

RESEARCH ARTICLE

Evaluation Method and Bidding Strategy of Load Aggregator Demand Response Potential Based on Spherical Fuzzy Numbers**Mohan Zhang^{1,2} Puliang Du^{1,2}***1 School of Economics and Management, Shanghai University of Electric Power, Shanghai, China**2 Marxism Research Institute of Shanghai University of Electric Power, Shanghai, China***ABSTRACT**

With the high proportion of new energy integrated into the power system, demand response, as a key technology for improving the flexible regulation capacity of power grids, has gained increasingly prominent resource value. Load aggregators, which integrate dispersed demand-side resources to participate in market transactions, are the core entities for the market-oriented implementation of demand response. Accurate evaluation of the demand response potential of load aggregators is the prerequisite for formulating scientific bidding strategies and improving market returns. Aiming at the problems of fuzzy information and strong uncertainty in demand response evaluation, this paper proposes a demand response potential evaluation and bidding optimization method for load aggregators based on spherical fuzzy numbers. First, a demand response potential evaluation system with 12 indicators is constructed from four dimensions: resource endowment, economic efficiency, operation and control, and environmental support. Second, spherical fuzzy numbers are introduced to characterize the uncertainty of evaluation information, and a score function is applied to realize the clarification of fuzzy information. Combined with the entropy weight method to objectively determine index weights, a comprehensive evaluation model is established to realize the quantitative ranking of load aggregators' demand response potential. On this basis, oriented to the quasi-linear demand response market mechanism, with the goal of maximizing the total profit of load aggregators, and comprehensively considering subsidy income, user incentive cost and response deviation penalty cost, an optimal bidding decision model for load aggregators is constructed and constraint conditions are derived. This method can effectively handle the fuzzy and uncertain information in the evaluation process, accurately quantify the difference in response potential among different load aggregators, and provide a scientific quantitative basis for bidding decisions.

Keywords: *load aggregator; demand response potential; spherical fuzzy number; entropy weight method; quasi-linear demand response; bidding strategy*

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1. Introduction

Guided by the "Dual Carbon" goal, China's power system is accelerating its transformation to a new power system dominated by new energy. New energy sources such as wind power and photovoltaics have strong randomness, volatility and intermittency. Large-scale grid integration of new energy has put forward higher requirements for the flexible regulation capacity of the power system. The traditional mode of maintaining the balance between supply and demand relying on generation-side regulation resources faces bottlenecks such as long construction cycles and high regulation costs, and it is difficult to adapt to the system operation requirements under the background of high-proportion new energy integration. In this context, fully tapping the regulation potential of demand-side resources and improving the active response capacity of the load side have become important ways to solve system regulation problems and promote new energy consumption.

Demand Response (DR) guides users to actively adjust their electricity consumption behavior through price signals and incentive mechanisms to achieve peak shaving and valley filling, and is the core technical means of demand-side management. With the advancement of power market reform, demand response has gradually developed into a market-oriented transaction mode. Due to the limited response potential and high participation threshold of individual users, load aggregators (LA), as intermediate entities connecting power grids and users, form large-scale tradable regulation capacity by integrating dispersed resources such as household loads, industrial adjustable loads and electric vehicles, and play a key role in the demand response market.

Scientific evaluation of the demand response potential of aggregators is the basis for resource allocation optimization and bidding strategy formulation. Most existing studies construct evaluation index systems from dimensions such as load characteristics and economic costs. However, in the evaluation process, there are both the fuzziness of expert subjective judgment and the uncertainty of user response behavior and market environment. Traditional precise evaluation methods are difficult to effectively characterize such complex information, leading to deviations between evaluation results and actual situations. Spherical fuzzy numbers describe uncertain information through three dimensions: membership degree, non-membership degree and hesitation degree, which can more fully reflect the fuzziness and unknownness in evaluation, and have been widely used in the field of multi-attribute decision-making.

To address the above problems, this paper proposes a demand response potential evaluation method for load aggregators based on spherical fuzzy numbers. First, a multi-dimensional evaluation index system is constructed, and spherical fuzzy numbers are introduced to deal with the uncertainty of evaluation information. Second, the entropy weight method is combined to objectively determine index weights to realize quantitative evaluation of demand response potential. On this basis, oriented to the quasi-linear demand response market mechanism, an optimal bidding decision model for load aggregators is constructed, and the enlightenment of method application is extracted from three levels:

theory, practice and policy, so as to provide decision support for load aggregators to participate in the market.

2. Demand Response Potential Evaluation Index System

2.1 Principles of Index Construction

To ensure the scientificity and rationality of the evaluation results, the index system is constructed following the principles below: (1) Scientific principle: Indicators are selected based on the actual operation and relevant theories of demand response, with traceable data sources and clear calculation methods, which can objectively reflect the core characteristics of load aggregators' demand response potential. (2) Systematic principle: It covers multiple levels such as resource base, economic benefit, operation capacity and external environment, and comprehensively covers the internal and external key factors affecting the response potential of aggregators. (3) Hierarchical principle: The index system is divided into two levels: first-level standard layer and second-level indicator layer, with clear hierarchical logic, clear positioning of indicators at each level, and no overlapping information of indicators at the same level. (4) Independence principle: The connotation of each indicator has clear boundaries to avoid cross repetition, so as to ensure the independence and discrimination of evaluation results. (5) Practical principle: Indicator data are easy to collect, the calculation method is simple, and it has operability for practical application, which can support the daily operation decisions of load aggregators.

2.2 Construction of Evaluation Index System

Centering on the core connotation of load aggregators' demand response potential, a comprehensive evaluation system containing 12 second-level indicators is constructed from four first-level dimensions: resource endowment layer, economic efficiency layer, operation and control layer, and environmental support layer. The specific connotations of each dimension and indicator are as follows.

2.2.1 Resource Endowment Layer

Resource endowment is the physical basis for load aggregators to carry out demand response, which directly determines the upper limit of response potential, and reflects the scale, intensity and constraint attributes of adjustable resources. (1) Proportion of adjustable resources: It refers to the proportion of the total load that can participate in demand response in the total operating load within the jurisdiction of the aggregator, covering three types of adjustable resources: interruptible load, transferable load and shiftable load. The higher the proportion, the larger the base of schedulable resources and the stronger the overall response potential. (2) Peak regulation range: It refers to the maximum load increase and maximum load decrease that the aggregator can achieve within a single period, reflecting the instantaneous regulation capacity of resources. The larger the regulation range, the stronger the ability to cope with peak loads or power deficits. (3) Load sensitivity level: It is classified according to the impact of load interruption or adjustment on production and life, and is usually divided into three levels: core guarantee level, important production level and general adjustable level. The higher the load sensitivity level, the stronger the response constraint, the smaller the adjustable space, and the relatively lower the response potential.

2.2.2 Economic Efficiency Layer

Economic efficiency is the direct reflection of the market value of demand response resources, which determines the profit space of aggregators participating in market transactions and users' willingness to participate. (1) Unit regulation cost: It refers to the comprehensive cost required to realize unit power load regulation, including user incentive cost, equipment loss cost, operation and management cost, etc. The lower the unit regulation cost, the larger the profit space of the aggregator and the higher the economic feasibility of response potential. (2) Marginal profit space: It refers to the marginal profit after deducting the unit regulation cost from the market subsidy income obtained per unit response volume, reflecting the profit efficiency of demand response resources. The larger the marginal profit space, the higher the market value of resources. (3) User participation elasticity: It refers to the variation range of user response volume with the change of incentive price, reflecting the regulation ability of price leverage on user behavior. The higher the participation elasticity, the easier it is to regulate the response scale by adjusting the incentive price, and the larger the flexible scheduling space of resources.

2.2.3 Operation and Control Layer

Operation and control capacity is the key support for aggregators to transform resource potential into actual response capacity, which directly affects the efficiency, accuracy and flexibility of response execution. (1) Response delay level: It refers to the total time from receiving the scheduling instruction or market signal to adjusting the load to the target value, including the whole process time of instruction transmission, equipment action and load regulation. The shorter the response delay, the stronger the fast response capability, and the more suitable for response scenarios with high real-time requirements. (2) Execution deviation rate: It refers to the average deviation ratio between the actual response volume and the bidding target or scheduling instruction, reflecting the accuracy of response execution. The lower the deviation rate, the higher the execution reliability, and the easier it is to meet the curve tracking requirements of quasi-linear response. (3) Scenario adaptation capability: It refers to the number of demand response scenario types that the aggregator can support, such as peak shaving, valley filling, reserve capacity, frequency support, etc. The richer the adaptation scenarios, the wider the application range of resources and the stronger the comprehensive response potential.

2.2.4 Environmental Support Layer

Environmental support is the external condition that affects the release of demand response potential, covering external factors in three dimensions: policy, market and society. (1) Policy incentive intensity: It refers to the intensity and perfection degree of support policies such as special subsidies, price preferences and tax reductions for demand response by local authorities. The higher the policy incentive intensity, the stronger the user participation motivation and the profit expectation of aggregators, and the easier the response potential is to be released. (2) Market maturity: It refers to the perfection degree of transaction rules, pricing mechanism, clearing process and richness of participants in the demand response market. The more mature the market mechanism, the lower the transaction cost and the smoother the channel for aggregators to participate in the market. (3) Social acceptance: It refers to the recognition degree and cooperation willingness of user groups and the surrounding public for load adjustment, including the acceptance of electricity consumption mode adjustment and short-term power outage. The higher the social acceptance, the less resistance to the implementation of demand response and the stronger the implementation feasibility.

Table 1. Evaluation Indicators for Demand Response Potential.

<i>Dimension</i>	<i>Indicators</i>
<i>Resource Endowment</i>	<i>Adjustable Resource Proportion; Peak Regulation Capacity; Load Sensitivity</i>
<i>Economic Efficiency</i>	<i>Unit Regulation Cost; Marginal Revenue Space; User Participation Elasticity</i>
<i>Operational Management</i>	<i>Response Delay; Execution Deviation Rate; Scenario Adaptability</i>

3 Comprehensive Evaluation Model Based on Spherical Fuzzy Entropy Weight Method

3.1 Basic Theory of Spherical Fuzzy Numbers

Spherical Fuzzy Set (SFS) is an extension of intuitionistic fuzzy sets. It characterizes uncertain information through three parameters: membership degree, non-membership degree and hesitation degree, which can more comprehensively describe the fuzziness and unknownness in decision-making.

Definition 1 Let the universe of discourse be X . For any $x \in X$, the spherical fuzzy set $\tilde{A}$ can be expressed as:

$$\tilde{A} = \left\{ \left\langle x, \mu_{\tilde{A}}(x), \nu_{\tilde{A}}(x), \pi_{\tilde{A}}(x) \right\rangle \mid x \in X \right\} \quad (1)$$

where $\mu_{\tilde{A}}(x) \in ([0, 1])$ is the membership degree of x belonging to $\tilde{A}$; $\nu_{\tilde{A}}(x) \in ([0, 1])$ is the non-membership degree of x not belonging to $\tilde{A}$; $\pi_{\tilde{A}}(x) \in ([0, 1])$ is the hesitation degree, and satisfies the constraint condition:

$$\mu_{\tilde{A}}(x) + \nu_{\tilde{A}}(x) + \pi_{\tilde{A}}(x) \leq 1 \quad (2)$$

To facilitate subsequent calculation and ranking, the score function is used to convert spherical fuzzy numbers into crisp values. For a spherical fuzzy number $\tilde{s} = (\mu, \nu, \pi)$, its score function is defined as:

$$S(\tilde{s}) = \frac{1 + \mu^2 - \nu^2 - \pi^2}{2} \leq 1 \quad (3)$$

The value range of the score function is $[0, 1]$. The higher the score, the better the evaluation object.

3.2 Construction of Spherical Fuzzy Decision Matrix

Let the set of load aggregators to be evaluated be $D = D_1, D_2, \dots, D_m$, and the set of evaluation indicators be $C = C_1, C_2, \dots, C_n$. Experts are invited to score the performance of each aggregator under each indicator, and the scoring results are expressed by spherical fuzzy numbers. Let the evaluation value

of aggregator D_i under indicator C_j be $\tilde{s}_{ij} = (\mu_{ij}, \nu_{ij}, \pi_{ij})$, then the spherical fuzzy decision matrix $\tilde{S}$ is constructed as:

$$\tilde{S} = \begin{bmatrix} \tilde{s}_{11} & \tilde{s}_{12} & \cdots & \tilde{s}_{1n} \\ \tilde{s}_{21} & \tilde{s}_{22} & \cdots & \tilde{s}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{s}_{m1} & \tilde{s}_{m2} & \cdots & \tilde{s}_{mn} \end{bmatrix} \quad (4)$$

3.3 Clarification of Fuzzy Information

According to the score function in Equation (1), each element in the spherical fuzzy decision matrix is converted into a crisp value, and the crisp decision matrix $R = (r_{ij})^{m \times n}$ is obtained, where:

$$r_{ij} = S(\tilde{s}_{ij}) = \frac{1 + \mu_{ij}^2 - \nu_{ij}^2 - \pi_{ij}^2}{2} \quad (5)$$

3.4 Determination of Index Weights by Entropy Weight Method

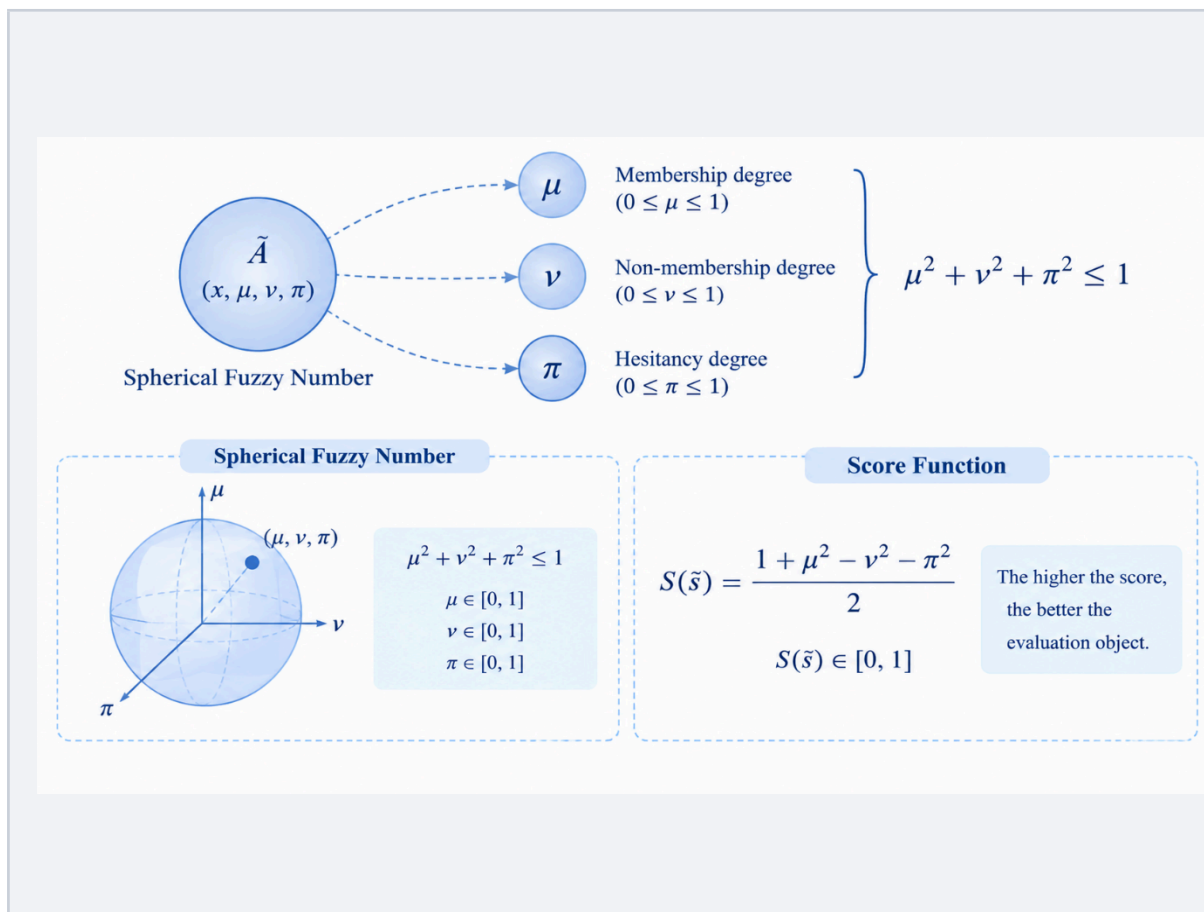


Figure 1. Illustration of Spherical Fuzzy Numbers and the Score Function.

The entropy weight method is an objective weighting method based on the degree of data dispersion. Its core idea is that the greater the dispersion degree of indicator data, the more information it carries, and the higher the corresponding weight. This method can avoid the artificial deviation of subjective weighting and make the evaluation results more objective. The specific calculation steps are as follows:

Step 1: Normalization of decision matrix

Due to the differences in dimensions and value ranges of different indicators, it is necessary to normalize the crisp decision matrix. According to indicator attributes, they are divided into benefit type and cost type:

Benefit-type indicators (the larger the value, the better, such as proportion of adjustable resources, marginal profit space, etc.):

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^m r_{ij}} \quad (6)$$

Cost-type indicators (the smaller the value, the better, such as unit regulation cost, execution deviation rate, etc.):

$$p_{ij} = \frac{1/r_{ij}}{\sum_{i=1}^m 1/r_{ij}} \quad (7)$$

After normalization, the matrix $P = (p_{ij})^{m \times n}$ is obtained, satisfying $0 \leq p_{ij} \leq 1$.

Step 2: Calculation of information entropy

The information entropy e_j of the j -th indicator reflects the disorder degree of the indicator information, and the calculation formula is:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m p_{ij} \ln p_{ij} \quad (8)$$

where if $p_{ij} = 0$, then $p_{ij} \ln p_{ij} = 0$ by convention. The value range of information entropy is $[0, 1]$. The smaller the entropy value, the greater the dispersion degree of indicator data and the richer the information.

Step 3: Calculation of index weights

The entropy weight of each indicator is calculated according to the information entropy:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)} \quad (9)$$

satisfying $\sum_{j=1}^n w_j = 1$ and $w_j \geq 0$.

3.5 Comprehensive Potential Score

The weighted summation method is used to calculate the comprehensive score of demand response potential of each load aggregator:

$$V_i = \sum_{j=1}^n w_j \cdot r_{ij} \quad (10)$$

where V_i is the comprehensive score of the i -th aggregator. The higher the score, the stronger the demand response potential. According to the ranking of comprehensive scores, high-potential aggregators can be identified to provide a basis for subsequent bidding decisions.

4. Bidding Framework for Demand Response Load Aggregators

On the basis of demand response potential evaluation, further oriented to the quasi-linear demand response market mechanism, an optimal bidding decision model for load aggregators is constructed to realize the transformation of potential evaluation results into market strategies.

4.1 Quasi-linear Demand Response Mechanism

Quasi-linear demand response means that the power grid company issues a standardized target load curve (load directrix) according to system demands such as peak shaving and reserve capacity. Participants adjust their own electricity consumption behavior to make the actual load curve as close to the load directrix as possible. The higher the similarity between the response curve and the load directrix, the more subsidy income is obtained; the larger the deviation, the less the income, and fines will be imposed for serious deviations.

Let the response period set be $T = t_1, t_2, \dots, t_k$. First, the load curve issued by the power grid is normalized to obtain the standardized load directrix l_t^{CDL} to simplify subsequent calculations.

4.2 Objective Function

The goal of load aggregators participating in the demand response market is to maximize total profit. Total profit equals subsidy income minus user incentive cost and response deviation penalty cost. The objective function is:

$$\max Q = \sum_{t \in T} [W_a(t) - C_U(t) - C_P(t)] \quad (11)$$

where Q is the total profit of the aggregator in the response cycle; $W_a(t)$ is the subsidy income obtained by the aggregator in period t ; $C_U(t)$ is the incentive cost paid to users in period t ; $C_P(t)$ is the penalty cost caused by response deviation in period t .

4.2.1 Subsidy Income

Subsidy income is positively correlated with the similarity of load curves. The Euclidean distance is used to measure the deviation degree between the actual load curve of the aggregator and the load directrix:

$$d = \sqrt{\sum_{t \in T} (l_t^{\text{agg}} - l_t^{\text{CDL}})^2} \quad (12)$$

where d is the Euclidean distance between the two curves; l_t^{agg} is the normalized load value of the aggregator in period t .

The similarity index is defined based on the Euclidean distance:

$$s = \frac{1}{1+d} \quad (13)$$

The value range of similarity s is $((0,1])$. The closer s is to 1, the higher the coincidence degree of the two curves.

The calculation formula of subsidy income is:

$$W_d(t) = \lambda \cdot s \cdot P_d(t) \cdot p^{\text{clearing}} \quad (14)$$

where λ is the subsidy adjustment coefficient, determined by market rules; $P_d(t)$ is the bidding response volume of the aggregator in period t ; p^{clearing} is the unified market clearing price.

4.2.2 User Incentive Cost

The aggregator integrates N user resources, and users' response behavior follows threshold characteristics: when the incentive price is lower than the initial response price, users do not participate in the response; when the incentive price is between the initial price and the saturation price, the response volume increases linearly with the price; when the incentive price exceeds the saturation price, the response volume reaches the maximum value and no longer increases. The user response volume model is:

$$q_n(t) = \begin{cases} 0, & p_n(t) < p_n^{\text{start}}, \\ q_n^{\text{max}}(t) \cdot \frac{p_n(t) - p_n^{\text{start}}}{p_n^{\text{sat}} - p_n^{\text{start}}}, & p_n^{\text{start}} \leq p_n(t) < p_n^{\text{sat}}, \\ q_n^{\text{max}}(t), & p_n(t) \geq p_n^{\text{sat}}. \end{cases} \quad (15)$$

where $q_n(t)$ is the actual response volume of user n in period t ; $q_n^{\text{max}}(t)$ is the maximum response capacity of user n in period t ; $p_n(t)$ is the incentive price of user n in period t ; p_n^{start} is the initial response price of the user; p_n^{sat} is the saturation response price of the user.

The total user incentive cost is the sum of incentive costs of all users:

(16)

$$C_U(t) = \sum_{n=1}^N p_n(t) \cdot q_n(t)$$

Considering the uncertainty of user response behavior, it is assumed that the deviation of response volume follows a normal distribution, and the standard deviation of the deviation is negatively correlated with the incentive price. The higher the incentive price, the more stable the user response and the smaller the deviation:

$$\sigma_n(t) = \sigma_0 - k \cdot p_n(t) \quad (17)$$

where $\sigma_n(t)$ is the standard deviation of the response volume deviation of user n in period t ; σ_0 is the benchmark deviation coefficient; k is the price influence coefficient.

4.2.3 Penalty Cost

When the actual total response volume of the aggregator is lower than the bidding response volume, a fine shall be paid for the unmet part. The calculation formula of penalty cost is:

$$C_P(t) = c \cdot \max \left(0, P_d(t) - \sum_{n=1}^N q_n(t) \right) \quad (18)$$

where c is the unit fine price for unmet volume.

4.3 Constraint Conditions

(1) Load electricity constraint

Users participating in demand response only adjust the time distribution of electricity consumption without changing the total electricity consumption, satisfying the conservation of electricity:

$$\sum_{t \in T} \Delta I_n(t) = 0 \quad (19)$$

where $\Delta I_n(t)$ is the load regulation amount of user n in period t . A positive value means load increase, and a negative value means load decrease.

(2) Regulation power constraint

The load regulation power of users is limited by the physical characteristics of equipment, with upper and lower limits:

$$-\Delta I_n^{down} \leq \Delta I_n(t) \leq \Delta I_n^{up} \quad (20)$$

where Δ_n^{up} is the upper limit of user's upward regulation power; Δ_n^{down} is the upper limit of user's downward regulation power.

(3) Bidding price constraint

The bidding price of the aggregator shall be within the price range specified by the market:

$$p^{min} \leq p^{bid} \leq p^{max} \quad (21)$$

where p^{bid} is the bidding price of the aggregator; p^{min} and p^{max} are the lower and upper limits of the bidding price specified by the market, respectively.

(4) Response capacity constraint

The total bidding response volume of the aggregator shall not exceed its maximum adjustable capacity:

$$\sum_{t \in T} P_d(t) \leq Q^{max} \quad (22)$$

where Q^{max} is the maximum adjustable capacity of the aggregator, which can be determined by the potential evaluation result.

5. Enlightenment of Method Application

The demand response potential evaluation method and bidding optimization model based on spherical fuzzy numbers not only provide quantitative tools for load aggregators' market decisions, but also have multi-level enlightenment for the development of demand response resources and the improvement of market mechanisms.

5.1 Enlightenment at the Theoretical Method Level

First, uncertainty characterization is the core premise of demand response evaluation. Demand response resources are inherently characterized by dispersion, heterogeneous user behavior, and dynamic market environment. Traditional precise evaluation methods are difficult to fully characterize the fuzzy information and unknown factors. Spherical fuzzy numbers describe evaluation information through three-dimensional parameters of membership degree, non-membership degree and hesitation degree. Compared with the single-dimensional characterization of traditional fuzzy sets that only consider membership degree, they can more comprehensively reflect subjective judgment deviation, incomplete information and future uncertainty in the evaluation process, and provide a more suitable mathematical tool for potential evaluation in complex scenarios. This also enlightens subsequent related research that the uncertainty characteristics in the field of demand response should be fully valued, and more suitable uncertainty mathematical methods should be introduced to improve the robustness of evaluation and decision models.

Second, objective weighting is a key path to improve the scientificity of evaluation. The entropy weight method adopted in this paper calculates weights completely based on the degree of data

dispersion, which avoids the artificial preference deviation of subjective weighting methods such as analytic hierarchy process and best-worst method, and ensures the objectivity of evaluation results. In practical applications, moderate subjective adjustment can be introduced on the basis of objective entropy weights combined with policy orientation and industry experience in specific scenarios, forming a combined subjective and objective weighting mode, which not only retains the objective law of data, but also reflects the experience orientation of actual decisions, and realizes the balance between scientificity and practicability.

Third, the "evaluation-decision" integrated framework is an effective way to enhance resource value. Traditional studies usually divide demand response potential evaluation and market bidding decisions into two independent links, and evaluation results are difficult to directly support strategy optimization. The complete framework from quantitative potential evaluation to bidding strategy optimization constructed in this paper opens up the link between resource capacity identification and market value transformation, so that evaluation results can directly serve bidding decisions, and realize the effective transformation of resource potential into economic benefits. This enlightens industry practice that a closed-loop management mechanism from resource investigation, capacity evaluation to strategy optimization should be established to improve the development and utilization efficiency of demand-side resources.

5.2 Enlightenment for Load Aggregator Operation Practice

First, establish a normalized demand response potential evaluation mechanism. Load aggregators should take potential evaluation as the basic link of resource management and market decision-making. Centering on the four dimensions of resource endowment, economic efficiency, operation and control, and environmental support, they should conduct a comprehensive investigation of various user resources under their jurisdiction on a regular basis. With the help of the spherical fuzzy evaluation method, they can quantify the response potential of different user groups and regions, identify high-value adjustable resources, and establish a hierarchical and classified resource account to provide accurate basic data support for market bidding. It is necessary to avoid judging resource capacity only by experience, which leads to mismatch between bidding strategies and actual response capacity, resulting in profit loss or default risk.

Second, formulate differentiated bidding strategies based on potential evaluation results. Aggregators should formulate differentiated bidding schemes for resources of different levels according to the quantitative scores of resource potential. For resources with high potential and high reliability, the bidding scale can be appropriately increased to strive for more market share and benefits; for resources with low potential and high uncertainty, the bidding proportion should be controlled to reduce the risk of response deviation. At the same time, combined with the curve tracking requirements of quasi-linear demand response, the distribution of bidding volume in each period should be optimized according to the resource response characteristics in different periods, so as to improve the matching degree between the overall load curve and the load directrix and maximize subsidy income.

Third, build a risk prevention and control system considering uncertainty. The uncertainty of user response behavior is the core risk source for aggregators' market operation. In bidding decisions, aggregators should fully consider the fluctuation characteristics of response volume and reserve a reasonable safety margin to avoid the default fine risk caused by full-load bidding. At the same time, a dynamic adjustment mechanism can be established to slightly adjust the bidding strategy in

subsequent periods according to the real-time response situation, so as to balance the profit target and risk level and improve operation stability.

5.3 Enlightenment for Industry Development and Policy

First, promote the standardization of demand response potential evaluation. At present, there is no unified standard for demand response potential evaluation in the industry. The evaluation indicators and methods of different entities vary greatly, and the evaluation results are difficult to compare horizontally and apply industrially. It is recommended that industry authorities take the lead in formulating a unified demand response potential evaluation index system and technical specifications around core dimensions such as resource endowment, economic efficiency, operation and control, and environmental support, clarify the evaluation process, methods and data requirements, and promote the standardization of evaluation work, so as to lay a foundation for the large-scale development of demand response resources.

Second, promote the application of quantitative evaluation methods in the industry. At present, the resource evaluation and bidding decisions of most aggregators still rely on empirical judgment, with insufficient refinement. Scientific methods such as spherical fuzzy evaluation and entropy weight quantification should be actively promoted to guide aggregators to establish digital resource evaluation and decision systems and improve the overall decision refinement level of the industry. At the same time, supporting potential evaluation toolkits can be developed relying on power trading platforms to reduce the application threshold for market participants.

Third, improve the design of quasi-linear demand response market mechanism. Quasi-linear demand response can accurately match system regulation demands and has broad application prospects. The transaction rules, subsidy mechanism and penalty standard of quasi-linear response should be further clarified, and the release mechanism and adjustment process of load directrix should be optimized to provide clear rule guidelines for aggregators to participate in market transactions. At the same time, a market credit evaluation system should be established, and the response potential and actual execution effect of aggregators should be included in the credit evaluation, so as to guide market participants to attach importance to resource capacity building and promote the healthy and orderly development of the market.

6. Conclusion

Aiming at the problems of fuzzy information and strong uncertainty in demand response potential evaluation, this paper proposes a demand response potential evaluation method for load aggregators based on spherical fuzzy numbers, and constructs an optimal bidding model under quasi-linear demand response. The main conclusions are as follows: (1) The 12-indicator system constructed from four dimensions of resource endowment, economic efficiency, operation and control, and environmental support can comprehensively cover the internal and external key factors affecting demand response potential, and provide a complete indicator framework for potential evaluation. (2) Introducing spherical fuzzy numbers to characterize the uncertainty of evaluation information, combined with objective weighting by entropy weight method, effectively reduces subjective judgment deviation and improves the scientificity and accuracy of evaluation results. (3) The constructed load aggregator bidding model under quasi-linear demand response, which comprehensively considers subsidy income, incentive cost and penalty cost, can realize the optimization of bidding strategies and provide a quantitative basis for aggregators' market decisions.

The method in this paper can provide theoretical support for resource evaluation and market bidding of load aggregators. Future research can further explore the optimization of bidding strategies under the competitive game of multiple load aggregators.

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