of the interval as analog values, respectively, conduct Monte Carlo sampling to obtain the power supply reliability of the system, as shown in Table A2 (only the results of PGCP 1 are given here, and the results of other PGCPs are obtained using the same method).

Table A2: Power supply reliability of PGCP 1

Indicator	Right endpoint value	Left endpoint value	Interval value
LOLP	0.08496	0.07622	[0.07622, 0.08496]
Reliability	0.91504	0.92378	[0.91504, 0.92378]

3) Reduction of line loss rate and number of heavy load transformers/lines

For the given system and current operation mode, calculate the power flow with/without each planning project, then the line loss rate of the system is obtained, and the reduction number of heavy load transformers and lines is gained, as shown in Table A3.

Table A3: Line loss rate, heavy load transformer/line reduction results

PGCP	Line loss rate/%	Reduction of heavy load transformer	Reduction of heavy haul lines
1	[0.114, 0.123]	[4, 6]	[7, 9]
2	[0.219, 0.232]	[3, 5]	[6, 8]
3	[0.158, 0.193]	[6, 7]	[8, 10]
4	[0.099, 0.112]	[4, 7]	[5, 8]

4) Investment income ratio

Reference [45] used the life-cycle method and uncertainty method to calculate the cost and benefit of each construction project. The total investment of the project T_0 is represented as

$$T_0 = \sum_{j=1}^{n_1} [T_j (1 + i_0)^{n_1-j+1}] \tag{A3}$$

where n_1 represents the construction period of the project, T_j represents the annual investment amount, and i_0 represents the discount rate.

The projected income R on the whole life cycle can be denoted as $R = R_1 + R_2 + R_3$, where R_1 is the income of the purchase and sales price difference, R_2 is the income of the network fees by participating market, and R_3 is the income of the change of line loss rate, which is respectively expressed as

$$R_1 = \sum_{j=1}^{n_2} \frac{P_{2j} (1 - \lambda) Q_j}{(1 + i_0)^j} - \sum_{j=1}^{n_2} \frac{P_{1j} (1 - \lambda) Q_j}{(1 - \eta_j) (1 + i_0)^j} \tag{A4}$$

$$R_2 = \sum_{j=1}^{n_2} \lambda P_{3j} Q_j \tag{A5}$$

$$R_3 = \sum_{j=1}^{n_2} \left\{ \mu \Delta \eta_j [(1 - \lambda) P_{2j} Q_j + \lambda P_{3j} Q_j] \frac{1}{(1 + i_0)^j} \right\} \tag{A6}$$

where n_2 represents the operation cycle of the project; P_1 , P_2 and P_3 are the average power purchase/sales/transmission and distribution prices; Q is increased electricity sales, λ is marketization rate, μ is verification coefficient of line loss rate, η is line loss rate, $\Delta \eta_j$ is change value of line loss rate, and generally μ is set to be 0.5. The subscript j means the j -th year. The project investment income ratio P in the whole life cycle can be

$$P = R/T_0 \tag{A7}$$

Because of the uncertainty of the increased electricity sales, the project investment income is uncertain. In this paper, the interval number is used to represent the uncertainty of the increased electricity sales. Therefore, the project investment income ratio is also an interval indicator, as shown in [Table A4](#).

Table A4: Investment income ratio

PGCP	Minimum NPV/10000 yuan	Maximum NPV/10000 yuan	Investment amount/10000 yuan	Investment income ratio
1	2948.5	3232.8	15886	[1.1856, 1.2035]
2	1728.2	3296.8	18700	[1.0924, 1.1763]
3	2199.2	2959.0	22400	[1.0982, 1.1321]
4	2163.7	2828.8	16640	[1.1300, 1.1700]

5) Increased sales of electricity per unit grid investment

According to the economic development situation, the grey prediction model [56] is employed to forecast the electricity demand, and increased electricity sales can be obtained. Taking PGCP 1 as an example, the original load of bus 6 is 136 MW, and the new load is 136 MW. The total load of bus 6 is increased at a rate of 6% every year, reaching the load saturation in the 13th year. Assuming that the annual electricity utilization hours of the load is 4000 h, and taking 110% of the load forecast as the maximum increase in sales, it can be obtained that the minimum and maximum values of PGCP 1’s full life cycle electricity sales are 1879.44 and 2067.38 million kWh, respectively, so the increased sales of electricity per unit grid investment of PGCP 1 is [11.8, 13.0]. For the other three PGCPs, the increased sales of electricity per unit grid investment are [10.6, 11.7], [11.5, 12.6], and [11.2, 12.4], respectively.

(2) Qualitative index calculation

The quantification of qualitative indicators is expressed by fuzzy triangle numbers, and the quantitative value of each indicator is calculated according to the expert evaluation results. Take the PGCP early planning ability as an example to illustrate, and the quantitative methods of other qualitative indicators are similar. 8 experts from power grid enterprises, construction units, and scientific research institutions are invited for evaluation, and the results are shown in [Table A5](#).

Table A5: Quantitative evaluation results of PGCP early planning ability

Expert	PGCP 1	PGCP 2	PGCP 3	PGCP 4
1	(0.4, 0.5, 0.6)	(0, 0.1, 0.2)	(0.5, 0.6, 0.7)	(0.2, 0.3, 0.4)
2	(0.4, 0.5, 0.6)	(0.1, 0.2, 0.3)	(0.5, 0.6, 0.7)	(0.3, 0.4, 0.5)
3	(0.5, 0.6, 0.7)	(0.2, 0.3, 0.4)	(0.6, 0.7, 0.8)	(0.3, 0.4, 0.5)
4	(0.6, 0.7, 0.8)	(0.3, 0.4, 0.5)	(0.6, 0.7, 0.8)	(0.4, 0.5, 0.6)
5	(0.1, 0.2, 0.3)	(0.3, 0.4, 0.5)	(0.7, 0.8, 0.9)	(0.5, 0.6, 0.7)
6	(0.3, 0.4, 0.5)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.5, 0.6, 0.7)
7	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.6, 0.7, 0.8)
8	(0.2, 0.3, 0.4)	(0.5, 0.6, 0.7)	(0.8, 0.9, 1.0)	(0.7, 0.8, 0.9)
Average	(0.4, 0.5, 0.6)	(0.275, 0.375, 0.475)	(0.6625, 0.7625, 0.8625)	(0.4375, 0.5375, 0.6375)