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Optimal Planning of User-side Scaled Distributed Generation Based on Stackelberg Game

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Abstract

BACKGROUND: User-side distributed generation represented by distributed photovoltaic and distributed wind turbine has shown an expansion trend of decentralized construction and disordered access, which is difficult to satisfy the demand for large-scale exploitation and sustainable development of distributed generation under the low-carbon transformation vision of the power system.
OBJECTIVES: To address the interest conflict and operation security problems caused by scaled distributed generation accessing the distribution network, this paper proposes the optimal planning method of user-side scaled distributed generation based on the Stackelberg game.
METHODS: Firstly, a cluster planning and operation mode of distributed generation is established. Then, a prediction method for planning behavior of user-side distributed generation is proposed in order to predict whether users will adopt the self-build mode or the leasing site mode for distributed generation. Finally, in order to reveal the game relationship between the distribution network operator and the users in the allocation of distributed generation resources, a bi-level planning model for scaled distributed generation is established based on the Stackelberg game.
RESULTS: The simulation results show that the revenue of the distribution network operator under the gaming model increases by 10.15% and 16.88% compared to the models of all users self-build distributed generation and all users leasing distributed generation site, respectively, while at the same time, individual users also realize different degrees of revenue increase.
CONCLUSION: The case analysis validates the effectiveness of the proposed method in guiding the rational and efficient planning of user-side distributed generation.

Keywords: User-side distributed generation, Distribution network operator, Cluster planning and operation mode, Distributed generation site lease, Stackelberg Game, bi-level planning model

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1. Introduction

China is committed to adopting more effective policies and measures to achieve carbon emissions peaking by 2030 and carbon neutrality by 2060 [1]. China's new installed capacity of wind and photovoltaic power generation is up to 125 GW in 2022, which is a new record level. China's cumulative electricity generation from wind turbines and photovoltaics amounted to 119 GWh, rising 21 percent from the previous year, and accounting for 13.8 percent of the total electricity consumption of the whole society [2-3]. However, some experts believe that carbon neutrality can only be achieved when China's cumulative electricity generation from wind

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turbines and photovoltaics reaches around 70% [4]. Therefore, the current level of renewable energy electricity generation is still far from the long-term development goal, while distributed generation with distributed photovoltaic and distributed wind turbines as the main components will become the key to realize the carbon neutrality and peaking goal [5].

As an important component of the new-type power system, the distributed generation can support the establishment of energy system with clean, low-carbon, safe and efficient, and in turn, the reform and promotion of the energy system has also promoted the large-scale development of distributed generation [6]. The large-scale development of distributed generation reduces the dependence on traditional centralized power supply, and thus improves the reliability of power supply. It also improves the energy security and increases the resilience and disaster resistance of the energy system [7-8]. Therefore, the planning and operation of large-scale distributed generation has become an urgent problem to be solved. Therefore, the planning and operation of scaled distributed generation has become a mainstream trend to realize the construction of new-type power system.

Currently, the planning body of distributed generation is mainly residents, businessmen and other individual users, who are utilizing their houses, buildings and other relatively decentralized building space to develop distributed generation on-site or leasing sites commissioned. However, due to the lacking for unified management and standardized operation of distributed generation, scaled user-side distributed generation presents the expansion trend of decentralized construction and disorderly access, and the local consumption problem is prominent, which brings numerous challenges to the safe and stable operation of the power system [9-10]. Under the above background, distribution network operators conduct planning and operation for large-scale distributed generation through leasing user sites is expected to become an effective solution for realizing the depth and sustainable development of scaled distributed generation. Compared with the investment and construction of distributed generation dedicated site, leasing site will greatly reduce the cost. Compared to user-independent planning and operation, cluster planning has cost, technical and efficiency advantages, with greater independent planning and energy management capabilities.

Traditional distributed generation planning methods are mostly from the perspective of the power system, with the objective of improving the operation status or satisfying the operation economy to launch the planning problem [11-13]. In literature [11], a multi-objective hierarchical optimization planning model for distributed generation is constructed to minimize the actual power loss and the operation cost of power system. In order to minimize power losses and improve the voltage profile, an improved least squares method is proposed to plan the capacity and location of distributed generation in distribution network in literature [12]. From the perspective of distributed generation access to the distribution network, a hierarchical optimization model for distribution network planning is constructed in Literature [13]. However, the above studies do not fully consider the practical benefits of distributed generation users, who confront high investment and construction costs.

With continuous advancement of electricity marketization, distributed generation planning has been transformed from traditional integration into a decision-making problem related to interests of multiple bodies, and presents an orderly game relationship. Based on the complete information dynamic game, a bi-level coordinated planning model for distributed generation and soft-open points is proposed in literature [14] to coordinate the interests among distributed generation investors, distribution network operators and electricity users. Based on the non-cooperative game theory, a multi-agent collaborative planning method for distributed generation is proposed in literature [15] to balance the economic benefits of each agent and realize the stable and friendly interactions among the agents. Obviously, the above studies show that game theory can be used to solve the distributed generation planning problem under multi-interested subjects, but mostly attribute all the investment costs of distributed generation to the user side, while lacking the differentiated operation and planning for the scaled distributed generation.

To sum up, this paper focuses on planning and operation interests of distributed generation users. Considering users have the right to lease and self-build distributed generation sites, the allocation of planning resources for scaled distributed generation will involve the game relationship between individual users and distribution network operators. To this end, this paper launch the optimal planning research of user-side scaled distributed generation based on the Stackelberg game theory. Firstly, a cluster planning and operation mode of distributed generation is established. Secondly, a prediction method for planning behavior of user-side distributed generation is proposed. Then, in order to reveal the game relationship between the distribution network operator and the users in the allocation of distributed generation resources, a bi-level planning model for scaled distributed generation is established based on the Stackelberg game. Finally, case study results demonstrate the feasibility and effectiveness of the proposed method in this paper.

2. User-side distributed generation cluster planning and operation mode

2.1 User-side distributed generation operation mode

With the extensive access of distributed generation to the distribution network, the user-side distributed generation presents the co-existence trend of decentralized individual self-operated and cluster industrialized development. The self-operated users and the distribution network operator become the main operating entities of distributed generation, and the specific operation mode is shown in Fig. 1.

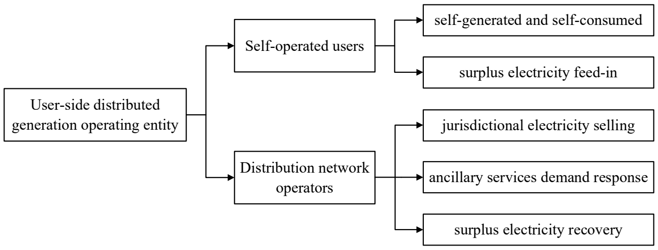


Figure 1. User-side distributed generation operation mode

Compared with distributed generation self-operated users, distribution network operators are aiming to master the planning and operation rights of user-side distributed generation, planning the user-side sites within the jurisdiction, dispatching uniformly large-scale distributed generation with geographic proximity and electricity interconnection, thus realizing friendly and flexible access of large-scale distributed generation to the distribution network and maximizing their own operational benefits.

Therefore, this paper constructs the operation mode of the distribution network operator as conducting the cluster planning and operation of distributed generation by leasing user-side sites, and its main business includes: i) delineating the distribution jurisdiction on the user side, conducting the electricity selling business, and realizing the local consumption of distributed generation; ii) providing the buffer space for electricity difference in the jurisdiction by leasing energy storage to realize price arbitrage; iii) Combining the power regulation capacity of the jurisdiction and the compensation mechanism for auxiliary services, formulate auxiliary service strategies; iv) Setting surplus electricity recovery tariffs to aggregate surplus electricity from distributed generation of self-operated users, thus lowering the cost of electricity purchases.

2.2 User planning behavior prediction and modeling

For users with distributed generation planning sites, they can choose two planning modes: self-built distributed generation or leased sites, and user planning behavior is the main factor influencing the distribution network operator to formulate distributed generation planning strategies. Unlike the distribution network operator, individual user planning behavior is affected by various factors and has certain irrational behavior.

The whole life cycle economy of distributed generation is the direct factor affecting users' willingness to install distributed generation, including installation cost, investment return period, subsidy strength, electricity price, etc. While individual characteristics of users are indirect factors affecting their willingness to install, and individual characteristics mainly include education level and income, prompting differences in user planning behavior. Therefore, this paper models the planning behavior of users from the investment economics of distributed generation and the individual characteristics of users.

In order to represent the return prospects of the two modes of user self-built distributed generation versus leasing the site, the net present value of the two modes is calculated separately. If user i chooses to self-build distributed generation, the net present value of its investment return is expressed as:

$$M_{B,i}=\sum_{y\in Y}\frac{(1+g)^{y}}{(1+d_{0})^{y}}(I_{B,i,y}-C_{B,i,y})$$

(1)

If user i chooses to lease distribution network site, the net present value of its investment return is expressed as:

$$M_{L,i}=\sum_{y\in Y}\frac{(1+g)^{y}}{(1+d_{0})^{y}}(I_{L,i,y}-C_{L,i,y})$$

(2)

where Y is the operating life of distributed generation. $I_{B,i,y}$ and $I_{L,i,y}$ are the y-th year self-built mode revenue and leased mode revenue, respectively. $C_{B,i,y}$ and $C_{L,i,y}$ are the y-th year self-built mode cost and leased mode cost, respectively. d_0 is the baseline discount rate, and g is the inflation rate.

Setting the net present value expectation for users' distributed generation planning as M_i^E, and establishing sensitivity factors $\lambda_{B,i}$ and $\lambda_{L,i}$ which reflecting the economic impact of self-build versus leasing site, respectively.

$$\lambda_{B,i}=e^{\left(M_{B,i}/M_{B,i,\max}-1\right)}-e^{\left(M_{B,i}^{E}/M_{B,i,\max}-1\right)}$$

(3)

$$\lambda_{L,i}=e^{\left(M_{L,i}/M_{L,i,\max}-1\right)}-e^{\left(M_{L,i}^{E}/M_{L,i,\max}-1\right)}$$

(4)

where $M_{B,i,\max}$ and $M_{L,i,\max}$ are the maximum net present value of self-build mode and leasing mode, respectively.

Establishing the sensitivity factor $\lambda_{C,i}$ that reflects the influence of user characteristics, which is given by

$$\lambda_{C,i} = \frac{\lambda_{Edc,i}\lambda_{Age,i}}{\max(\lambda_{Edc,i}, \lambda_{Age,i})}$$

(5)

where $\lambda_{Edc,i}$ and $\lambda_{Age,i}$ are the education level and age influence factors, respectively.

The positive, negative and size of the sensitivity factor can reflect the strength of the user's willingness to choose relevant mode, a positive value indicates the user's attitude is positive, while a negative value indicates the willingness is negative.

2.3 User planning behavior judgment process.

From the user distributed generation planning behavior model established in the previous section, the user planning behavior judgment process is derived as follows:

Step 1: Calculate the sensitivity factors for the two modes of self-build and leasing sites for user-side distributed generation from Eq. (3) to Eq. (5), respectively;

Step 2: Calculate the product of the direct and indirect sensitivity factors of the two modes separately only if at least one of $\lambda_{B,i}$ and $\lambda_{L,i}$ is positive, i.e.

$$\begin{cases} S_{B,i} = \lambda_{B,i} \cdot \lambda_{C,i}^{B} & \lambda_{B,i} > 0 \\ S_{L,i} = \lambda_{L,i} \cdot \lambda_{C,i}^{L} & \lambda_{L,i} > 0 \end{cases}$$

(6)

where $S_{B,i}$ and $S_{L,i}$ are the sensitivity factors of self-build and leasing sites for user i, respectively.

Step 3: Compare the value size of $S_{B,i}$ and $S_{L,i}$, and select the planning mode that corresponds to the larger value, which is the final planning mode selected by the user.

3. Bi-level planning model for scaled distributed generations on user side

3.1 Bi-level planning model structure based on the Stackelberg game

According to game relationship between the distribution network operator and users in scaled distributed generation planning, a bi-level planning model is established based on the Stackelberg game theory, which can be expressed as:

$$G = \left\{ \left(DNO \cup L_i \right); \left(\gamma_{sell}, \varphi_{lease}^{ave} \right); \left(S_{L,i} \right); F_{DNO}; F_{L,i} \right\}$$

(7)

where distribution network operator DNO is the leader, each user L_i is the follower, both entities constitute the participants set. Average site lease φ_{lease}^{ave} and selling tariff γ_{sell} are the strategy set of the distribution network operator, and the installed capacity of distributed generation $S_{L,i}$ is the strategy set of each user. F_{DNO} and F_L are the revenue function of the distribution network operator and users.

The above Stackelberg game model belongs to a bi-level optimization problem, the upper-level model is the operating model of the distribution network operator, which collects distributed generation installation information from users as a leader, sets the site lease instructions and tariff sales instructions of user-side distributed generations with the goal of maximizing its own operating revenue, and passes it to distributed generation users. The lower-level model is the user benefit model, in which the user as a follower decides the distributed generation planning mode according to the site lease instructions and tariff sales instructions with the goal of maximizing its own benefit, and returns self-build distributed generation capacity or site lease areas to distribution network operator, which dynamically adjusts the planning strategy accordingly. After repeated iterations between upper-level model and lower-level model, the game is terminated when both entities are unable to increase their own interests by changing their strategies, thus realizing the optimal planning of distributed generation and balanced allocation of investment income.

3.2 Distribution network operator operating model

3.2.1 Objective function

The upper-level model aims to maximize the annual operating revenue of the distribution network operator which is expressed as:

$$\max F_{DNO} = I_S + I_A - C_C - C_{O\&M} - C_L - C_S - C_E$$

(8)

where I_S is the jurisdictional electricity sales revenue, I_A is the ancillary services revenue, C_C is the construction costs for cluster operating, C_M is the O&M cost of scaled distributed generation, C_L is the site lease cost, C_S is the surplus electricity recovery cost, and C_E is the energy storage lease cost.

(1) Jurisdictional electricity sales revenue

$$I_S = \sum_{t \in T} P_{Load}(t) \gamma_{sell}(t)$$

(9)

where T is the operation period, $\gamma_{sell}(t)$ is the electricity selling price of the jurisdiction in time period t, and $P_{Load}(t)$ is the jurisdictional load demand in time period t.

(2) Ancillary services revenue

$$I_A = \sum_{t \in T} P_{bid}(t) \gamma_{bid}(t)$$

(10)

where $P_{bid}(t)$ and $\gamma_{bid}(t)$ are the bidding power and bidding tariff of auxiliary services in time period t, respectively.

(3) Construction costs for cluster operating

$$C_C = \left[\frac{r(1+r)^Y}{(1+r)^Y - 1} \right] (C_{dis} + C_f) S_{dis}^{DNO}$$

(11)

$$S_{dis}^{DNO} = \sum_{i \in \Omega_L} U_i S_{dis,i}^L$$

(12)

Where r is the discount rate, C_{dis} is the distributed generation installation cost per unit capacity, C_f is the regulation cost required to support cluster operating, S_{dis}^{DNO} and S_{dis}^{L} are the installed capacity of distributed generation for cluster operating and user i, respectively. Ω_L is the user set that participates in the game, and U_i is the selection result of the distributed generation planning mode for user i, which is taken as 1 for leasing, and 0 for self-build.

(4) Scaled distributed generation O&M cost

$$C_{O\&M} = \sum_{t \in T} C_{o\&m} P_{out}(t)$$

(13)

where $C_{o\&m}$ is the distributed generation O&M cost per unit of power, and $P_{out}(t)$ is the distributed generation output in time period t.

(5) Site lease costs

Considering the variability of user distributed generation sites due to spatial shading, site type, etc., which leads to different installable capacity of distributed generation under the same area. In order to reflect the fairness principle, the distribution network operator should set differentiated rent levels based on the utilizing degree of the user's site.

Setting the site area of user i as A_i and the site utilizing coefficients of different building types as u_i, the installable capacity $S_{L,i}$ of the user's site is denoted as:

$$S_{L.i} = A_i u_i \cdot \left(kW / m^2 \right)$$

(14)

According to the utilizing degree of the user's site, the site lease floating factor is set to be μ_i. If the average price of site lease per unit area set by the distribution network operator is φ_{lease}^{ave}, the unit price of site lease for user $\varphi_{lease,i}$ is given by

$$\varphi_{lease,i} = \mu_i \varphi_{lease}^{ave}$$

(15)

Based on the above, the lease costs for distributed generation sites are express as:

$$C_L = \sum_{i \in \Omega_L} U_i \varphi_{lease,i} A_i$$

(16)

(6) Surplus electricity recovery cost

$$C_S = \sum_{t=1}^{T} \sum_{i \in \Omega_L} P_{sur,i}(t) \gamma_{sur}$$

(17)

where $P_{sur,i}(t)$ and γ_{sur} are the surplus electricity feed-in power and recovery tariff of user i, respectively.

(7) Energy storage lease cost

$$C_E = \sum_{t=1}^{T} \left[P_{es}^{c}(t) + P_{es}^{d}(t) \right] \gamma_{es}(t)$$

(18)

where $P_{es}^{c}(t)$ and $P_{es}^{d}(t)$ are the charging-discharging power of the leased energy storage in time period t, respectively, and $\gamma_{es}(t)$ is the leasing fee to be paid for the unit power of charging and discharging.

3.2.2 Constraint condition

(1) Distributed generation installed capacity constraints

$$0 \le \left[S_{dis}^{DNO} + (1 - U_i) \sum_{i \in \Omega_L} S_{dis,i}^{L} \right] \le S_{dis,\max}$$

(19)

where $S_{dis,\max}$ is the maximum installable capacity of distributed generation in the jurisdiction.

(2) Electricity sales tariff constraints

$$\gamma_{sell,\min} \le \gamma_{sell}(t) \le \gamma_{sell,\max}$$

(20)

where $\gamma_{sell,\min}$ and $\gamma_{sell,\max}$ are the upper and lower limits of the tariff for electricity sales, respectively.

(3) Ancillary services bidding capacity constraints

The bidding capacity for ancillary services in each time period should be less than a certain percentage of the jurisdiction's baseload capacity, which can be express as:

$$0 \le P_{bid}\left(t\right) \le \varepsilon P_{Load}\left(t\right) \tag{21}$$

where ε is the bidding capacity coefficient.

(4) Distributed generation site lease constraints

$$\varphi^{ave}_{lease,\min} \le \varphi^{ave}_{lease} \le \varphi^{ave}_{lease,\max} \tag{22}$$

where $\varphi^{ave}_{lease,\min}$ and $\varphi^{ave}_{lease,\max}$ are the upper and lower limit values of the site lease average price, respectively.

(5) Surplus electricity recovery tariff constraints

In order to encourage self-built users to sell surplus electricity from distributed generation output to distribution network operators, setting the surplus electricity recovery tariff not lower than the local coal-fired generation feed-in tariff, which is given by

$$\gamma_{coal} \le \gamma_{sur} \le \gamma_{sur,\max} \tag{23}$$

where γ_{coal} is the local feed-in tariff for coal-fired generation, and $\gamma_{sur,\max}$ is the maximum tariff within profitability interval.

3.3. User-side benefits model

3.3.1 Objective function

Based on the site lease instructions and tariff sales instructions set by the distribution network operator, the user makes a decision on self-build distributed generation or leasing site with the objective of maximizing the annual return on the distributed generation planning, and the objective function can be described as follows:

$$\max F_{L,i} = \begin{cases} \lambda_{B,i} \ge \lambda_{L,i}\text{:} \\ I_{Sur,i} - C_{Ins,i} - C_{o\&m,i} - C_{Buy,i} \\ \lambda_{B,i} < \lambda_{L,i}\text{:} \quad I_{Lease,i} - C_{Buy,i} \end{cases} \tag{24}$$

where $I_{Sur,i}$ is the surplus electricity feed-in revenue of user i, and $I_{Lease,i}$ is the site lease revenue of user i. $C_{Ins,i}$ is the installation cost of user i, $C_{o\&m,i}$ is the O&M cost of user i, and $C_{Buy,i}$ is the electricity buying cost of user i.

(1) Surplus electricity feed-in revenue

$$I_{Sur,i} = \sum_{t=1}^{T}\left[1-\tau\left(t\right)\right]\left[P_{out,i}\left(t\right) - P_{load,i}\left(t\right)\right]\gamma_{sur} \tag{25}$$

where $P_{out,i}\left(t\right)$ is the distributed generation output of user i in time period t, and $P_{load,i}\left(t\right)$ is the load demand of user i in time period t. $\tau\left(t\right)$ is a state variable which takes 1 to indicate user is in the electricity buying state in time period and 0 otherwise.

(2) Site lease revenue

$$I_{Lease,i} = \varphi_{lease,i} A_i \tag{26}$$

(3) Distributed generation installation cost

$$C_{Ins,i} = \left[\frac{r\left(1+r\right)^{Y}}{\left(1+r\right)^{Y}-1}\right] C_{dis} S^{L}_{dis,i} \tag{27}$$

(4) Distributed generation O&M cost

$$C_{o\&m,i} = \sum_{t=1}^{T} C_{o\&m} P_{out,i}\left(t\right) \tag{28}$$

(5) Electricity buying cost

$$C_{Buy,i} = \begin{cases} \lambda_{B,i} \ge \lambda_{L,i}\text{:} \\ \sum_{t=1}^{T} \tau\left(t\right)\left[P_{load,i}\left(t\right) - P_{out,i}\left(t\right)\right]\gamma_{sell}\left(t\right) \\ \lambda_{B,i} < \lambda_{L,i}\text{:} \qquad \sum_{t=1}^{T} P_{load,i}\left(t\right)\gamma_{sell}\left(t\right) \end{cases} \tag{29}$$

3.3.2 Constraint condition

(1) Individual user installation capacity limit constraints

$$0 \le S_{L,i} \le A_i u_i \tag{30}$$

(2) Individual user site lease constraints

The user sites involved in the game are required to satisfy the following constraints:

$$\begin{cases} A_i \geq A_{\min} \\ k_i \geq k_{\min} \end{cases}$$

(31)

where $A_{\min}$ and $k_{\min}$ are the minimum utilizing area and minimum utilizing factor, respectively.

4. Solution method

The solution essence of the bi-level planning model for distributed generation resources is to find the intersection of the maximum benefit curves of each game participant, i.e., the iterative solution between the upper-level model and the lower-level model. The upper-level model is a mixed-integer quadratic programming problem, and the particle swarm optimization algorithm can reduce the solving difficulty and improve the optimization ability, while the lower-level model is a mixed-integer linear programming problem, which can be solved directly by CPLEX solver. The specific solution process is as follows:

Step 1: Initialization parameters. Including distributed generation operation data, load demand data, and gaming participant revenue data;

Step 2: Strategy space generation for game participants. The strategy space of the distribution network operator is the set of site lease and electricity selling price, which can be denoted as $J_{DNO}\left(\gamma_{sell}, \varphi_{lease}^{ave}\right) = \left(j_{DNO,1}, j_{DNO,2}, \cdots, j_{DNO,x}\right)$, where x denotes the number of game iterations. While the user-side distributed generation planning capacity set $S_{dis,i}^{L} = \left(S_{dis,i,1}^{L}, S_{dis,i,2}^{L}, \cdots, S_{dis,i,x}^{L}\right)$ is the user strategy space which characterizes the willingness of distributed generation planning.

Step 3: Setting the initial values of the strategy space. Randomly select $j_{DNO,0}$ and $S_{dis,i,0}^{L}$ as iterative initial values in the strategy space of both sides of the game.

Step 4: Lower-level model optimization. In the x-th round of the game, the user optimizes its planning decision in the $x-1$-th round of the game by taking the distribution network operator's decision result $S_{dis,i,x}^{L}$ in the x-th round as input, which can be express as:

$$S_{dis,i,x}^{L} = \arg\max f\left(j_{DNO,x-1}, S_{dis,i,x-1}^{L}\right)$$

Step 5: Determine whether the lower-level model solves the Nash equilibrium solution. In the x-th round of the game, if the lower-level model under the decision of the upper-level model has the same planning benefit in the x-th round and $x-1$-th round, that is:

$$S_{dis,i}^{L*} = S_{dis,i,x-1}^{L} = S_{dis,i,x}^{L}$$

Then it is shown that the lower-level model is solved to obtain the maximum revenue under Nash equilibrium in the x-th round of the game, and go to step 6; otherwise, repeat steps 4 to 5 until Nash equilibrium solution $S_{dis,i}^{L*}$ is obtained.

Step 6: Upper-level model optimization. The distribution network operation solves the Eq. (8) at the x-th round based on its optimization result $j_{DNO,x-1}$ at the $x-1$-th round, and the Nash equilibrium solution $S_{dis,i,x}^{L}$ is obtained from the lower-level model at the x-th round, which is given by

$$\begin{cases} \gamma_{sell,x} = \arg\max F\left[\left(\gamma_{sell,x}, \varphi_{lease,x-1}^{ave}\right), S_{dis,i,x}^{L}\right] \\ \varphi_{lease,x}^{ave} = \arg\max F\left[\left(\gamma_{sell,x-1}, \varphi_{lease,x}^{ave}\right), S_{dis,i,x}^{L}\right] \end{cases}$$

Step 7: If the upper-level model optimization result is the same in the x-th round as in the $x-1$-th round.

$$j_{DNO}^{*} = j_{DNO,x} = j_{DNO,x-1}$$

Then Nash equilibrium and output $\left(j_{DNO}^{*}, S_{dis,i}^{L*}\right)$ is considered to be obtained. Otherwise, repeat steps 4 to 7. The solution flowchart is shown in Fig. 2.

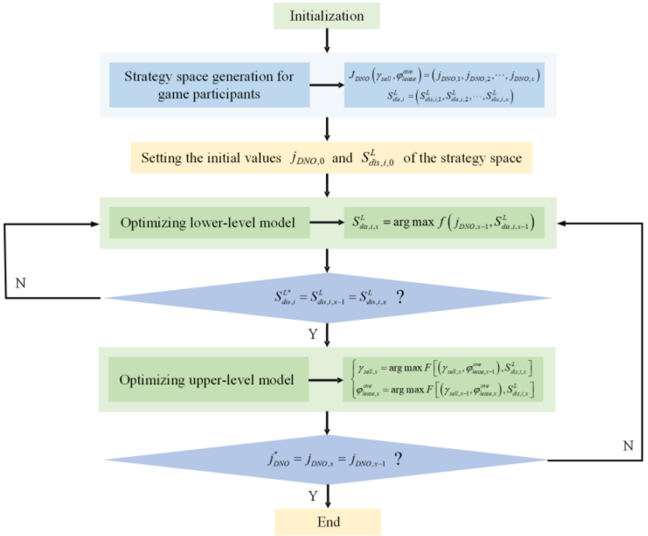


Figure 2. Solution flowchart

5. Case study

5.1. Basic data

This paper takes an area distribution network in Chaoyang City, Liaoning Province as the case study object, the existing residential users in this area are 800, the annual electricity consumption is about 3,000MWh. The maximum load in summer and winter is 3MW and 2.5MW, and the maximum installation capacity of distributed generation is 2.0MW with the maximum output power is 380W. The standard area of site lease for distribution network operators is not less than 200 m^2, the site lease fee is not less than 20 $\mathrm{RMB/m}^2$, and the number of users in the region that have the willingness to install distributed generation is 6. The 24h data are used to simulate the daily operation timing characteristics, and 6 typical scenarios with the minimum value of distributed generation output and the maximum value of load demand are selected as the limit scenarios, and then 1 day per week in a year is randomly screened, which makes a total of 58 typical days as the operation timing scenarios of the gaming model.

5.2. Stackelberg game results analysis

The iterative convergence process of the Stackelberg game-based bi-level planning model is shown in Fig. 3. It can be seen that the convergence is achieved in the 8-th iteration, which verifies the effectiveness of the proposed method. Specifically, as the number of iterations increases, the distributed generation planning capacity and site lease price continuously search for the optimal solution, and when the Nash equilibrium is reached, the distributed generation planning capacity and the site lease no longer change, which reflects the equilibrium process of the game between both entities. Eventually, the annual site lease price is 152 RMB per square meter, and the planning capacity of the user is reduced from 1.96 MW to 0.76 MW.

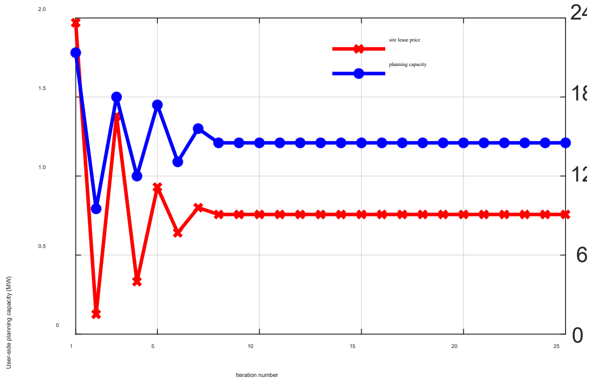


Figure 3. Nash equilibrium results for decision variables of game entities

Nash equilibrium results for objective revenues of game entities is shown in Fig. 4, both entities realize the maximum revenue of their own after the game, and the revenue of the distribution network operator is increased from the initial 3,821,006 RMB to 4,733,845 RMB, which is an increase of 23.89%, while all users also realize different degrees of revenue increase.

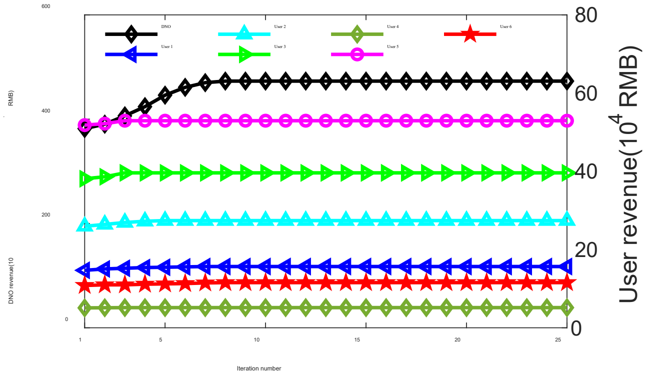


Figure 4. Objective revenues of game entities

The comparison of electricity selling tariffs of the distribution network operator before and after the game is shown in Fig. 5. In the 06:00~22:00 time period, the electricity selling tariff of distribution network operator after gaming is lower than that before gaming, which is mainly due to two aspects. On the one hand, the distribution network operator can utilize the distributed generation in its jurisdiction to save the market cost of purchasing electricity, which in turn reduces the electricity selling tariffs to users. On the other hand, some users choose to lease distributed generation sites, which increases the amount of electricity sold by the distribution network operator, thus contributing to a further reduction in the electricity tariff. Therefore, it can be seen that the game strategy proposed in this paper can effectively reduce the user's electricity cost.

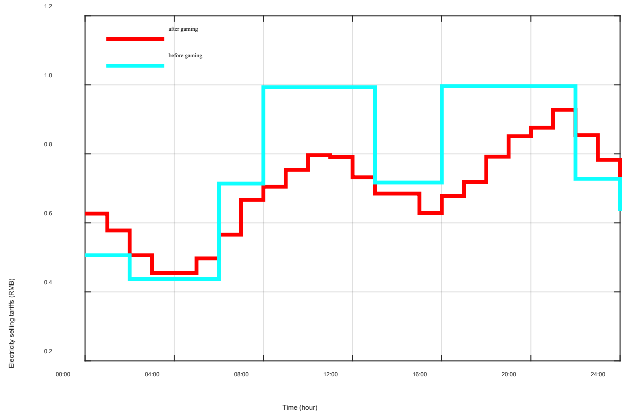
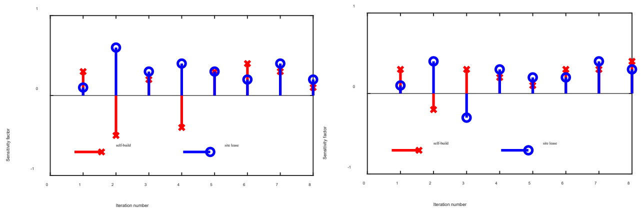


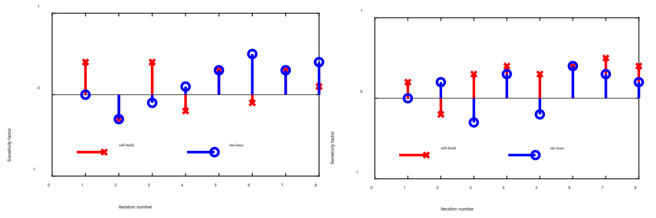
Figure 5. Electricity selling tariffs of distribution network operators before and after the game

5.3. Predictive results analysis of user-side distributed generation planning behavior

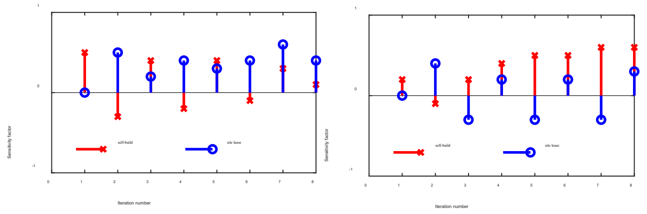
The sensitivity factor results for each user in the gaming process can be obtained as shown in Fig. 6 by adopting the proposed user-side distributed power planning behavior prediction method. As can be seen in Fig. 6, the sensitivity of each user to face different distributed generation planning modes under each iteration is different, because the continuous change of the site lease and electricity selling tariff of the distribution network operator in the gaming process will have an impact on the economy of the user's distributed generation planning, which proves the validity of the gaming strategy in this paper, and further demonstrates that the economy of the investment return of the distributed generation is the main factor affecting the user's distributed generation planning behavior.



(a)User 1 (b)User 2



(c)User 3 (d)User 4



(e)User 5 (f)User 6

Figure 6. Sensitivity factor results for each user in the gaming process

5.4. Economic analysis of cluster planning and operation mode

In order to further verify the superiority of cluster planning and operation of scaled distributed generation, the following three scenarios are designed to compare and analyze the economic results under different scenarios:

Scenario 1: Assuming the distribution network operator leases all user sites, the bi-level planning model is solved according to the lowest lease price and electricity selling tariff that can lease all user sites;

Scenario 2: Assuming that all users build their own distributed generation, the bi-level planning model is solved according to the original electricity price;

Scenario 3: Solve the bi-level planning model by using the cluster planning and operation mode proposed in this paper.

The results of operating costs and revenues of the distribution network operator under different scenarios are shown in Table 1.

Table 1. Operating costs and revenues of distribution network operator

Costs and revenue (10^4 RMB)	Scenario 1	Scenario 2	Scenario 3
construction and installation costs	66.72	——	40.16
operation and maintenance costs	48.86	——	31.22
site lease cost	336.88	——	198.26
surplus electricity recovery cost	——	337.76	89.25
energy storage lease cost	94.25	——	66.23
jurisdictional electricity sales revenue	893.21	706.53	819.25
ancillary services revenue	83.24	36.25	79.25
cluster operation total revenue	429.77	405.02	473.38

Table 1 shows that the cluster planning and operation revenue of the distribution network operator in scenario 3 is 4,733,810 RMB, which is increased by 436,110 RMB and 683,608 RMB compared to scenario 1 and 2, respectively. Specifically, the distribution network operator can only lease all the distributed generation sites at the annual site lease price of 240 RMB per square meter in scenario 1, which in turn spends nearly twice as much as the site lease fee in scenario 3, resulting in a significant decline in the operating revenues of the distribution network operator. While in scenario 2, although the distribution network operator saves the construction cost of distributed generation, the high cost of surplus electricity recovery and the low revenue from the jurisdiction's electricity selling also make the total revenue of the distribution network operator's cluster operating far lower than that of scenario 3. Therefore, compared with all self-build versus all lease, Therefore, compared with all self-build versus all lease, the benefits of each entity of distributed generation planning are accommodated in Scenario 3, causing the decision result to be more rational.

The costs and revenues result of each user's distributed generation planning behavior are shown in Table 2. In combination with the typical daily electricity consumption characteristics of each user, it can be seen that the distributed generation planning behavior is highly interrelated with the user's electricity consumption characteristics. Specifically, users who choose to lease their sites generally have low electricity consumption during the day and high electricity consumption at night, which is contrary to the output characteristics of distributed generation mainly composed of distributed photovoltaic (PV), resulting in the requirement for users to purchase huge amounts of electricity at night. Therefore, both user 1 and 3 choose to lease their distributed generation sites rather than to self-build distributed generation.

For user 5, the revenues from leasing the site are higher than the revenues from self-built distributed generation by 159,700 RMB, because user 5's electricity consumption is less than the installed capacity of its distributed generation. Therefore, the electricity buying cost has a smaller impact on its overall revenue, and thus the economics of leasing the site is better.

For user 2, 4 and 6 who choose to self-build distributed generation, their power consumption characteristics are consistent with the output characteristics of distributed generation, and the installable capacity is greater than their electricity consumption. Therefore, choose to self-build distributed generation not only save the electricity buying cost during daytime hours, but also can improve the revenue by selling the surplus electricity to the distribution network.

Table 2. Costs and revenues of each user

Costs and revenue (10^4 RMB)	planning behavior	installation cost	O&M cost	electricity buying cost	site lease revenue	surplus electricity feed-in revenue	total revenue
User 1	self-build	8.66	6.15	12.46	——	36.44	9.17
	lease	——	——	18.87	33.24	——	14.37
User 2	self-build	15.69	12.20	7.54	——	61.24	25.81
	lease	——	——	44.25	63.47	——	19.22
User 3	self-build	11.66	8.52	9.16	——	51.06	21.72
	lease	——	——	21.28	58.39	——	37.11
User 4	self-build	1.90	1.42	0.58	——	8.69	4.79
	lease	——	——	3.06	7.65	——	4.59
User 5	self-build	12.88	9.25	0.68	——	56.51	33.70
	lease	——	——	2.34	52.01	——	49.67
User 6	self-build	7.65	5.88	2.49	——	26.85	10.83
	lease	——	——	19.25	29.96	——	10.71

6. Conclusion

This paper proposes the optimal planning method of user-side scaled distributed generation based on the Stackelberg game, which realizes the economic planning of scaled distributed generation and the mutual benefit between multiple entities. after theoretical modeling and simulation verification, the following conclusions are as follows:

(1) The proposed cluster planning and operation mode is a specialized user-side distributed generation management mode through comparison with the self-operated mode, which has practical significance in guiding the orderly and reasonable planning of distributed generation, improving the operation and management quality of distributed generation, and enhancing the consumption capability of distributed generation;

(2) The constructed bi-level planning model for distributed generation resources accurately simulates the game behaviors of the distribution network operator and users in distributed generation resources planning, which enables both entities to optimize their own decision-making in the game process, and then obtains the optimal planning scheme of distributed generation resources under the balanced interests of each entity.

(3) The simulation results show that the revenue of the distribution network operator under the gaming model increases by 10.15% and 16.88% compared to the models of all users self-build and site lease, respectively, while at the same time, individual users also realize different degrees of revenue increase.

Conflict of interest

The authors declare no conflict of interest, financial or otherwise.

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