Market Trading Strategy of Integrated Energy Park from the Perspective of Non-cooperative Game

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Abstract

This paper introduces a park trading framework including energy managers, distributed photovoltaic and wind power users and electric vehicle charging service providers, and establishes a non-cooperative game model in which three subjects pursue maximum benefits. Taking a typical winter day in a park as an example, the simulation results show that: in the game equilibrium, energy managers profit from energy supply, distributed photovoltaic and wind power users improve resource utilization and reduce costs through margin online sales, and electric vehicle charging service providers choose low-bid charging to reduce costs and assist users to absorb excess resources and reduce the load of distribution network.

Keywords: integrated energy market, electric automobile, photovoltaic power generation, energy scheduling

1. Background

With the aggravation of the global greenhouse effect and energy crisis, the contradiction between energy demand and the natural environment became increasingly obvious. Countries began to attach importance to a safe, efficient, low-carbon, and clean energy operation mode to promote energy supply-side reform. The integrated energy system (IES) is a system coupling power, natural gas, heating, and transportation. It became an important research direction for the efficient utilization of distributed renewable energy. The IES effectively reduced carbon emissions and helped achieve the "double carbon" goal by jointly scheduling multiple energy sources. In the park IES, it was of great practical significance to use renewable energy, improve the flexibility of demand-side scheduling. And realize multi-energy complementarity[1].

In the integrated energy park, multiple market entities such as system energy operators, distributed photovoltaic users. And electric vehicle charging agents needed to conduct energy transactions to achieve efficient use and optimal allocation of resources. However, the traditional cooperative trading methods faced problems such as information asymmetry and game strategies, which resulted in low transaction efficiency. To address this issue, this paper studied the integrated energy market mechanism in which different market players operated in coordination. And established a three-party model of park energy operators, distributed photovoltaic user clusters, and EV charging agents, including the CHP system. And discussed the game bidding model within the park IES. Finally, taking a business park IES as an example, the improved particle swarm optimization algorithm was used to verify the model.

The rest of this article was organized as follows. The second section introduced the integrated energy park scenario. In the third part, the trading strategy game model of the three party market players were discussed. In the fourth section, PSO algorithm principle was introduced. The fifth section provided an examples to verify the availability of the designed model. The sixth part summarized the main content of this paper.

2. Scene Analysis of Integrated Energy Park

The structure of the integrated energy park studied in this paper is shown in Fig.1, which mainly included the park energy trading center (ETC) and three market players:park energy operators, distributed photovoltaic users, and electric vehicle (EV) charging agents.The ETC of the park transmitted transaction information and scheduling instructions to these market players through their respective energy management systems (EMS). The EMS was responsible for formulating energy quotation strategies and managing energy demand. While the ETC collected, distributed, and calculated information according to the market trading mechanism. The electric energy produced by the park followed the principle of local consumption and did not sell electricity to the superior distribution network.

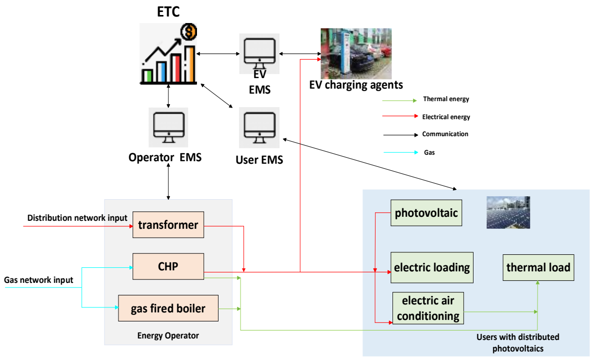

Fig.1 Structure of integrated energy park

2.1. Energy operator

As the leader of the market, energy operators are responsible for the supply of electric energy and heat energy in the park. Its main task is to formulate reasonable energy prices, connect the external energy supply network with the internal distribution network. And ensure that the energy needs of the park are met. Operators optimize the production and distribution of energy by scheduling their own energy equipment to maximize revenue. The pricing model is shown as Eq. (1) Eq. (2) and Eq. (3).

$$P_{opr}=[P_{e,opr},P_{h,op}r] \tag{1}$$

$$P_{e,opr}=[P_{e,opr}(1),P_{e,opr}(2),...P_{e,opr}(T)] \tag{2}$$

$$P_{h,opr}=[P_{h,opr}(1),P_{h,opr}(2),...P_{h,opr}(T)] \tag{3}$$

Where $P_{e,opr}$ and $P_{h,opr}$ are the prices of electricity and heat sold by energy operators respectively; T is the total number of scheduling periods in a day.

2.2. Users with distributed photovoltaics

Users with distributed photovoltaics are both energy producers and consumers. The user is equipped with photovoltaic power generation facilities, mainly relying on photovoltaic power generation to meet their own needs. When photovoltaic power generation is insufficient, users purchase electricity from energy operators; in the case of excess power generation, users can sell excess power to EV charging agents to maximize revenue[2]. The electricity price model of electricity sales is shown as Eq.(4).

$$P_{user}=[P_{e,user}(1),P_{e,user}(2),...P_{e,user}(T)] \tag{4}$$

Where P_{user} is the user 's electricity sales price.

2.3. EV charging agents

The EV charging agent is responsible for managing the charging demand of electric vehicles in the park. According to the market quotation, the charging agent selects the optimal power supplier and formulates the charging strategy to reduce the charging cost and promote the consumption of photovoltaic resources. Through interaction with users and energy operators, charging agents can effectively adjust the charging load and reduce the pressure on the distribution network. When choosing the power supplier, the charging agent will give priority to operators and users with lower electricity prices. The selection strategy is shown as Eq.(5).

$$P_{ch}(t)=\min\{P_{e,user}(t),\ p_{e,opr}(t)\} \tag{5}$$

The trading mechanism is shown in Fig.2.

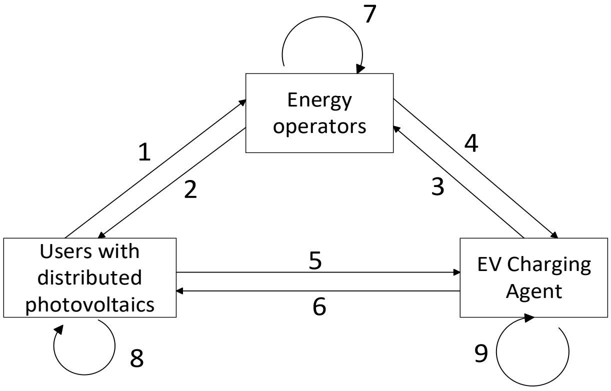

Fig.2 The trading mechanism

The explanation of the trading mechanism diagram is shown in Table 1.

Number	Interpretation
1	Report the adjusted energy consumption plan
2	Publish quotations $P_{e,opr}$ and $P_{h,opr}$
3	Reporting the energy required by the operator
4	Publish quotations
5	According to $P_{e,opr}$ specified quotation P_{user}
6	Users need to be reported
7	Adjust its own operating status and energy sales quotation
8	Adjust its own operating status and energy sales quotation
9	Select two quotations

Table 1. The explanation of trading mechanism diagram

As the leader of the internal market transaction of the park, the energy operator first publishes the initial energy supply quotation to the ETC of the park according to the historical data. And then passes the quotation to the EMS of the user and the EV charging agent. After receiving the quotation, users with distributed photovoltaics formulate a competitive photovoltaic on-grid price and feed it back to ETC. EV charging agents compare quotes, determine the optimal power consumption strategy and manage EV charging to maximize benefits. After the charging agent uploads the required power, the user 's EMS formulates. And uploads the energy consumption plan according to the power demand, photovoltaic power generation forecast. And the output of the operator 's electricity and heat price adjustment equipment. After receiving the energy plan, the operator 's EMS adjusts the energy equipment and energy sales quotation to increase revenue. The electricity price adjustment of operators may affect other subjects, prompting them to make corresponding adjustments. ETC will repeat this process until the three parties reach the best trading strategy. The analysis shows that the transaction strategies among energy operators, users with distributed photovoltaics and EV charging agents constitute a three-party non-cooperative game model. Through communication and interaction, the three parties finally reach Nash equilibrium and achieve the best trading state.

3. The Trading Strategy Game Model of the Three Party Market Players

This section introduced in detail the trading strategy game model of three types of market trading entities in the park: energy suppliers, users with distributed photovoltaics, and EV charging agents.

3.1. Park energy operator transaction model

The park 's energy operators are the main participants in market transactions, usually only one. As the main energy supplier, operators are responsible for providing continuous and stable power and thermal energy services. When energy operators optimize the allocation of energy, they aim to maximize their own net income, which is the difference between electricity sales revenue and operating costs. In the case of fixed energy demand of users and electric vehicle charging agents, operators can reduce operating costs by scheduling energy supply equipment. Or adjust electricity sales prices to obtain higher returns.

The revenue of energy operators refers to the difference between the revenue from selling energy to users and EV agents and their own operating costs is shown as Eq.(6).

$$R_{opr} = C_{opr}^{sale} - C_{opr}^{buy} - C_{opr}^{op} \tag{6}$$

Where P_{opr} is a gain for energy operators.

C_{opr}^{sale} refers to the energy sales revenue of energy operators, specifically from the sales of electricity and heat to other loads,which is shown as Eq.(7).

$$C_{opr}^{sale} = \sum_{t=1}^{T} (p_{e,opr}(t)P_{e,opr}(t) + p_{h,opr}(t)P_{h,opr}(t)\Delta t) \tag{7}$$

Where $P_{e,opr}$ and $P_{h,opr}$ are the power to supply electric energy and thermal energy to the park at each time ; δt is the scheduling time interval.

C_{opr}^{buy} refers to the cost of energy operators purchasing energy from power grid companies and natural gas companies,which is shown as Eq.(8).

$$C_{opr}^{buy} = \sum_{t=1}^{T} (P_{grid}(t)P_{grid}(t) + P_{gas}(t)q_{gas}(t))\Delta t \tag{8}$$

Where P_{grid} is the price of electricity sold by the grid company;p_{gas} is the price at which gas sells gas to gas companies;P_{grid} is the electric power injected into the grid side at any time;q_{gas} is the unit gas purchase at any scheduling time.

C_{opr}^{op} refers to the operation and maintenance cost of equipment sold by energy operators, which is composed of electricity sales operation and maintenance cost $C_{h,opr}^{op}$ and heat sales operation and maintenance cost $C_{h,opr}^{op}$,which is shown as Eq.(9).

$$\begin{cases} C^{op}_{opr} = C^{op}_{e,opr} + C^{op}_{h,opr} \\ C^{op}_{e,opr} = \sum_{t=1}^{T} (c^{T}_{e,opr} P^{T}_{e,opr}(t) + c^{CHP}_{e,opr} P^{CHP}_{e,opr}(t))\Delta t \\ C^{op}_{h,opr} = \sum_{t=1}^{T} (c^{CHP}_{e,opr} P^{CHP}_{h,opr}(t) + c^{GB}_{h,opr} P^{GB}_{h,opr}(t))\Delta t \end{cases} \tag{9}$$

In the formula, $C^{T}_{e,opr}$, $C^{CHP}_{e,opr}$, $C^{CHP}_{h,opr}$, $C^{GB}_{h,opr}$ are the unit capacity operation costs of energy operator transformers, CHP units, and gas boilers. $P^{T}_{e,opr}$, $P^{CHP}_{e,opr}$, $P^{CHP}_{h,opr}$, $P^{GB}_{h,opr}$ are the output values of energy operator transformers, CHP units, and gas boilers at each moment.

The power supplied by energy operators to the outside world should be balanced with the output power of their own production capacity equipment in real time,which is shown as Eq.(10).

$$\begin{cases} P_{e,opr}(t) = P^{T}_{e,opr}(t) + P^{CHP}_{e,opr}(t) \\ P_{h,opr}(t) = P^{GB}_{h,opr}(t) + P^{CHP}_{h,opr}(t) \end{cases} \tag{10}$$

Energy operators cannot adjust their quotations without limit in the pricing process, and they need to formulate within a certain market constraint range,which is shown as Eq.(11).

$$\begin{cases} P^{\min}_{e,opr} \le P_{e,opr}(t) \le P^{\max}_{e,opr} \\ P^{\min}_{h,opr} \le P_{h,opr}(t) \le P^{\max}_{h,opr} \end{cases} \tag{11}$$

Where, $P^{\min}_{e,opr}$, $P^{\max}_{e,opr}$ represents the upper and lower limit constraints of the electricity selling price; $P^{\min}_{h,opr}$, $P^{\min}_{\mathrm{h},opr}$ represents the upper and lower limit constraints of heating price.

3.2. User transaction model with distributed photovoltaic

When users with distributed photovoltaics formulate energy use strategies, the goal is to maximize revenue. Users can increase revenue by adjusting the electricity price and equipment operation status. When photovoltaic power generation meets its own needs and has a surplus, users can formulate competitive quotations to win the power sales right of electric vehicle charging agents, so as to obtain income. In addition, after receiving the charging demand, the user 's energy management system (EMS) will schedule the equipment according to the photovoltaic power generation forecast. And the electricity sales quotation to reduce the operating cost. The user 's income with distributed PV refers to the difference between the income from selling electricity to EV power agents and the operating cost is shown as Eq.(12).

$$R_{user} = C^{sale}_{user} - C^{buy}_{user} - C^{op}_{user} \tag{12}$$

Where $\mathrm{R}_{\mathrm{user}}$ is user revenue.

C^{sale}_{user} refers to the electricity sales revenue of users with distributed photovoltaics, including two parts. Part of the revenue comes from selling electricity to EV charging agents, and the other part comes from government subsidies for full-power PV access,which is shown as Eq.(13).

$$C^{sale}_{user} = \sum_{t=1}^{T} (P_{e,user}(t) P^{ch}_{e,user}(t) + p_{alow} P^{PV}_{e,user}(t))\Delta t \tag{13}$$

Where $P^{ch}_{e,user}$ is the power supplied to the EV charging agent at any time, and $\mathrm{P}_{\mathrm{alow}}$ is the government 's subsidy price for photovoltaic power generation.

C^{buy}_{user} refers to the cost of users with distributed photovoltaics purchasing additional electrical and thermal energy from energy operators,which is shown as Eq.(14).

$$C^{buy}_{user} = \sum_{t=1}^{T} (P_{e,opt}(t) P^{user}_{e,opr}(t) + p_{h,opr} P_{h,opr}(t))\Delta t \tag{14}$$

Where $P^{user}_{e,opr}$ is the power that energy operators sell to users at any time.

C^{op}_{user} refers to the operation and maintenance cost of user equipment with distributed photovoltaic,which is shown as Eq.(15).

$$C^{op}_{e,user} = \sum_{t=1}^{T} (C^{pv}_{e,user}(t) P^{PV}_{e,user}(t) + C^{AC}_{e,user} P^{AC}_{e,users}(t))\Delta t \tag{15}$$

Where $C^{PV}_{\mathrm{e,user}}$ and $C^{AC}_{e,user}$ are the unit capacity operation cost of photovoltaic power generation and electric air conditioning respectively; $P^{PV}_{e,user}$ and $P^{AC}_{e,users}$ are the output values of photovoltaic power generation and electric air conditioning at any time.

3.3. EV charging agent transaction model

The electric vehicle charging agent is responsible for charging the electric vehicle to meet the needs of the owner. The energy management system (EMS) of the agent selects the power supplier with a lower quotation. If the power supply is insufficient, it is supplemented by the other party with a higher quotation. Energy operators can usually provide sufficient energy and meet all needs during low-cost periods. While users with distributed photovoltaics preferentially meet their own needs. And only sell electricity to charging agents when photovoltaic power generation is surplus. If the demand for electric vehicles is large, even if the photovoltaic power generation is fully supplied, it may still be unable to meet the demand. At this time, it is necessary to purchase the gap power from energy operators at a higher price.

C_{ch}^{buy} indicates the charging cost of EV charging agents, which is the sum of the cost of purchasing electricity from energy operators and users,which is shown as Eq.(16).

$$C_{ch}^{buy}=\sum_{t=1}^{T}(P_{e,opt}(t)P_{e,opr}^{ch}(t)+p_{e,user}P_{e,user}^{ch}(t))\Delta t \tag{16}$$

Because the goal of the game is to maximize the utility of the game, the utility function of the EV charging agent is defined as Eq.(17).

$$R_{ch}=-C_{ch}^{buy}(t) \tag{17}$$

The power value of the input agent at any time should be the sum of the electric power provided by the energy operator and the user,which is shown as Eq.(18).

$$P_{e,opr}^{ch}(t)+P_{e,user}^{ch}(t)=\sum_{i=1}^{N}P_{ch}^{i}(t) \tag{18}$$

Where $P_{ch}^{i}(t)$ represents the charging power of the i th EV at that time, and N represents the total number of EVs managed by the agent.

Each EV charging needs to reach the preset power to meet the traffic demand of the owner,which is shown as Eq.(19).

$$Ei(t_{i,dept})=E_{i,set}=E_i(t_{i,arr})+\eta_{ch}^{i}\Delta t\cdot\sum_{t=1}^{T}P_{ch}^{i}(t) \tag{19}$$

Where E represents the power function of EV, and Ei, set represents the final charging power required by the owner;$t_{i,arr}$ and $t_{i,dept}$ indicate the arrival and departure time of the i th EV;η_{ch}^{i}indicates the vehicle charging efficiency of the i th EV.

4. Algorithm Principle

The three market trading entities constitute a three-party non-cooperative game model. The three goals are to rationally pursue their own maximum returns. This paper uses particle swarm optimization (PSO) to solve the problem.

PSO is a classical swarm intelligence algorithm inspired by the flight and foraging behavior of birds. Birds find the global optimal solution through information interaction between individuals. PSO regards the problem to be optimized as a flock of birds, the solution space is regarded as the flight space of the flock of birds. And the position of each bird represents a solution. In this paper, the PSO algorithm simplifies the original 1×5T dimensional problem into 1×3T dimensional, which significantly reduces the difficulty of optimal particle search in the iterative process. The particle swarm is composed of n particles, and the position of each particle is 3T dimension vector a, which represents the potential game strategy set. The speed is 3T dimension vector; the local optimal strategy is 3T-dimensional vector pbest, and the global optimal strategy is 3T-dimensional vector gbest. In the process of algorithm evolution, particles track the optimal position of individual history and the optimal position of population history.

The individual position change of particle swarm optimization algorithm is based on two basic formulas,which are shown as Eq.(20) and Eq.(21).

$$v_{id}^{t+1}=\omega v_{id}^{t}+c_1r_1(p_{id}^{t}-x_{id}^{t})+c_2r_2(p_{gd}^{t}-x_{id}^{t}) \tag{20}$$

$$x_{id}^{t+1}=x_{id}^{t}+v_{id}^{t+1} \tag{21}$$

Where r1 and r2 are random numbers between (0,1), c1 and c2 represent learning factors, and the value is generally c1 = c2 = 2.

In order to solve the problem of premature convergence in the traditional particle swarm optimization algorithm, this paper adopts a linear decreasing strategy for the inertia weight. In the early stage of iteration, the larger inertia weight helps to enhance the global search ability and jump out of the local optimum. At the end of the iteration, the reduced inertia weight is conducive to accurate search near the global optimum, thus promoting the convergence of the algorithm. In addition, the learning factor adopts a nonlinear inverse cosine acceleration strategy, so that the particles mainly refer to their own historical information in the early stage. And focus more on group information in the later stage to avoid falling into local convergence. The value of inertia weight and learning factor c1, c2 is shown as Eq.(22).

$$\begin{cases}\omega=\omega_s-\dfrac{k}{k_{\max}}(\omega_s-\omega_e)\\ c_1=c_{1e}+(c_{1s}-c_{1e})[1-\dfrac{\arccos(-2k/k_{\max}+1)}{\pi}]\\ c_2=c_{2e}+(c_{2s}-c_{2e})[1-\dfrac{\arccos(-2k/k_{\max}+1)}{\pi}]\end{cases} \tag{22}$$

In the formula:$k_{\max}$ is the maximum number of iterations, ω_s and ω_e represent the initial and final values of the iteration of the inertia weight respectively.c_s and c_e represent the initial and final values of the iteration of the learning factor respectively. The fitness function in the PSO algorithm of the three-party game is shown as Eq.(23).

$$fitness(\varphi)=\max\{|\Delta R_{opr}|,0\}+\max\{|\Delta R_{user}|,0\} \tag{23}$$

The algorithm flow diagram of solving the equilibrium solution of the game model in this paper is shown in Fig.3.

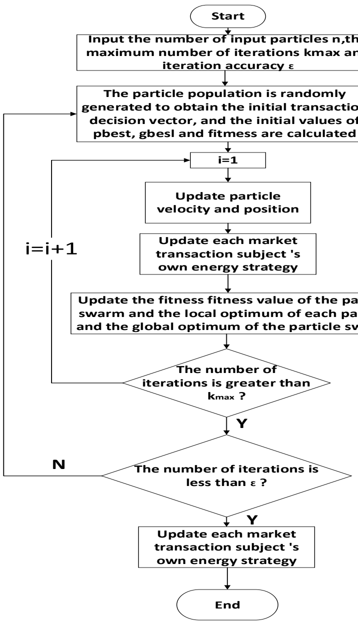

Fig.3 Algorithm flow chart

5. Example Analysis

5.1. Parameter setting

In this paper, the IES of a business park shown in fig.1 is taken as the object for simulation calculation. The park has an energy operator, a user cluster with photovoltaics and an electric vehicle charging agent. The PV-containing user cluster includes five commercial buildings with distributed PV panels. The equipment parameters of the integrated energy park are shown in Table 2.

Trade subject	Equipment name	Number	Parameter	Value
Energy operator	CHP unit	1	Maximum power supply/kW	500
			Maximum heating power/kW	650
			ratio of heat to electricity	1.3
			transmission efficiency/%	35
			heating efficiency/%	45.5
			maintenance cost/(RMB/kW·h)	0.070
			Uphill and downhill climb/(kW/min)	5
	Gas fired boiler	1	Maximum heating power/kW	500
			heating efficiency/%	90
			maintenance cost/(RMB/kW·h)	0.002
			Uphill and downhill climb/(kW/min)	5
	Distribution transformer	1	Maximum power supply/kW	500
			maintenance cost/(RMB/kW·h)	0.002
Users with distributed photovoltaics	Photovoltaic panel	5	Maximum power supply/kW	200
			energy generation subsidy/(RMB/kW·h)	0.3
			maintenance cost/(RMB/kW·h)	0.006
	Heating air conditioning	5	Maximum heating power/kW	108
			energy efficiency ratio	2.7
			maintenance cost/(RMB/kW·h)	0.002
EV charging agents	EV	40	Maximum charging power/kW	7
			charge efficiency/%	90
			Power battery capacity(kW·h)	24
			Maximum state of charge	0.95

Table 2. Equipment parameters of integrated energy park

5.2. Simulation results and analysis

The fitness curve of the particle swarm optimization algorithm is shown in Fig4.

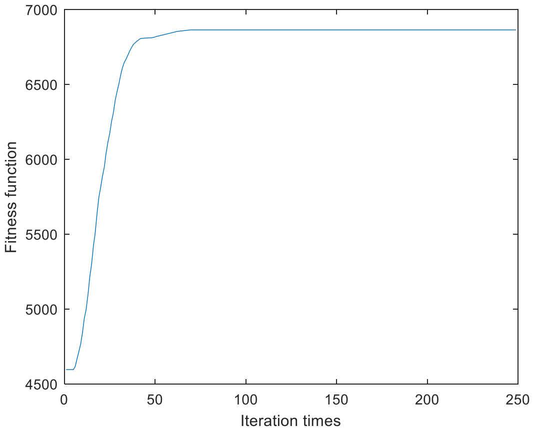

Fig.4 Particle swarm algorithm fitness curve

The electric load, heat load and photovoltaic output of the park are shown in fig.5.

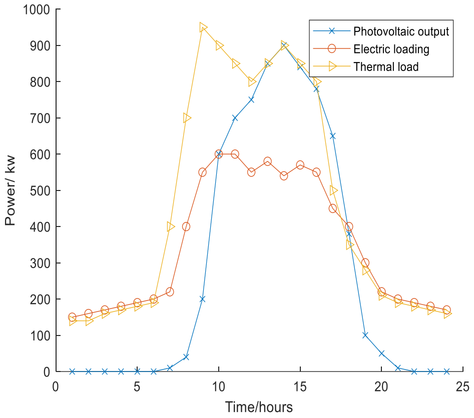

Fig.5 The park's electric load, heat load, and photovoltaic output.

The output of photovoltaic power generation reaches its peak during the daytime (about 09 : 00 to 17 : 00). And the electrical load coincides with the output of photovoltaic power generation during the peak period of the daytime (about 12 : 00 to 15 : 00). Indicating that users have a higher demand for electricity during this period. The change of thermal load during the day is relatively stable. And the overall level is lower than that of electric load and photovoltaic output, indicating that the thermal energy demand is low during this period.

In the game equilibrium state, the power and heat sales of energy operators adopt the time-of-use pricing strategy. And the power sales of user groups adopt the time-of-use electricity price. The bidding results of energy operators and users are shown in Fig.6.

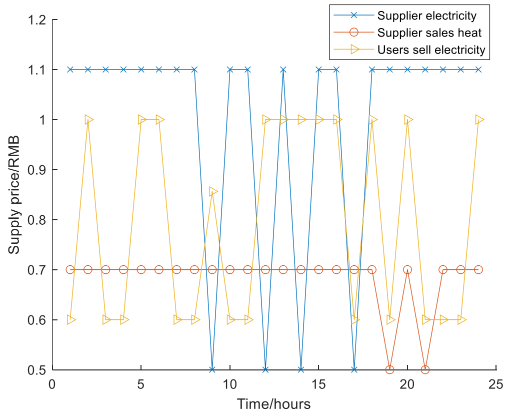

Fig.6.The bidding results of energy operators and users

From the diagram, it can be seen that in most of the time period, the user 's electricity sales quotation is generally lower than the operator 's quotation. Due to the low electricity quotation of photovoltaic users, EV charging agents are more inclined to choose the photovoltaic power sold by users to reduce costs. If users do not take price incentives during the high incidence of photovoltaics, it may lead to a situation of ' oversupply '. Resulting in waste of photovoltaic power generation, thus affecting their own income. Therefore, the user 's bidding strategy should be adjusted in the direction of improving their own income. In addition, the heat quotation of energy operators is relatively low. This is because if the heat price is too high, users will be more inclined to use their own photovoltaic power generation to drive the electric air conditioning for heating. Thereby reducing the demand for heat energy from energy operators. This situation may reduce the potential heat sales revenue of operators. Therefore, they will adjust the heat bidding strategy to keep the heat price at a low level during this period[3].

When the game is balanced, the output of the energy operator 's power supply and heating system is shown in Fig.7.

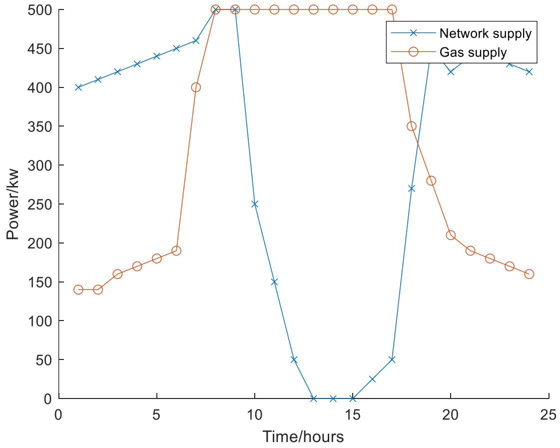

Fig.7 The output of the energy operator 's power supply and heating system

The power supply of the power grid remains relatively stable for most of the time. And the gas heating fluctuates greatly during the day, especially in the morning and evening, and the power drops to near zero at the trough. The two can complement each other to meet the different needs of users.

The power supply of the power grid to the charging station and the power supply of the user to the charging station are shown in Fig.8.

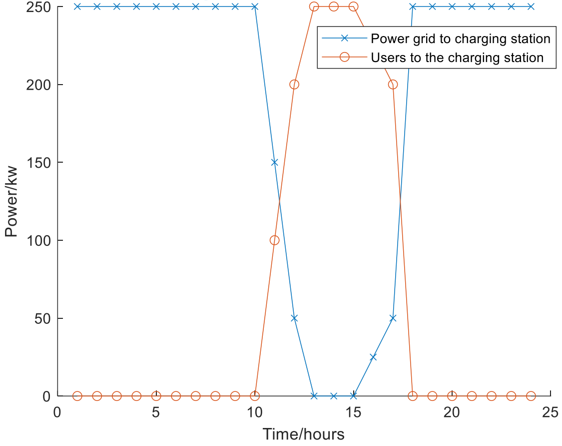

Fig.8 The power grid and users supply energy to the charging station.

From the diagram, it can be seen that during the period of large photovoltaic output, the power of the charging station is mainly provided by the user, and the rest of the time is mainly provided by the power grid.

The load of the grid supply charging station, the user 's electric load and the heat load of the heating network supply user are shown in Fig9.

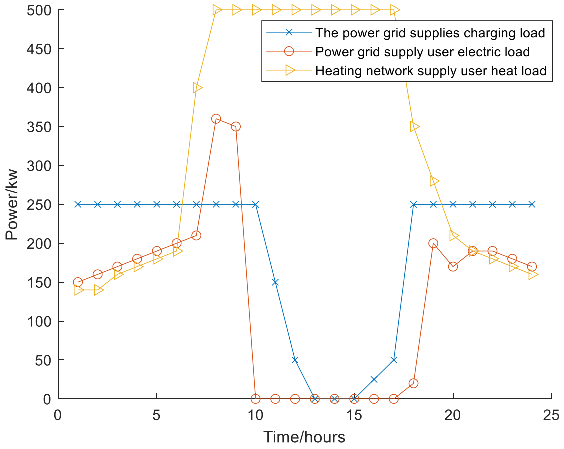

Fig.9 The grid and users supply each other's loads

The charging load of the power grid supply peaked during the day (about 09 : 00 to 18 : 00), indicating that the charging demand was higher during this period. The user 's electrical load has obvious peaks in the morning and evening. Especially at 08 : 00 and 18 : 00, indicating that the user has a greater demand for electricity in these two periods. The heat load is relatively low throughout the period, and the change is not large, indicating that the heat demand is relatively stable during this period.

Finally, when the game is balanced, the operator 's energy sales income is 15265.5RMB. Minus the cost of equipment operation and maintenance and the cost of purchasing energy from the distribution network and the gas network. The full-day net income is 1075.38RMB. The user 's energy sales income is 3268.69 RMB, and the user 's energy cost is 10840.8RMB. For EV charging agents, the all-day charging cost is 224.47RMB. If EVs do not participate in the market game, they are all connected to the distribution network in a disorderly charging state. According to the calculation, the charging cost is 480.54RMB;if all the power of the energy operator is used, the charging cost is 325.16RMB.

6. Conclusion

This paper studied the market trading framework of the integrated energy park, including energy operators, distributed photovoltaic users, and EV charging agents. And established a three-party non-cooperative game model. The studies showed that integrated energy parks could significantly reduce energy costs and improve the flexibility of clean energy consumption. The three-party game model promoted the balance of benefits among all parties, facilitated the effective utilization of photovoltaic resources, and reduced user energy costs. Energy operators profited by selling electricity and heat, distributed PV users profited by supplying energy to EV agents, and receiving PV subsidies. While EV agents reduced charging costs and helped users absorb excess PV resources.

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