Research on Cluster Economy Operation Model Considering Customer Satisfaction

WEI ZHAO1, (Associate Member, IEEE), WENQI XUE2, PEIQIANG LI2, XUEXIAN TANG3,4, ERTAO LEI1, (Member, IEEE), HANBIN DIAO2, and XIAOXIU LV2

1Electric Power Research Institute of Guangdong Power Grid Corporation, Guangzhou 510000, China
2College of Electrical and Information Engineering, Hunan University, Changsha 410082, China
3State Grid Hunan Electric Power Company Ltd., Changsha 410007, China
4State Grid Shaoyang Power Supply Company, Shaoyang 422000, China

Corresponding authors: Peiqiang Li (lpqc@hnu.edu.cn) and Wenqi Xue (664624759@qq.com)

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ABSTRACT A Real-time electricity market transaction is an important method that is used to realize the interactive balance of source-network-load in a new generation power system. Based on the multi-camp economic choice and the needs of national conditions, the emergence of cluster operators is inevitable. Due to stability and development of photovoltaic users, it is important to evaluate the importance of users in a photovoltaic user group. In the existing model, users are too sensitive to the electricity price, which will lead to too high electricity adjustment rate. In order to make up for the lack of importance ranking research and the high adjustment rate of electricity consumption, this paper will introduce the electric power consumption satisfaction function and propose an optimal pricing model that is based on the master-slave game. The study analyzes the nature of operators’ revenue, and presents a method to calculate the contribution value using the cooperative game theory. The TOPSIS method is proposed to evaluate the ranking of the producers and sellers in the group. The developed illustration verifies the superiority of the cluster economic operation model.

INDEX TERMS Photovoltaic user group, optimal pricing, Stackelberg game, TOPSIS method, importance assessment, demand response.

I. INTRODUCTION Photovoltaic power generation can effectively alleviate the current energy shortage and environmental pollution problems. Its major application is distributed household photovoltaic, which has advantages of being close to the user side, flexible in construction scale, simple in installation, and wide in application range. The implementation of policies and cost reductions has improved the development of power generation [2]. Presently, the grid-connected power operation mode is “self-use, surplus electricity access to the Internet” [3]. Most of the producers and sellers trade with the power grid in cluster mode, to gain more from the electricity utility [4]. Based on China’s national conditions and the state of the multi-party economy, it will be historically inevitable to construct operators that are within the electricity-selling market and the market structure regulations. It is therefore, necessary to execute the cluster economic operation model that is widely dominated by intermediate operators. This is to improve on market vitality.

The operation model of cluster economy has three elements: of pricing, benefit and ranking. Scholars have established several pricing strategies and benefit models. LIU et al. [5] outlined a benefit-cost model of user participation in Demand Response (DR). LI et al. [6] used fuzzy maximum satisfaction method, by applying the 1-n master-slave game to construct the user benefit function, the price response, and power supply pricing optimization of micro-grid. Referring to the domestic policy of household photovoltaic, Mary and others put forward a DR model for photovoltaic users based on game theory and proved that there is a unique Nash equilibrium strategy for this game problem [4], [7]. Ma et al. [8]
outlined a game model between community operators and consumers using the master-slave game theory. The study, verified the advantages of improving the benefits of both parties and optimizing the load characteristics of the system. Tushar et al. [9] applied the energy management scheme of wireless city, based on the non-cooperative Stackelberg game, which reduces the total operating cost of the community energy management center and improves the residential units with maximum distributed energy. Wang et al. [10] and Liu et al. [11] researched on the users’ photovoltaic output power and electricity consumption, and found that it has an accurate prediction of at least one hour. The former puts forward a pricing model of photovoltaic users’ group electricity price based on Stackelberg game. The latter continues to study the influence of user behavior on operators’ revenue, and finally proposes an economic penalty model aiming at the difference between the actual output of photovoltaic power and the predicted value of load power. Ma et al. [12] studied the joint operation mode of cogeneration and photovoltaic users, and proposed an internal pricing model of microgrid. Lin et al. [13], [14] applied fuzzy double-objective method to normalize user’s cost and dissatisfaction. However, literature [13] used energy transaction model based on double Stackelberg game for power supply companies, micro-energy networks and users, while literature [14] used an optimization model and solution method based on non-cooperative game for CCHP energy supply network. The daily electricity consumption of users mainly considers three factors: electricity utility, economy and satisfaction. User benefit model proposed [5], [6], [13]–[15] does not consider the utility of electricity. Literature [4], [7]–[12] did not consider the user’s satisfaction with electricity consumption thus lacking its comprehension.

Several studies have focused on photovoltaic user groups on its economic operation, but limited on the evaluation of the importance of users in the group. However, to establish a stable and prosperous photovoltaic user group, it is necessary to solve the technical difficulties and the evaluation of user contribution [16]. From the perspective of user group managers, it was found out that distinguishing significant users and giving incentives (usually economic rewards) is beneficial to the stability of the group. From the user’s point of view, motivated users are likely to consume more electricity, thus, promoting the development and improvement of photovoltaic user groups. The PV (photovoltaic) user group has a reasonable importance evaluation and reward system, which will attract other PV users to join the group and make the PV user group grow and develop.

Therefore, this paper used the users’ electricity consumption benefit model, that takes into account the utility, economy, and satisfaction retrieved from the user’s point of view. For the photovoltaic users, the optimal operation of internal electricity price included: First, computing the contribution value of users in the group to operators’ revenue. This was done by studying the revenue essence of group operators using, the cooperative game theory. Second, the evaluation index of users, operators, and power grid was defined, and the photovoltaic user group evaluated and ranked using the TOPSIS method. Finally, using the Stackelberg game, a 1-n electric energy trading model of “operator-photovoltaic user group” was constructed to complete the design of cluster economic operation.

![FIGURE 1. Cluster trading mechanism framework.](image_url)

**II. CLUSTER OPERATION MODE**

Photovoltaic user group is composed of users and cluster operators. Users are both producers and consumers. The transaction relationship and price setting are shown in Figure 1.

The cluster operator formulates the cluster tariff $p_s$ and $p_b$, $\lambda_b$ and $\lambda_s$. It uses $p_s$ to acquire the surplus energy of surplus power users, and uses $p_b$ to sell energy to the consumers who are short of electricity. If the overall power consumption of the cluster is greater than its photovoltaic capacity, the cluster operator will purchase the power of the large grid with $\lambda_b$, and the cluster operator will purchase power from the large grid with $\lambda_s$ if the overall power consumption of the cluster is greater than its photovoltaic capacity. In this process, it maximizes its own income through price difference. Therefore, $p_s$ is not lower than the grid price $\lambda_s$, and $p_b$ is not greater than the grid price $\lambda_b$.

Users follow the cluster operator and respond to the demand according to the electricity price to maximize their own electricity use efficiency. All electric energy transactions in the cluster are realized by cluster operator. A day is divided into $m$ periods on average to form period set $I = \{1, 2, 3 \ldots m\}$. The number of users constitutes the PV user group set $NP = \{1, 2, 3 \ldots N\}$. In the $i$ period, the cluster price set by the cluster operator is $p_{si}$ and $p_{bi}$. When user n trades with the grid separately, the energy consumed by user $n$ is $x_{ani}$, which is also known as the original planned electricity consumption. The actual energy consumed in the photovoltaic user group is $x_{ani}$, and the energy generated by the photovoltaic system is $e_{ni}$, then the amount of electricity the user needs to trade with the cluster operator is $e_{ni} - x_{ani}$. When $e_{ni} - x_{ani} > 0$, user $n$ needs to sell electricity to cluster operator; when $e_{ni} - x_{ani} < 0$, user $n$ needs to purchase electricity from cluster operator.
Therefore, it is not necessary for users to participate in the transaction. According to the purchase and sale behaviors of consumers and power grid at that time, all users are divided into power purchase users and power sales users [11].

A. CUSTOMER SATISFACTION MODEL

In the existing literature, the difference between the actual power consumption and the original planned power consumption is used as a function of power consumption comfort or satisfaction [5, 6, 13–15]. When the actual consumption of electricity is less than the original plan, the satisfaction function of electricity consumption is negative, otherwise, the reproduction is positive. Equal is zero. For PV users

\[ S_n(x_{ani}, x_{ni}) \]

the power consumption satisfaction function \( S_n(x_{ani}, x_{ni}) \) has the following characteristics:

1. If the actual power consumption \( x_{ani} \) is less than the planned power consumption \( x_{ni} \), that is \( x_{ani} < x_{ni} \), the power consumption satisfaction value is negative, which indicates that the power consumption satisfaction of consumers decreases, and the function value decreases rapidly with the decrease of actual power consumption:

\[ S_n(x_{ani}, x_{ni}) < 0, \quad \frac{\partial S_n}{\partial x_{ani}} > 0, \quad \frac{\partial^2 S_n}{\partial x_{ani}^2} < 0 \quad (1) \]

2. When the actual electricity consumption is equal to the planned power consumption, that is \( x_{ani} = x_{ni} \), the satisfaction function of electricity consumption is \( S_n(x_{ani}, x_{ni}) = 0 \).

3. If the actual power consumption is greater than the planned power consumption, that is \( x_{ani} > x_{ni} \), the power consumption satisfaction value is positive, which indicates that the power consumption satisfaction of consumers increases. The function value increases slowly with the increase of actual power consumption, and the increase speed decreases gradually:

\[ S_n(x_{ani}, x_{ni}) > 0, \quad \frac{\partial S_n}{\partial x_{ani}} > 0, \quad \frac{\partial^2 S_n}{\partial x_{ani}^2} < 0 \quad (2) \]

In this paper, the power consumption satisfaction model of PV user \( n \) in the \( i \)-th period is as follows.

\[ S_{ni}(x_{ani}, x_{ni}) = \beta_{ni}x_{ni} \left[ \frac{x_{ani}}{x_{ni}} - 1 \right] \quad (3) \]

In formula, \( \alpha_{ni} \) and \( \beta_{ni} \) are the satisfaction parameters of user \( n \) in \( i \)-th period, \( \alpha_{ni} < 0 \) and \( \beta_{ni} < 0 \), and the requirements of different types of users for electricity consumption satisfaction can be described by adjusting \( \alpha_{ni} \) and \( \beta_{ni} \). Let the planned power consumption of user \( n \) in the \( i \)-th period be \( x_{ni} = 100 \text{ kwh} \), and by adjusting the actual power consumption \( x_{ani} \), the user satisfaction function under different parameter values is shown in Figure 2.

B. POWER CONSUMPTION BENEFIT OF PHOTOVOLTAIC USERS

The use of logarithmic function to describe the utility of electricity consumption [8–12, 17–19] has achieved positive results. The overall electricity consumption benefit of users is composed of the utility of prosumers and the electricity transaction cost. The cluster operator makes the maximum profit by setting the cluster price, and users respond to the demand according to the cluster price. In the existing power consumption benefit model [14–17], the sensitivity of user power consumption adjustment to cluster electricity price is too high, which will lead to excessive adjustment rate of user power consumption. This new function is used to solve the problem of user satisfaction.

\[ U_{ni} = \begin{cases} 
K_{ni} \ln(1 + x_{ani}) + p_{ti}(E_{gni} - x_{ani}) \\
+ \beta_{ni}x_{ni} \left[ \frac{x_{ani}}{x_{ni}} - 1 \right], & E_{ni} - x_{ni} > 0 \\
K_{ni} \ln(1 + x_{ani}) + p_{bi}(E_{ni} - x_{ani}) \\
+ \beta_{ni}x_{ni} \left[ \frac{E_{ni}}{x_{ni}} - 1 \right], & E_{ni} - x_{ni} < 0 
\end{cases} \quad (4) \]

In the formula: \( U_{ni} \)—the overall electricity consumption benefit of user \( n \) in the \( i \)-th period; \( K_{ni} \)—Utility coefficient, whose value is related to user demand and time period. It can be seen from formula (4) that when the actual electricity consumption \( x_{ani} \) increases, the electricity utility and satisfaction of electricity sales users increase, and the electricity sales income decreases; the electricity consumption utility and satisfaction of power consumers also increase, and the electricity purchase cost increases and shows a negative decrease. The actual power consumption \( x_{ani} \) is determined by balancing the electricity sales revenue or purchase cost, customer satisfaction and electricity utility, so as to maximize the overall power consumption benefit. The first derivative of benefit function \( U'_{ni}(x_{ani}) \) is as follows.

\[ \frac{\partial U_{ni}}{\partial x_{ani}} = \begin{cases} 
\frac{K_{ni}}{1 + x_{ani}} - p_{si} + \alpha_{ni} \beta_{ni} \left[ \frac{x_{ani}}{x_{ni}} - 1 \right], & E_{ni} - x_{ni} > 0 \\
\frac{K_{ni}}{1 + x_{ani}} - p_{bi} + \alpha_{ni} \beta_{ni} \left[ \frac{x_{ani}}{x_{ni}} - 1 \right], & E_{ni} - x_{ni} < 0 
\end{cases} \quad (5) \]

By continuing to derive the user benefit function with respect to the actual electricity consumption \( x_{ani} \), the second derivative of the benefit function \( U''_{ni}(x_{ani}) \) can be obtained as
follows.
\[
\frac{\partial^2 U_{ni}}{\partial x_{ani}^2} = -\frac{K_{ni}}{(1 + x_{ani})^2} + \alpha_{ni}\beta_{ni}(\alpha_{ni} - 1)\frac{\alpha_{ani} - 2}{x_{ani}^{2\alpha_{ani} - 1}}
\]
(6)
In this formula, \(K_{ni} > 0\), \(\alpha_{ni}\beta_{ni} > 0\) and \(\alpha_{ni} - 1 < 0\), so \(U_{ni}'(x_{ani}) < 0\), thus the benefit function \(U_{ni}\) is a strictly convex function about \(x_{ani}\). For the maximum benefit \(U_{nio}\) of user \(n\) in the \(i\)-th period, the optimal power consumption \(x_{anio}\) is unique.

Suppose that when the cluster electricity price \(p_{si} = \lambda_{s}, p_{bi} = \lambda\), the photovoltaic users use electricity according to the original plan, that is, \(x_{ani} = x_{ni}\), and the benefit is the most. When \(U_{ni}'(x_{ani}) = 0\), the utility coefficient \(K_{ni}\) can be obtained by calculation

\[
K_{ni} = \begin{cases} 
(\lambda_{s} - \alpha_{ni}\beta_{ni})(1 + x_{ani}) & E_{ni} - x_{ni} > 0 \\
(\lambda_{b} - \alpha_{ni}\beta_{ni})(1 + x_{ani}) & E_{ni} - x_{ni} < 0 
\end{cases}
\]
(7)
In which \(0 < \alpha_{ni}\beta_{ni} < \lambda_{s} < \lambda_{b}, K_{ni}\) is a positive value. When \(E_{ni} - x_{ni} \neq 0\), the cluster electricity price formulated by CO is \(p_{si}\) and \(p_{bi}\), and other parameters are known, so that \(U_{ni}(x_{ani}) = 0\). The theoretical optimal electricity consumption \(x_{nio}\) of user \(n\) in the \(i\)-th period can be obtained by using zero function in MATLAB.

**Theorem 1:** In the \(i\)-th period, the role of purchasing and selling electricity in the cluster of photovoltaic users is determined by the net power under the initial situation. When the power price \(p_{si}\) and \(p_{bi}\) set by the operators meet the conditions of \(\lambda_{s} < p_{si} < p_{bi} < \lambda_{b}\), the users will not change their roles and their benefits will increase [16].

The proof is as follows:

(1) For electricity consumers, \(E_{ni} - x_{ni} > 0\). When the price of internal electricity sales is \(p_{si}\), then the user’s electricity consumption benefit function \(U_{ni}\) and its first derivative \(U_{ni}'(x_{ani})\) are as follows.

\[
U_{ni} = K_{ni}\ln(1 + x_{ani}) + p_{si}(E_{ni} - x_{ani}) + p_{ni}x_{ni}\left[\frac{x_{ani}}{x_{ani}} - 1\right]
\]
(8)
\[
U_{ni}' = K_{ni}\ln(1 + x_{ani}) + p_{si}(E_{ni} - x_{ani}) + p_{ni}x_{ni}\left[\frac{x_{ani}}{x_{ani}} - 1\right]
\]
(9)
When \(x_{ani} = x_{ni}\), \(U_{ni}'(x_{ani}) = \lambda_{s} - p_{si} < 0\), and \(U_{ni}''(x_{ani}) < 0\), the derivative of utility function \(U_{ni}'(x_{ani})\) is a decreasing function of \(x_{ani}\), so \(x_{nio} < x_{ni}\) makes \(U_{ni}'(x_{nio}) = 0\), and the benefit of users is maximum. Therefore, the user’s role in selling electricity does not change and the amount of electricity sold increases.

When the electricity-selling user trades with the power grid at the price \(\lambda_{s}\) and the electricity consumption of the user is \(x_{ni}\), the benefit function of the user reaches the maximum. According to formula (4), the value of the benefit function at this time is:

\[
U_{ni}(\lambda_{s}, x_{ni}) = K_{ni}\ln(1 + x_{ni}) + \lambda_{s}(E_{ni} - x_{ni})
\]
(10)
When the electricity selling consumers trade with the operator CO at the cluster price \(p_{si}\), assuming that the actual electricity consumption \(x_{ani} = x_{ni}\), according to formula (4), the value of benefit function of power selling users is as follows.

\[
U_{ni}(p_{si}, x_{ni}) = K_{ni}\ln(1 + x_{ni}) + p_{si}(E_{ni} - x_{ni})
\]
(11)
It is known that \(p_{si} > \lambda_{s}, K_{ni} > 0\), and by comparing equation (10) with equation (11), we can know that \(U_{ni}(p_{si}, x_{ni}) > U_{ni}(\lambda_{s}, x_{ni})\). And because \(U_{ni}'(x_{nmo}) = \lambda_{s} - p_{si} < 0, x_{ani} = x_{ni}\) is not the optimal power consumption under the cluster electricity price \(p_{si}\). According to the foregoing, it can be known that there is an optimal electricity consumption \(x_{nio}\) which makes \(U_{ni}'(x_{nio}) = 0\) and \(U_{ni}(p_{si}, x_{nio}) > U_{ni}(p_{si}, x_{ni})\), so \(U_{ni}(p_{si}, x_{nio}) > U_{ni}(\lambda_{s}, x_{ni})\) means that the benefits will increase after the sales users trade with operators.

When the optimal power consumption satisfies the condition \(x_{nimo}(\min) \leq x_{nio} \leq x_{nio}(\max)\), the optimal power consumption of users is \(x_{nio} = x_{nmo}\). When the solution does not satisfy the condition \(x_{nimo}(\min) \leq x_{nio} \leq x_{nio}(\max)\), that is, \(x_{nio} < x_{nio}(\min)\), because \(U_{ni}(x_{nio}) = 0, U_{ni}(x_{nio}) = \lambda_{s} - p_{si} < 0, x_{nio} < x_{nii}\), the power consumption benefit of users decreases in the interval \([x_{nio}, x_{nio}]\). In addition, because \(x_{nio} < x_{nio}(\min)\), \(x_{nio}(\min)\) is adopted at this time, which can maximize the power utilization benefit of users under the condition of satisfying the power consumption restriction.

(2) In the same way, the power consumers will not change their role in purchasing electricity, and with the increase of purchasing power, the benefits of users will increase. When the power consumption restriction condition is satisfied, \(x_{anio} = x_{nio}\), but when it is not satisfied, that is, \(x_{nio} > x_{nio}(\max)\), then \(x_{nio} = x_{nio}(\max)\). The proof is over. In order to study the relationship between the overall electricity use efficiency and the cluster electricity price. Suppose that the electricity consumption \(x_{bio} = 130, E_{bi}^0 = 150\). The power consumption \(x_{bio} = 70, E_{bi}^1 = 50\). The power consumption satisfaction parameters are \(\alpha_s = -2, \beta_s = -0.1\); the power grid price is \(\lambda_{s} = 0.4, \lambda_{b} = 1\); the relationship between power consumption efficiency and electricity consumption under different electricity prices is shown in Figure 3.

**FIGURE 3.** Relationship between user’s benefit with power consumption in different price.

It can be seen from the figure that when the cluster selling price increases, the optimal power consumption of power selling users decreases and its power consumption benefit...
increases; when the cluster purchase price decreases, the optimal power consumption of power purchasing users increases, and its benefit also increases.

**C. THE PROFIT MODEL OF CLUSTER OPERATOR**

As the leader of cluster power trading, cluster operator guides users’ electricity consumption behavior by setting internal transaction price, and it is also the settlement center of all users’ income and expenditure. Users who buy electricity \( n \in B \) and sell electricity \( n \in S \), then the total amount of users who buy and sell electricity in the \( i \)-th period is:

\[
E_{Bi} = \sum_{n \in B} (x_{ani} - E_{ni}) \quad (12)
\]

\[
E_{Si} = \sum_{n \in S} (E_{ni} - x_{ani}) \quad (13)
\]

When \( E_{Si} > E_{Bi} \), the operator sells the remaining electric energy to the grid at the price of \( \lambda_s \); when \( E_{Si} < E_{Bi} \), the operator purchases power from the grid at the price of \( \lambda_b \) to meet the load demand of users. In order to maximize the revenue, CO needs to formulate appropriate cluster tariff. At this time, the operator’s revenue can be expressed as follows:

\[
R_i(p_{bi}, p_{si}) = \begin{cases} 
 p_{bi}E_{Bi} - p_{si}E_{Bi} + \lambda_s(E_{Si} - E_{Bi}), & E_{Si} > E_{Bi} \\
 p_{bi}E_{Bi} - p_{si}E_{Si} + \lambda_b(E_{Si} - E_{Bi}), & E_{Si} \leq E_{Bi} 
\end{cases} \quad (14)
\]

The internal price \( psi \) and \( pb \) are decision variables, and the solution of the optimal cluster price of period \( i \) can be expressed as follows.

\[
(p_{bio}, p_{sio}) = \arg \max (p_{bi}, p_{si}) \quad (15)
\]

s.t. \( \lambda_s \leq p_{si} \leq p_{bi} \leq \lambda_b \)

The above formula is a nonlinear programming problem, and the optimal cluster price can be solved by using the interior penalty function method [19].

**III. DEMAND RESPONSE MODEL AND SOLUTION OF PHOTOVOLTAIC USER**

**A. FRAMEWORK OF BILEVEL PROGRAMMING MODEL**

For one cluster operator, N photovoltaic users who can respond to the demand of Stackelberg game. The game rules are as follows: a leader (cluster operator) formulates and publishes its strategy \( SL \) (cluster tariff \( p_{si} \) and \( p_{bi} \)) from its strategic space \( SL \) in the \( i \)-th period, and the other N players (PV users) who become followers observe it \( SL \). Select its optimal response (power consumption \( x_{anio} \)) and ensure that \( x_{nio}(\text{min}) \leq x_{anio} \leq x_{nio}(\text{max}) \). The leader maximizes his own income \( R(p_{si}, p_{bi}) \), and the follower adjusts the electricity consumption according to the cluster electricity price to maximize its own power consumption benefit function \( U_{ni}(x_{ani}) \). The cluster price set by operators in the I period is \( p_{si} \) and \( p_{bi} \), which satisfies \( \lambda_s < p_{si} < p_{bi} < \lambda_b \). The game process is shown in Figure 4.

**B. PROOF AND SOLUTION METHOD OF THE UNIQUE EXISTENCE OF EQUILIBRIUM SOLUTION**

If the Stackelberg game is to reach Nash equilibrium solution, the profit of the leader cluster operators and the benefits of the following photovoltaic users should reach the maximum. Theorem 2 in [10] and Theorem 1 in [11] prove in detail that the corresponding optimal cluster electricity prices \( p_{sio} \) and \( p_{bio} \) exist and are unique when the operator’s income is maximum. Using the interior penalty function method to solve equation (15), the optimal cluster price can be obtained. When the internal optimal electricity price is determined, let \( U_{ni}(x_{ani}) = 0 \), use the fzero function of MATLAB software to solve the ideal optimal electricity consumption \( x_{nio} \), and then according to the user’s power consumption constraints, determine the only optimal electricity consumption \( x_{anio} \) of user \( n \) in the \( i \)-th period, so as to maximize the benefits of users. At this time, Stackelberg game reaches Nash equilibrium.

**C. DEMAND RESPONSE PROCESS OF PHOTOVOLTAIC USER**

The demand response process, that is, the optimal pricing process of photovoltaic user group, is shown in Figure 5.

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![Game process flow chart.](image)

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**FIGURE 4. Game process flow chart.**

**FIGURE 5. Game process flow chart.**

Detailed description is as follows: \( \Box \) In the \( i \)-th period, the electricity consumption \( x_{ni} \) and photovoltaic power generation \( E_{ni} \) of each user in the next time period \( i \) are predicted, and they are determined as user types according to the net power. Substituting the optimal power consumption \( x_{nio} \) when photovoltaic users trade with the power grid, the power consumption satisfaction parameters \( \alpha_{ni} \), \( \beta_{ni} \) of
users at the $i$-th moment and the power grid price $\lambda_s$, $\lambda_b$ into formula (7), and calculating the utility parameter $K_{ni}$ of the next optimization section. Each user sends information such as $E_{ni}$, $K_{ni}$, $a_{ni}$, $b_{ni}$, $x_{ni}(\text{min})$, $x_{ni}(\text{max})$ and the role of participating in the transaction to the operator. Operators can get the optimal internal electricity price ($p_{sio}$, $p_{bio}$) that can maximize their profits according to user information and formula (15). Each user determines the optimal electricity consumption $x_{niu}$ that maximizes its utility according to the cluster electricity price ($p_{sio}$, $p_{bio}$) issued by the operator, and the demand response process in the next optimization period is completed. From the previous part, it can be seen that adjusting the electricity load in response to the user’s demand will not change their participation role.

**IV. USER IMPORTANCE EVALUATION AND RANKING BASED ON TOPSIS**

**A. DEFINING EVALUATION CRITERIA**

From the user’s point of view, the main benefit of photovoltaic users is the power consumption cost saved by their own use. When the users have surplus electricity to share with the users in the group, it can reduce the power purchase price within the group and save the power consumption cost of the power shortage users. Moreover, users are more willing to join the photovoltaic user group with relatively abundant surplus power, so the users who share more energy will be loved by other users.

From the operator’s point of view, the revenue of operators is related to the mutual use of electricity by producers and sellers. Whether users are surplus or short of electricity, they contribute to its income. The greater the contribution value is, the more important it is.

From the perspective of power grid, the larger the total installed capacity of the whole photovoltaic user group, the more attention the grid attaches to the PV user group. The larger the installed capacity of the whole PV group is, the more important it is.

Therefore, the installed capacity $F_i$ of user $i$ should also be considered in order to rank the importance of users in the cluster.

**B. PRIORITY AND WEIGHT CALCULATION OF EVALUATION CRITERIA**

Power sharing can not only save the cost of electricity purchase, but also increase the profit of cluster operator. In addition, in order to encourage users to share electric energy, this paper puts the evaluation index $A$ in the first place. Indicator $B$ can not only reflect the profit contribution of residual power users to the cluster operator, but also indicate the revenue contribution of power shortage users to the cluster operator. Therefore, the evaluation index $B$ is ranked second and the evaluation index $C$ is ranked third. The ranking results are as follows: 1) sharing photovoltaic energy; 2) contribution to operators’ revenue; 3) installed capacity of users.

The higher the ranking of evaluation indicators, the greater the weight coefficient. According to the “weights from ranks” method, the weight coefficient of evaluation criteria [20] was calculated.

$$\lambda_j = \frac{f - j + 1}{\sum_{j=1}^{f} (f - j + 1)}$$  \hspace{1cm} (18)

In the formula, $f$ represents the total number of evaluation criteria, and $\lambda_j$ represents the weight coefficient of the $j$ evaluation criteria.

**C. USER IMPORTANCE EVALUATION AND RANKING BASED ON TOPSIS METHOD**

The basic principle of TOPSIS evaluation method (the idea of approaching the ideal solution): Based on the normalized original matrix, the optimal scheme and the worst scheme (expressed by the optimal vector and the most column vector respectively) in the finite scheme are found out, and then the distance between the evaluation object and the optimal scheme and the worst scheme is calculated respectively to obtain the relative closeness between the evaluation object and the optimal scheme, This is the basis of evaluation.
This paper defines the value of user $i$ under $j$ ($j = 1, 2, 3$)

$$y_{ij} = \begin{cases} H_i & j = 1 \\ C_i & j = 2 \\ F_i & j = 3 \end{cases}$$ (19)

After preprocessing the user’s data $y_{ij}$ by linear transformation, the normalized decision matrix $Z$ is obtained.

$$z_{ij} = \frac{y_{ij}}{y_{ij}^{\max}}$$ (20)

In the formula, $y_{ij}^{\max}$ represents the maximum value of all users corresponding to the $j$ standard.

The weighted normal matrix $X$ is obtained by multiplying $Z$ by the weight coefficient.

$$x_{ij} = \lambda_j \cdot z_{ij}$$ (21)

Defining ideal solutions $x^*_i$ and negative ideal solution $x^0_i$ by

$$x^*_j = \max_i (x_{ij})$$ (22)

$$x^0_j = \min_i (x_{ij})$$ (23)

The distance from user $i$ to ideal user and negative ideal user is calculated.

$$d^*_i = \sqrt{\sum_{j=1}^{f} (x_{ij} - x^*_j)^2}$$ (24)

$$d^0_i = \sqrt{\sum_{j=1}^{f} (x_{ij} - x^0_j)^2}$$ (25)

Calculate how close the user is to the ideal user in the cluster.

$$C^*_i = \frac{d^0_i}{d^0_i + d^*_i}$$ (26)

Rank the importance of photovoltaic users from big to small by $C^*_i$.

V. EXAMPLE ANALYSIS

Five users with photovoltaic power generation system in a region constitute a photovoltaic user group. They respond to the demand through Stackelberg algorithm under the guidance of cluster operator. When the distributed generation output of the cluster is 0, all the electricity is purchased directly from the grid by the operators [17]. At this time, $p_{si} = \lambda_s$, $p_{bi} = \lambda_b$. Therefore, this paper only studies the time period of distributed photovoltaic power output. The installed capacity of each user in the photovoltaic user group is shown in Table 1. The typical solar volt output power curve and the daily load consumption curve of users are shown in figures 6 and 7.

According to the distributed photovoltaic grid price in most regions of China, the benchmark grid price of coal-fired units is 0.4 yuan/(kW.h) for parameter $\lambda_s$, and $\lambda_b$ is the commercial electricity price, which is 1.0 yuan/(kW.h) Users’ electricity satisfaction parameters $\alpha_{ni}$ and $\beta_{ni}$ can take any value under the condition of satisfaction according to the requirements of users in each time period. For the convenience of calculation, here we uniformly take $\alpha_{ni} = -2$, $\beta_{ni} = -0.1$. It is assumed that the requirements of five users on electricity consumption satisfaction are the same in each period. Due to the need to meet the profit demand of operators and power grid in real life, as well as the power supply line demand of power load, the supplementary conditions of simulation are as follows.

$$\lambda_s < p_{si} < p_{bi} < \lambda_b$$ and $x_{ni}(min) \leq x_{ni} \leq x_{ni}(max)$.

A. USER IMPORTANCE EVALUATION AND RANKING RATIONALITY ANALYSIS

The shared photovoltaic energy in the user calculation period $T$ is as follows.

Table 3 and table 4 show the user’s income within cycle $T$ under the cooperative alliance mode and the internal tariff mode, respectively.

Based on the data in tables 3 and 4, the revenue of users to operators is calculated according to formula (17), as shown in Table 5.
TABLE 3. Benefits in the cooperative alliance model.

| User number | 1    | 2    | 3    | 4    | 5    |
|-------------|------|------|------|------|------|
| Income (yuan) | 1180.8 | 1349.3 | 728.73 | 707.91 | 943.01 |

TABLE 4. Benefits in the internal electricity price model.

| User number | 1    | 2    | 3    | 4    | 5    |
|-------------|------|------|------|------|------|
| Income (yuan) | 1107.9 | 1216.9 | 661.08 | 675.3 | 775.6 |

TABLE 5. Photovoltaic users’ contribution to cluster operator revenue.

| User number | 1    | 2    | 3    | 4    | 5    |
|-------------|------|------|------|------|------|
| Income contribution (yuan) | 72.9 | 132.4 | 67.65 | 32.61 | 167.41 |

TABLE 6. User proximity to ideal users in the PV cluster.

| User number | 1    | 2    | 3    | 4    | 5    |
|-------------|------|------|------|------|------|
| Proximity   | 0.5417 | 0.8856 | 0.4881 | 0.0236 | 0.3467 |

When the internal electricity price is implemented, the revenue of cluster operator in calculation period T is 473.07 yuan, and the sum of users’ contribution to cluster operator’s revenue is equal to that of cluster operator, which verifies the correctness of calculation of contribution value.

According to the data in Tables 1 to 3 and equations (19)–(20), the normative decision matrix $Z$ is calculated

$$Z = \begin{bmatrix} 0.6016 & 0.4355 & 1 \\ 1 & 0.7909 & 0.9474 \\ 0.5579 & 0.4044 & 0.6404 \\ 0.0272 & 0.1947 & 0.4649 \\ 0 & 1 & 0.5263 \end{bmatrix}$$

According to formula (18), the weight coefficients of evaluation criteria are calculated as follows: $\lambda_1 = 0.5$, $\lambda_2 = 0.3333$ and $\lambda_3 = 0.1667$. According to formula (21), the weighted gauge matrix $X$ is obtained.

$$X = \begin{bmatrix} 0.3008 & 0.1452 & 0.1667 \\ 0.5 & 0.2636 & 0.1579 \\ 0.2789 & 0.1348 & 0.1068 \\ 0.0136 & 0.0649 & 0.0775 \\ 0 & 0.3333 & 0.0877 \end{bmatrix}$$

The value of the closeness $C_i^*$ between the user and the ideal user in the photovoltaic group calculated by formula (22)-(26) is shown in Table 6.

According to table 1, table 2 and table 5, the installed capacity of user 1 is the largest and that of user 4 is the smallest. User 5 has the largest contribution to the operator’s revenue, and user 4 has the smallest contribution to the operator’s revenue. User 2 shares the most electric energy, while user 5 shares the least and 0 energy. It needs to purchase electricity from the cluster operator at each time. There is no research on the importance evaluation and ranking of users in the photovoltaic user group in the existing literature, so this paper assumes that the importance evaluation and ranking is based on the single attribute of users. Photovoltaic user group is operated under the management of operators, assuming that operators start from their own revenue and rank according to the contribution value of users to their own revenue. Compared with the comprehensive evaluation method proposed in this paper, the comparison of user ranking results is shown in Figure 8.

FIGURE 8. User importance ranking.

As can be seen from the above figure, the ranking results of user 4 are the same under the two evaluation methods. Other users rank differently under the two evaluation methods. User 5 ranks first in the evaluation method based on contribution value, but ranks fourth in the comprehensive evaluation method. The ranking results of the two evaluation methods are quite different. Based on the analysis of user 5’s electricity consumption behavior, it does not share energy with other users during the day’s operation of photovoltaic user group. From the original intention of establishing photovoltaic user group, encouraging users to share electricity has poor performance. In the comprehensive evaluation method, users are encouraged to share electric energy, and their ability to absorb excess photovoltaic energy and installed capacity are also considered. Therefore, the ranking under the comprehensive evaluation is more reasonable and fair.

B. ANALYSIS OF POWER CONSUMPTION ADJUSTMENT RATE OF USERS

The operator formulates the internal price to maximize its own revenue. The user carries out demand response according to the cluster electricity price to maximize its comprehensive benefit. The calculation formula of the electricity consumption adjustment rate of user $n$ in the $i$ period is as follows:

$$\delta_{ni} = (x_{ani} - x_{ni})/x_{ni} \times 100\%$$  \hspace{1cm} (27)

In this paper, The comprehensive benefit model ($\alpha_{ni} = -2$, $\beta_{ni} = -0.1$) considering the satisfaction degree...
of electricity consumption and the original benefit model \((\alpha = \beta = 0)\) without introducing the satisfaction degree function are used to calculate respectively. The adjustment rate of electricity consumption in each time period after each user’s demand response is shown in Figure 9 – 10.

According to the figure, the maximum load adjustment rates of users 1, 2 and 3 all occur at the time of selling electricity, and the maximum load adjustment rates of users 4 and 5 occur at the time of buying electricity. The five users are reduced by 49%, 54%, 50%, 96% and 68%, respectively. Compared with the above figure, the new power consumption benefit model can effectively reduce their own power consumption adjustment rate, thus ensuring users’ power consumption comfort.

It is assumed that users in the group use the same satisfaction parameters in one day. \(\alpha = \beta = 0\) means that the user does not consider the power consumption satisfaction, and the other three groups of satisfaction parameters meet the requirements of \(\alpha \beta = 0.2\). In this way, the utility coefficient of electricity consumption is the same when the satisfaction parameters of users are different. The absolute value of maximum adjustment rate of users under different satisfaction parameters is shown in Table 7.

| \(\| \delta \|_{\text{max}}\) | \(\alpha = 0 \beta = 0\) | \(\alpha = 0.5 \beta = 0.4\) | \(\alpha = 1 \beta = 0.2\) | \(\alpha = 2 \beta = 0.1\) |
|-----------------------------|----------------|----------------|----------------|----------------|
| \(\delta \|_{\text{max}}\)  | 35.76%         | 29.17%         | 24.45%         | 18.11%         |
| \(\delta \|_{\text{max}}\)  | 31.64%         | 25.42%         | 20.72%         | 14.46%         |
| \(\delta \|_{\text{max}}\)  | 23.5%          | 16.93%         | 13.29%         | 11.74%         |
| \(\delta \|_{\text{max}}\)  | 20.31%         | 13.83%         | 8.96%          | 0.8%           |
| \(\delta \|_{\text{max}}\)  | 4.54%          | 0.83%          | 1.79e-14%      | 1.42e-14%      |

C. OPERATOR PROFIT COMPARISON

In order to maximize the profit, operators will adjust the internal price. The internal price of the typical day is shown in Figure 11 below.

It can be seen from the figure that after taking into account the user’s satisfaction with electricity consumption, the price of electricity purchased by power consumers through operators is higher than that before. The price of electricity sales is lower than the original internal price except 12:00.

According to the above analysis, it can be seen that the income of cluster operator is increased; secondly, compared with the non-cluster mode, users can reduce the electricity consumption cost of power consumers and improve the electricity sales income of residual power users, and the comprehensive benefit of electricity consumption of users is increased. Finally, compared with the electricity consumption benefit model without considering the satisfaction degree, the model users can effectively reduce the adjustment rate of electricity consumption, and implement the optimal power consumption according to the different requirements of different users.
VI. CONCLUSION
To solve the problem of high electricity consumption adjustment rate when the PV users respond to the cluster electricity price demand, the paper introduces the electricity consumption price satisfaction function and proposes an optimal pricing model for PV users using the master-slave game. Moreover, to promote the stability and development of photovoltaic user groups, the paper analyzes the nature of operators’ revenue, and uses cooperative game theory to calculate the contribution value of users in the group to operators’ revenue. From the three aspects: users, operators, and power grid, the importance index of users is defined, and a strategy for evaluating the importance using TOPSIS method is proposed with the aim of completing the comprehensive ranking of producers and sellers. The proposed model revealed that, comprehensive ranking of users is more fair and reasonable, which can effectively encourage users to install household photovoltaic equipment and share electricity, hence promoting the virtuous circle of household photovoltaic industry. On electricity consumption adjustment rate, the proposed model showed that the electricity sellers are reduced by 50%, and electricity buyers are more than 50%, which effectively guarantees the user’s electricity experience and is more suitable in real life. It can be implemented according to different requirements of different users. On optimal electricity consumption aspect, the utility electricity showed that, cluster mode is beneficial where by it reduces the electricity consumption cost of users, improves the electricity sales income of surplus users, and increases the comprehensive users’ electricity consumption. In terms of operators’ revenue, it was proven from the price comparison chart that there is increase in profitability.

The developed example verifies the superiority of optimized pricing model, the effectiveness of the user benefit model, the feasibility of the calculation method of the contribution value, and the rationality of the evaluation method. Compared with the existing mode, the electricity price calculation mode and the ranking strategy of users in this model are more reasonable, and its operation mode can more powerfully encourage users to generate electricity, stimulate the development of household photovoltaic, increase the installed capacity, and further move towards “carbon neutrality”.

In conclusion, the model proposed in this paper has a strong practical reference value in the future of the ever-expanding household photovoltaic industry. However, the proposed model assumes that the satisfaction parameters of users in the group are similar. This is not the case in the real life, where different families have different satisfaction parameters for electricity consumption at varied time period. Therefore, the study recommends further study on the influence of power consumption satisfaction parameters on cluster economic operation model.

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