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Time-of-Use Pricing Strategy of Integrated Energy System Based on Game Theory

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Abstract: The integrated energy system is the mainstream energy utilization form of integrating a power system, natural gas system and thermal system, which provides a new way to solve the problem of renewable energy accommodation. The integrated energy system includes a variety of energy generation and conversion equipment, and its internal electricity, gas, cooling and thermal systems must balance the multiple energy supplies required by users. The integrated energy supplier (IES) and integrated energy user (IEU), as different stakeholders, pursue the maximization of their own profit. However, integrated energy suppliers should consider their market share and the sustainability of participating in market competition. Based on the constraints of energy access, conversion and accommodation, and the equipment for energy generation, conversion and consumption, we established an energy flow model. Constrained by the dynamic equilibrium of the supply of integrated energy suppliers and the demand of integrated energy users, a Stackelberg game model of integrated energy suppliers and users was established, and the existence of a Nash equilibrium solution of the game was proved. A genetic algorithm was used to solve the Nash equilibrium solution under two conditions aiming at the integrated energy supplier's maximum profit and target profit. Considering the demand of integrated energy users in different time periods, we analyzed the time-of-use pricing strategy of the integrated energy based on the balance of the energy supply and demand. The results of a case study show that if integrated energy suppliers adopt the time-of-use pricing strategy of maximum profit, the energy load distribution of integrated energy users can be smoothed, and energy utilization and economic benefits of the system can be improved. If integrated energy suppliers adopt the time-of-use pricing strategy of target profit, enlarge the market by limiting their own profit and obtain the purchase willingness of integrated energy users by reducing the energy price, they can have a larger market share, a more reliable profit and a guarantee of long-term participation in market transactions.

Keywords: integrated energy system; Stackelberg game; time-of-use pricing; demand response; Nash equilibrium

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1. Introduction

With the expansion of the scale of renewable energy development, power systems have new requirements on the intermittent and fluctuating nature of renewable energy. Traditional power systems usually increase investment on both the supply and demand sides, such as the use of deep peak shaving technology, and distributed energy storage technologies and the allocation of renewable energy based on demand-side response alleviate the intermittent and fluctuation problems of renewable energy, and high investment costs and insufficient energy consumption should be faced at the same time. Therefore, improving energy utilization and realizing the large-scale use of renewable energy have become the inevitable choices in the process of integrated energy system development [1].

The integrated energy supplier (IES) is based on an integrated energy system and uses renewable energy as the main energy source. The energy supply methods tend to diversify, which provides great power supply flexibility to the traditional power system.

The grid power supply, renewable energy system power supply and gas-driven combined cooling and heating and power (CCHP) system are conducive to the use of energy in the cascade transfer process, while improving the integrated energy utilization rate and reducing pollutant emissions [2]. After considering the needs of the integrated energy users (IEUs), the supply and demand relationship can be balanced through the price incentive mechanism. While stimulating the IEU to adjust the allocation of energy demand to achieve a balanced optimization of the supply and demand side, the utility function is maximized to ensure IEU satisfaction. IEU uses different energy sources in different periods of time. According to IEU's demand for integrated energy, IES obtains the current maximum profit through the establishment of time-of-use prices.

With the continuous improvement of the Energy Internet [3], IES can supply energy to multiple groups of IEUs at the same time, achieving energy interconnection [4–6]. In traditional research, energy consumption is optimized separately from the perspective of the participants, without considering the interaction between them. The game strategy can solve the rational optimal strategy set of market participants, which is of great significance to the formulation of energy prices and the planning and operation of IES. Reference [7] pointed out the effectiveness and validity of price linkage in the game. Reference [8] proposed a regional integrated energy game optimization strategy considering load demand response and aiming at optimal comprehensive profits. Reference [9] proposed a double-layer Stackelberg game model aiming at maximizing the profits of IES and minimizing the costs of IEU. Reference [10] proposed to take potential function as the solution method and obtained the game strategy of a multi-energy market including electricity, thermal and gas. Reference [11] took the maximum profit as the comparison index, and analyzed different operation strategies under the non-cooperative game, semi-cooperative game and cooperative game of the integrated energy system. Reference [12] established a game model by using two-level optimization, and compared and analyzed the profit difference of IES in the retail and wholesale markets. Reference [13] proposed a two-level collaborative control strategy model of "electricity–thermal–gas" integrated energy system based on multi-agent deep reinforcement learning to improve the energy efficiency of the integrated energy system and reduce costs. Reference [14], taking energy efficiency and cost as optimization objectives, proposed a two-stage energy management method of a thermal–electricity integrated energy system considering dynamic pricing of the Stackelberg game and operation strategy optimization. However, the above dynamic game models related to energy trading are all aimed at maximizing profits or minimizing costs. They only consider economics without considering the energy trading volume of IES after the game or analyzing the willingness of IEU to purchase energy in the face of energy prices after the game. These two are related to whether IES can participate in the market operation and maintain reliable profit for a long time. In order to analyze this problem, we consider the demand response of IEU and the time-of-use price of IES, and compare the profit, energy trading volume and price dynamic curve after equilibrium pricing from the perspective of maximum profit and target profit.

When considering IEU demand response, IES first initializes the energy price. As a follower, IEU can determine the energy consumption according to the price strategy and its own demand constraints [15]. The game relationship between IES and IEU is in order. According to this characteristic, this paper focuses on the equilibrium pricing and quantitative energy interaction between IES and IEU. Firstly, a multi-energy flow Stackelberg game model with a master–slave relationship is established, and then the objective functions with the maximum profit and target profit of IES are constructed. Secondly, it is proved that the equilibrium solution of the established game model exists in the process of multi-agent participation. Finally, the time-of-use pricing strategy is solved for different time periods under the two different objective profits. Integrated energy trading volume and pricing curves are obtained and the integrated energy interaction between IES and IEU is analyzed. If the IES adopts the time-of-use pricing strategy of maximum profit, the load distributions of IEUs are smoothed, and the energy utilization rate and economic efficiency of the system are improved. If IES adopts the time-of-use pricing strategy of target profit, integrated energy trading volume is increased and energy unit price is decreased. For IES, increased integrated energy trading volume means more market share. For IEU, decreased energy unit price means more energy trading volume at the same price. This strategy is helpful for integrated energy suppliers to participate in market operations for a long time and maintain reliable profit.

The remainder of this paper is organized as follows. In Section 2, game model subjects of IESs and IEUs are established. In Section 3, the Stackelberg game model is presented and the existence of a Nash equilibrium solution is proved. In Section 4, a case study is detailed to demonstrate the proposed game strategy. In Section 5, several important conclusions are summarized.

2. The IES and IEU Model

2.1. IES Model

The profit of IES is determined by operating costs, spot market price and integrated energy trading volume as IES enters the integrated energy market. In this study, energy trading between IES and IEU was treated as a completely competitive market behavior, and the bidding behavior within IESs was not considered. The IES formulates a price strategy based on the IEU's demand for integrated energy. The interaction between IES (leader) and IEU (follower) was based on Stackelberg game theory [16–18]. An integrated energy interaction Stackelberg game model considering IEU's energy consumption behavior was established. Figure 1 is the decision model of IES.

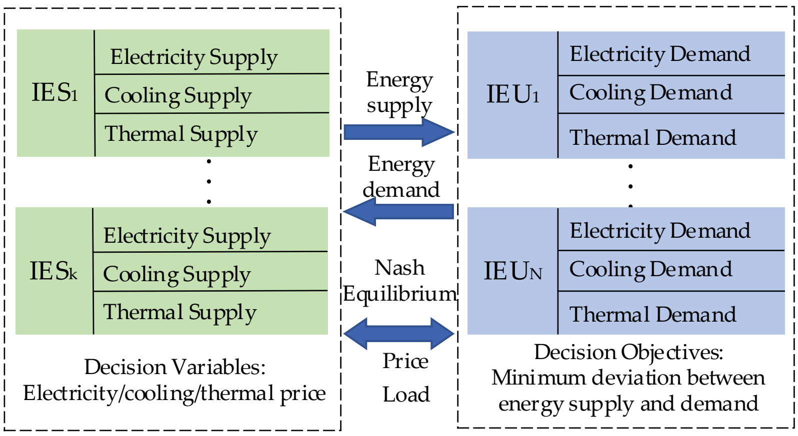


Figure 1. Framework of decision model of IES.

2.1.1. Multi-Energy Flow Modeling of Integrated Energy Systems

The integrated energy system studied in this paper is mainly composed of an energy supply network, energy exchange link and terminal integrated energy consumption unit. It is a multi-energy flow system consisting of cooling, thermal energy and electricity. The system has low cost, high flexibility and reliability in the actual application process. When the integrated energy system is operating, the waste thermal generated during electricity generation can be reused. The gas turbine consumes the natural gas input from the gas supply system to generate electricity and high-temperature steam. The steam is recovered by the waste heat boiler to generate high-pressure steam and low-pressure steam. The former enters the unit steam turbine to generate electricity, and the latter is used by the deaerator of the waste heat boiler. There is a heating surface at the end of the waste heat boiler, which can generate heat medium water to meet the heating energy requirements. In addition, steam turbines provide extraction services for thermal power needs. The heating medium water is first supplied with hot water, and the remaining absorption refrigeration unit is used for cooling. The extracted steam can be used for cooling the hot water heat exchanger. The electricity generated by gas and steam turbines is used to meet electrical loads. In addition, electric refrigeration equipment and absorption refrigeration machines supplement the insufficient cooling. The combined cooling, heating and electricity system based on natural gas can effectively improve the integrated energy utilization rate by combining electric generation and heating. The input power of the grid power supply system and the renewable energy power supply system is used for the user's electricity demand. At the same time, the insufficient cooling/thermal demand of the IEU can be supplemented by electric refrigeration equipment and electric heating equipment through energy allocation.

In order to accurately reflect the characteristics of the system energy flow conversion, the energy flow function is used to characterize the balance between electricity/cooling/thermal energy [19]. A regional integrated energy system based on grid power supply, renewable energy supply and natural gas input is shown in Figure 2.

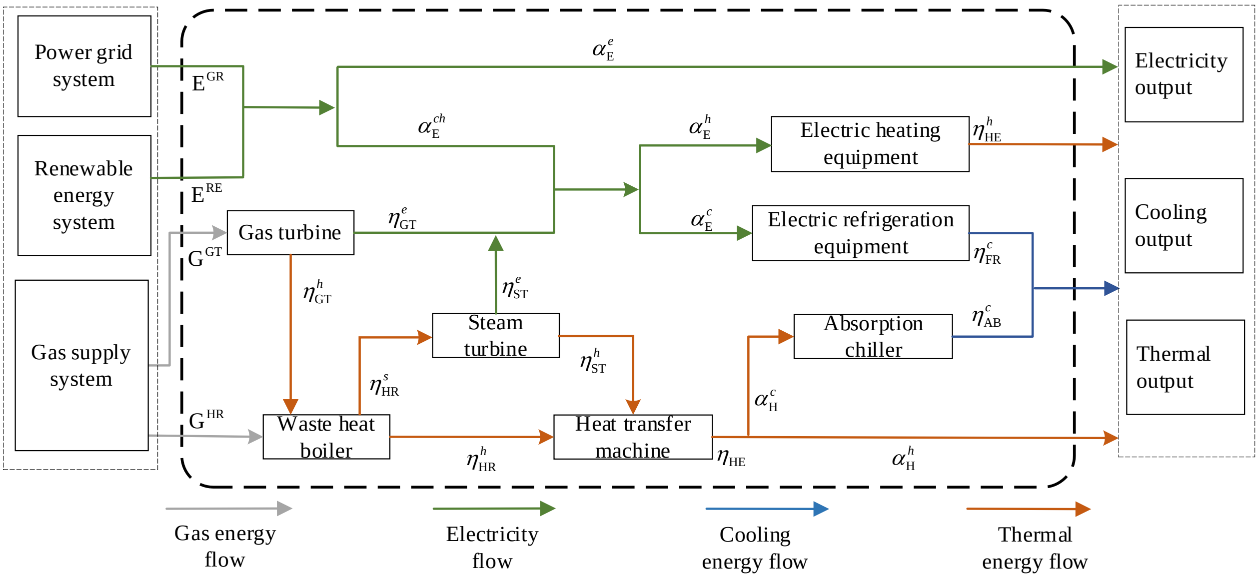


Figure 2. Schematic diagram of regional integrated energy system.

Equation (1) is the energy conversion equation of the regional integrated energy system.

$$\begin{cases} O^e & = \alpha_E^e \left(E^{GR} + E^{RE}\right) \\ O^c & = \alpha_H^c \eta_{AB}^c \eta_{HE} \left(\eta_{HR}^h + \eta_{ST}^h \eta_{HR}^s\right) \left(\eta_{GT}^h G^{GT} + G^{HR}\right) + \alpha_E^c \eta_{FR}^c \\ & \quad \left[\eta_{GT}^e G^{GT} + \eta_{ST}^e \eta_{HR}^h \left(\eta_{GT}^h G^{GT} + G^{HR}\right) + \alpha_E^{ch} \left(E^{GR} + E^{RE}\right)\right] \\ O^h & = \alpha_H^h \eta_{HE} \left(\eta_{ST}^h \eta_{HR}^s + \eta_{HR}^h\right) \left(\eta_{GT}^h G^{GT} + G^{HR}\right) + \alpha_E^h \eta_{HE}^h \\ & \quad \left[\eta_{GT}^e G^{GT} + \eta_{ST}^e \eta_{HR}^h \left(\eta_{GT}^h G^{GT} + G^{HR}\right) + \alpha_E^{ch} \left(E^{GR} + E^{RE}\right)\right] \end{cases} \tag{1}$$

where O^e,O^c and O^h are electricity output, cooling output and thermal output of the integrated energy system, respectively. α_E^e is the energy distribution coefficient of direct electricity output, and α_E^{ch} is the energy distribution coefficient supplementing cooling and thermal supply. α_E^h is the energy distribution coefficient of electric heating equipment, and α_E^c is the energy distribution coefficient of electric refrigeration equipment. α_H^c is the energy distribution coefficient of the thermal exchanger supplying the absorption chiller, and α_H^h is the energy distribution coefficient of the thermal exchanger directly outputting thermal energy. η_{GT}^e and η_{GT}^h are the electrical efficiency and thermal efficiency of the gas turbine, respectively. η_{HR}^s and η_{HR}^h are the steam efficiency and thermal efficiency of the waste heat boiler, respectively. η_{ST}^e and η_{ST}^h are the electrical efficiency and thermal efficiency of the steam turbine, respectively. η_{HE} is the thermal energy efficiency of the heat transfer machine. η_{HE}^h is the thermal energy conversion efficiency of electric heating equipment, η_{FR}^c

is the cooling energy conversion efficiency of electric refrigeration equipment and η^{c}_{AB} is the conversion efficiency of thermal energy to cooling energy of the absorption refrigeration machine. G^{GT} is the volume of natural gas input to the gas turbine, and G^{HR} is the volume of natural gas input to the waste heat boiler. E^{GR} is the power supply of the grid, and E^{RE} is the power supply of the renewable energy.

2.1.2. IES Objective Function

As the energy producer and converter in the integrated energy system, the IES needs to price the unit-integrated energy. We consider the pricing strategy of IES under the conditions of maximum profit and target profit.

(1) Maximum profit. IES adjusts the input of power supply and natural gas according to users' demand, prices unit-integrated energy and obtains maximum profit. Equation (2) represents the objective function of IES with maximum profit.

$$\begin{aligned} \max U^{\mathrm{IES}} = p^{e}O^{e} + p^{c}O^{c} + p^{h}O^{h} - (c^{re}E^{\mathrm{RE}} + \\ f^{re} + c^{gr}E^{\mathrm{GR}} + f^{gr} + c^{g}\left(G^{\mathrm{GT}} + G^{\mathrm{HR}}\right) + f^{g}) \end{aligned} \tag{2}$$

where p^{e} is the unit electricity price, p^{c} is the unit cooling price, p^{h} is the unit thermal price, c^{re} is the variable cost coefficient of the renewable energy system and f^{re} is the fixed cost of the renewable energy system. c^{gr} is the variable cost coefficient of the grid system, f^{gr} is the fixed cost of the grid system, c^{g} is the variable cost coefficient of the gas supply system and f^{g} is the fixed cost of the gas supply system.

(2) Target profit. IES adjusts the power input and volume of natural gas required for production according to users' demand, appropriately reduces the overall energy price, enlarges the market and obtains the target profit. Equation (3) represents the objective function of IES with the target profit.

$$\begin{aligned} \min\left|U^{\mathrm{IES}} - U^{\mathrm{IES}*}\right| = |p^{e}O^{e} + p^{c}O^{c} + p^{h}O^{h} - (c^{re}E^{\mathrm{RE}} + f^{re} + \\ c^{gr}E^{\mathrm{GR}} + f^{gr} + c^{g}\left(G^{\mathrm{GT}} + G^{\mathrm{HR}}\right) + f^{g}) - U^{\mathrm{IES}*}| \end{aligned} \tag{3}$$

where $U^{\mathrm{IES}*}$ is the target profit. IES can maintain its own operation under the target profit. IES supplies integrated energy to satisfy the energy demand of IEUs after the energy loss in the transmission and conversion.

$$\begin{cases} O^{e} = (1+\alpha^{e})d^{e} \\ O^{c} = (1+\alpha^{c})d^{c} \\ O^{h} = (1+\alpha^{h})d^{h} \end{cases} \tag{4}$$

where α^{e},α^{c} and α^{h} are network loss parameters of electrical, cooling and thermal energy, respectively. d^{e} is electricity demand, d^{c} is cooling demand and d^{h} is thermal demand.

2.2. IEU Model

The IEU is different from traditional electrical energy users. The energy consumption pattern is more complicated, and it requires the supply of multiple types of energy (cooling/thermal/electricity). From the perspective of the IEU's own interests, on the premise of ensuring satisfaction with energy consumption, energy prices will affect the IEUs' initiative to adjust their energy consumption strategy to minimize energy costs [20].

The implementation of price incentive strategy enables IEUs to maximize the satisfaction of energy consumption. A quadratic function U_{n}^{IEU} is used to represent the consumption satisfaction of IEUs. The quadratic utility function U_{n}^{IEU} is described as Equation (5) [21].

$$U_{n}^{\mathrm{IEU}} = \left[v_{n}^{e}d_{n}^{e} - \frac{u_{n}^{e}}{2}\left(d_{n}^{e}\right)^{2}\right] + \left[v_{n}^{c}d_{n}^{c} - \frac{u_{n}^{c}}{2}\left(d_{n}^{c}\right)^{2}\right] + \left[v_{n}^{h}d_{n}^{h} - \frac{u_{n}^{h}}{2}\left(d_{n}^{h}\right)^{2}\right] \tag{5}$$

where v_n^e and u_n^e are the constant coefficients of preference of IEU n concerning electricity, v_n^c and u_n^c are the constant coefficients of preference of IEU n regarding cooling and v_n^c and u_n^c are the constant coefficients of preference of IEU n in terms of thermal energy, which are used to describe the relationship between utility function and demand. d_n^e is the electricity demand of IEU n, d_n^c is the cooling demand of IEU n and d_n^h is the thermal demand of IEU n.

Each IEU determines the demand for electricity supply, cooling supply and thermal supply based on unit electricity price p^e, unit cooling price p^c and unit thermal price p^h. For IEUs, the consumption function C_n^{IEU} of purchasing energy is described as Equation (6).

$$C_n^{\text{IEU}} = p^e d_n^e + p^c d_n^c + p^h d_n^h \tag{6}$$

The objective function of IEUs, W_n, is defined as the difference between the consumption function and the quadratic utility function.

$$\min W_n = C_n^{\text{IEU}} - U_n^{\text{IEU}} \tag{7}$$

Calculating the first-order partial derivative of W_n, the optimal demand of IEU is obtained as Equation (8).

$$\begin{cases} d_n^e = \frac{v_n^e}{u_n^e} - \frac{1}{u_n^e} p^e \\ d_n^c = \frac{v_n^c}{u_n^c} - \frac{1}{u_n^c} p^c \\ d_n^h = \frac{v_n^h}{u_n^h} - \frac{1}{u_n^h} p^h \end{cases} \tag{8}$$

$$\text{s.t.} \begin{cases} d_n^e \geqslant d_{n,f}^e \\ d_n^c \geqslant d_{n,f}^c \\ d_n^h \geqslant d_{n,f}^h \end{cases} \tag{9}$$

where $d_{n,f}^e$, $d_{n,f}^c$ and $d_{n,f}^h$ are the user's base load on electricity, cooling and thermal energy, respectively.

3. Stackelberg Game Model

In the process of solving the Stackelberg equilibrium solution, the game subjects restrict each other to coordinate the equilibrium state of the Stackelberg game model. When IES evaluates the original integrated energy price, the base energy demand of the IEU in each time period is fully considered. Energy prices are updated continuously until the supply and the demand are balanced. The i-th integrated energy price is updated as Equation (10).

$$\begin{cases} p_{i+1}^e = \max\{p_i^e + \tau_i^e \left[(1+\alpha^e) \sum\limits_{n=1}^{N} d_{n,i}^e - O_i^e \right], p_{min}^e\} \\ p_{i+1}^c = p_i^c + \tau_i^c \left[(1+\alpha^c) \sum\limits_{n=1}^{N} d_{n,i}^c - O_i^c \right] \\ p_{i+1}^h = p_i^h + \tau_i^h \left[\left(1+\alpha^h\right) \sum\limits_{n=1}^{N} d_{n,i}^h - O_i^h \right] \end{cases} \tag{10}$$

where p_{min}^e is the IEU's willingness price of electricity, and ${\tau_i}^e$, ${\tau_i}^c$ and ${\tau_i}^h$ are the dynamic speed adjustment parameters of electricity price, cooling price and thermal price, respectively. N is the number of IEUs. $d_{n,i}^c$, $d_{n,i}^e$ and $d_{n,i}^h$ are the cooling demand, electricity demand and thermal demand of IEU n in the i-th update, respectively. O_i^c, O_i^e and O_i^h are the cooling output, electricity output and thermal output of the integrated energy system in the i-th update, respectively. p_i^c, p_i^e and p_i^h are the unit cooling price, unit electricity price and unit thermal price of the integrated energy system in the i-th update, respectively. p_{i+1}^c, p_{i+1}^e and

p^h_{i+1} are the unit cooling price, unit electricity price and unit thermal price of the integrated energy system in the i + 1-th update, respectively.

Dynamic speed adjustment parameters related to the current number of iterations are used as Equation (11) [21] to improve the convergence speed of the algorithm.

$$\begin{cases} \tau_i^e = \frac{1}{\lambda^e + \mu^e i} \\ \tau_i^c = \frac{1}{\lambda^c + \mu^c i} \\ \tau_i^h = \frac{1}{\lambda^h + \mu^h i} \end{cases} \tag{11}$$

where λ^e, μ^e, λ^c, μ^c, λ^h and μ^h are constants.

3.1. Equilibrium Existence in Stackelberg Game

In a multi-subject strategic game, if the utility function of each participant is continuous, and the utility function of its own strategy is quasi-concave, then the Nash equilibrium of pure strategy must exist [22].

The utility function of the IEU is continuous. There is an optimal response strategy for the utility function of IEU $U_n^{\text{IEU}}(p_n^e, p_n^c, p_n^h)$, if the unit electricity price p_n^e, the unit cooling price p_n^c and the unit thermal price p_n^h are satisfied (Equation (12)).

$$U_n^{\text{IEU}}(p^{e*}, p^{c*}, p^{h*}) \geqslant U_n^{\text{IEU}}(p^e, p^c, p^h), \forall p^e, p^c, p^h \in R^+ \tag{12}$$

where U_n^{IEU} is the quadratic utility function value of IEU n. p_n^c, p_n^e and p_n^h are the unit cooling price, unit electricity price and unit thermal price of IEU n, respectively. p^{e*}, p^{c*} and p^{h*} are the target unit electricity price, cooling price and thermal price, respectively.

The Hessian matrix of $U_n^{\text{IEU}}(p^e, p^c, p^h)$ is as in Equation (13).

$$\nabla^2_{p^e,p^c,p^h}(U^{\text{IEU}}) = diag\begin{bmatrix} \frac{\partial^2 U_n^{\text{IEU}}}{\partial p_n^{e2}} & \frac{\partial^2 U_n^{\text{IEU}}}{\partial p_n^e \partial p_n^c} & \frac{\partial^2 U_n^{\text{IEU}}}{\partial p_n^e \partial p_n^h} \\ \frac{\partial^2 U_n^{\text{IEU}}}{\partial p_n^c \partial p_n^e} & \frac{\partial^2 U_n^{\text{IEU}}}{\partial p_n^{c2}} & \frac{\partial^2 U_n^{\text{IEU}}}{\partial p_n^c \partial p_n^h} \\ \frac{\partial^2 U_n^{\text{IEU}}}{\partial p_n^h \partial p_n^e} & \frac{\partial^2 U_n^{\text{IEU}}}{\partial p_n^h \partial p_n^c} & \frac{\partial^2 U_n^{\text{IEU}}}{\partial p_n^{h2}} \end{bmatrix}_{n=1}^{N} \tag{13}$$

Then,

$$\nabla^2_{p^e,p^c,p^h}(U^{\text{IEU}}) = diag\begin{bmatrix} -u_n^e & 0 & 0 \\ 0 & -u_n^c & 0 \\ 0 & 0 & -u_n^h \end{bmatrix}_{n=1}^{N} \tag{14}$$

According to Equation (14), the Hessian matrix of utility function is a negative definite matrix; that is, the utility function of IEU is strictly a concave function of p_n^e, p_n^c and p_n^h. Therefore, the equilibrium solution of the Stackelberg game model exists.

3.2. Algorithm Flow

Under the constraints of price and renewable energy output, IES maximizes the profit by adjusting the power supply of the grid, the renewable energy output, the gas volume of the gas turbine and the waste heat boiler. The energy demand of IEU adjusts the overall energy price. A genetic algorithm (GA) was used to solve the game model. The number of populations is set to 10, the maximum number of iterations is 5000, the crossover rate between chromosomes is 60% and the random mutation rate is 1% to prevent the model from falling into a local optimum solution. The game model updates the next integrated energy unit price based on the difference in the integrated energy price for each iteration, and accelerates convergence through dynamic speed adjustment parameters related to the number of iterations. According to the existence of the Nash equilibrium solution, there is a solution balance the integrated energy demand and supply, and the corresponding unit price of the integrated energy is the transaction price at that moment.

Based on the above process, the algorithm flowchart of the Stackelberg game model is shown in Figure 3.

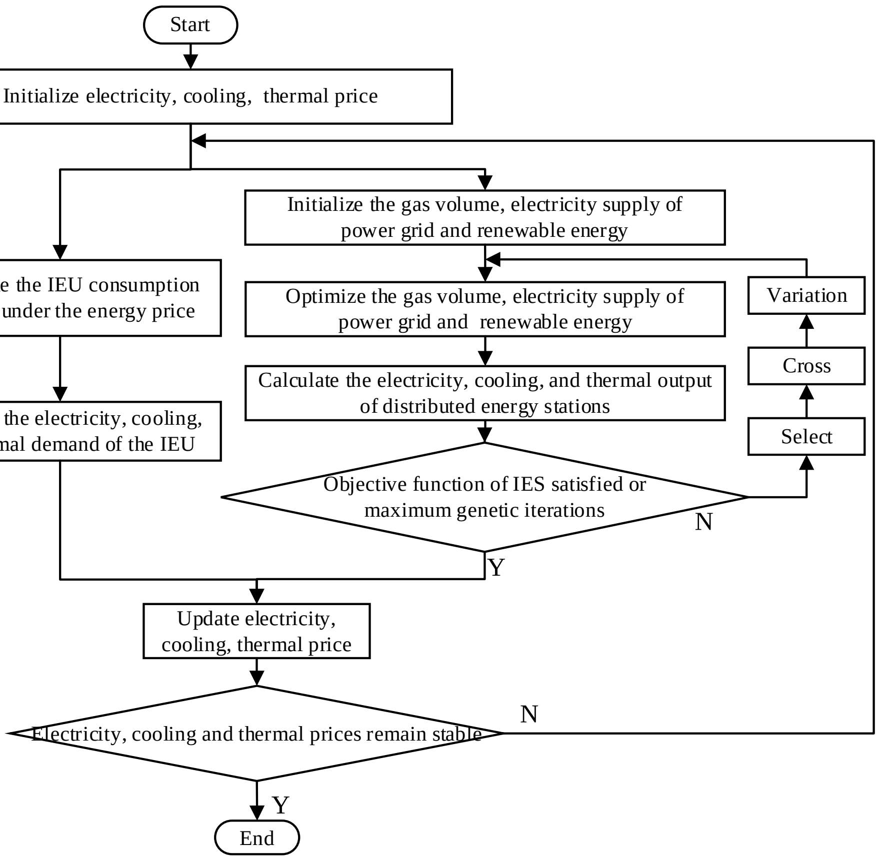


Figure 3. Flowchart of decision model of IES.

The unit prices are initialized randomly before the game begins. IEU balances consumption behavior based on the base load in various time periods and different preferences of integrated energy. For IES, the output of renewable energy is uncertain and fluctuating, so it is assumed that the power supply of power grid and the gas supply of the gas supply system are sufficient to satisfy the energy demand of the IEU at any time. IES iterates on the target of profit after each price adjustment.

In order to verify the correctness and effectiveness of the model and algorithm proposed in this paper, 200 IEUs were set for simulation analysis on a typical day with a unit operation period of 1 h. We analyzed the changes in energy trading volume and price after the game model reaches the Nash equilibrium considering the IEU's energy consumption behavior.

4. Case Study

4.1. Case Data

For the renewable energy system, the IES has a 150 kW wind farm and a 50 kW photovoltaic farm as electricity supply. Assuming the system has sufficient capacity, the renewable energy output is shown in Figure 4.

The main types and efficiency parameters of the production equipment of the integrated energy system are shown in Table 1.

The energy distribution coefficient, cost coefficient of equipment, loss coefficient in the process of energy transmission and user preference constant for integrated energy are shown in Table 2 [21].

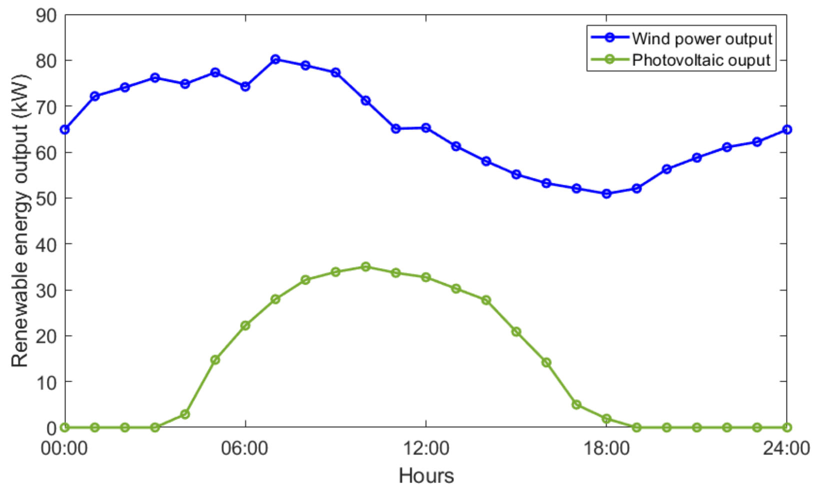


Figure 4. Hourly power output curve of the wind and photovoltaic farms on a typical day.

Table 1. Experimental data classification of cooling, thermal and electricity-generating units.

Equipment	Parameter	Value
Gas turbine	Capacity /kW Electricity generation efficiency η_{GT}^{e} Heat production efficiency η_{GT}^{h}	400 0.35 0.5
Waste heat boiler	Capacity /kW Boiler steam efficiency η_{HR}^{s} Heat production efficiency η_{HR}^{s}	200 0.1 0.7
Steam turbine	Capacity /kW Electricity generation efficiency η_{ST}^{e} Heat production efficiency η_{ST}^{h}	160 0.42 0.38
Heat transfer machine	Capacity /kW Heat production efficiency η_{HE}	300 0.8
Absorption refrigerator	Capacity /kW Cooling efficiency η_{AB}^{c}	100 1.3
Electric heating equipment	Capacity /kW Heat production efficiency η_{HE}^{h}	250 0.8
Electric refrigeration equipment	Capacity /kW Cooling efficiency η_{FR}^{c}	200 4

Table 2. Loss, cost and preference coefficients.

α_{H}^{c}	0.15	c^{g}	0.18	α^{e}	0.04	λ^{e}	0.05	v_{e}	0.05
α_{H}^{h}	0.85	c^{re}	0.05	α^{c}	0.08	λ^{c}	0.04	v_{c}	0.03
α_{E}^{c}	0.5	c^{gr}	0.25	α^{h}	0.06	λ^{h}	0.03	v_{h}	0.04
α_{E}^{h}	0.5	f^{g}	10	-	-	μ^{e}	4	u_{e}	4
α_{E}^{e}	0.9	f^{re}	2	-	-	μ^{c}	4	u_{c}	4
α_{E}^{ch}	0.1	f^{gr}	5	-	-	μ^{h}	4	u_{h}	4

Figure 5 is the base load of the IEU for electrical/cooling/thermal energy on a typical day. During the day, the IEU has a high demand for electricity between 9:00 and 18:00, and the demand for electricity peaks at 12:00. Cooling/thermal demands of IEU rise from 6:00 to 12:00 and stabilize after 12:00. The demand for the thermal load decreases after 19:00 and the demand for the cooling load declines after 22:00.

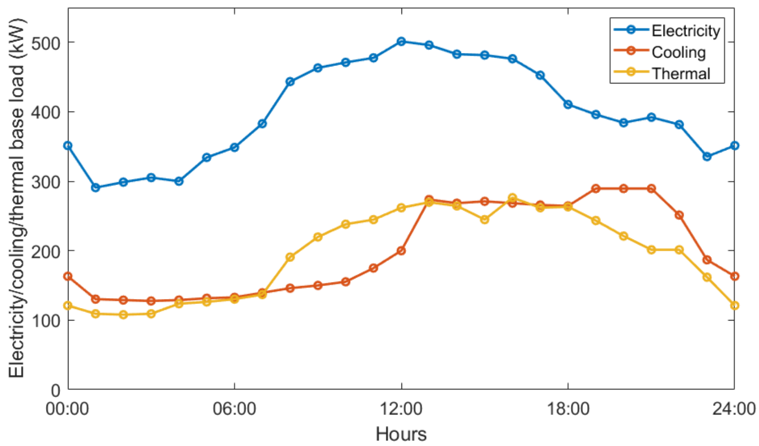


Figure 5. Hourly base load curves of IEU on a typical day.

4.2. Result Analysis in the Case of IES Maximizing Profit

From the perspective of the power grid, during the peak period of the electrical demand of the IEU, the power output of renewable energy is constrained by the equipment itself, and cannot fully satisfy the demand of the IEU. The shortage of power can be supplemented by the power grid.

The cooling/thermal demand of the IEU is mainly a transferable load in the valley period, and the electric refrigeration equipment and electric heating equipment with electric energy as input can dynamically adjust the input gas turbine and waste heat for part of the cooling/thermal demand of the IEU. The natural gas volume in the boiler is adjusted. Figure 6 shows the natural gas volume input into the gas turbine and waste heat boiler.

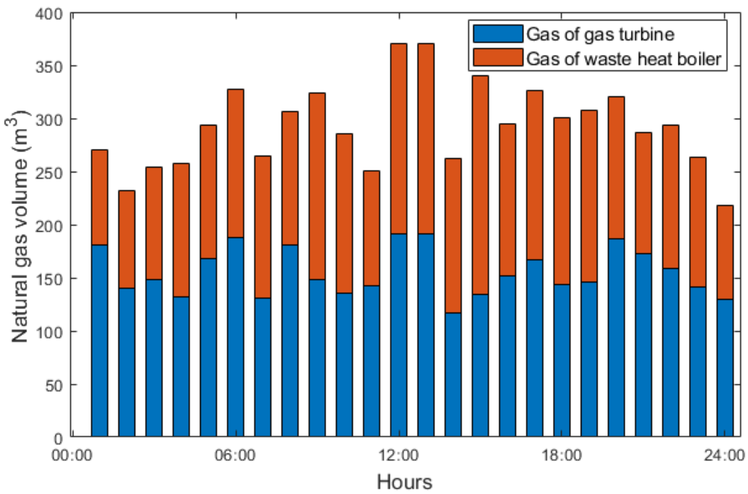


Figure 6. Hourly gas input volume of IES.

After considering the balance of the game model of the demand-side response, the energy use of the integrated energy system appears in the form of complementary mutually beneficial. The cost of renewable energy generation is extremely low, and the supply of energy is preferentially based on renewable energy. For the insufficient demand, when the electricity price is high, natural gas is used first, and the power grid is used for power supply assistance. When the electricity price is low, the power grid is used first, and natural gas is used for assistance.

In the process of energy supply, IES's energy input and output are always in a dynamic balance. Figure 7 shows the amount of interactive energy in the integrated energy system in a game.

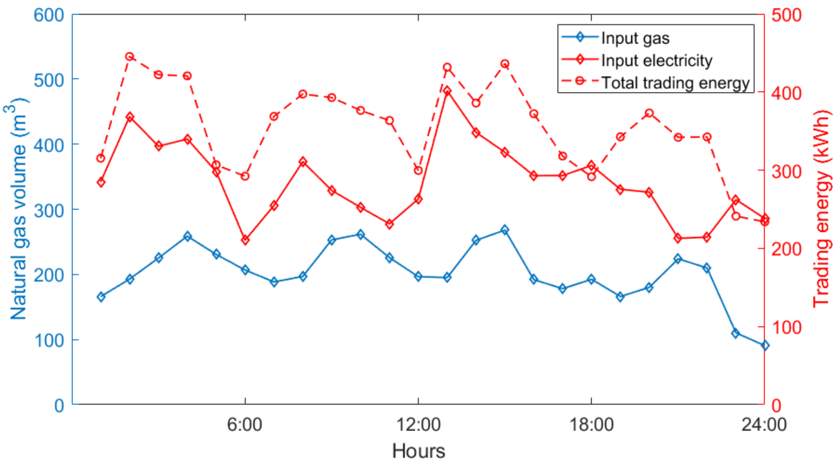
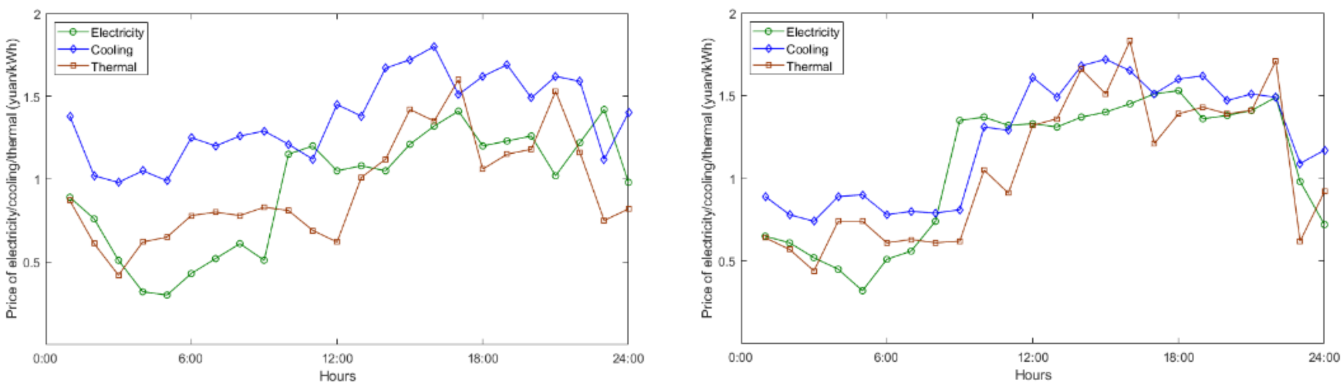


Figure 7. Input and output volume of the integrated energy system in a game.

As energy prices continue to adjust, the IEU responds optimally with the goal of maximizing the utility function, thereby determining the amount of energy demand. IES formulates time-of-use pricing of integrated energy for maximum profit. The unit-integrated energy price changes before and after the game equilibrium are shown in Figure 8.

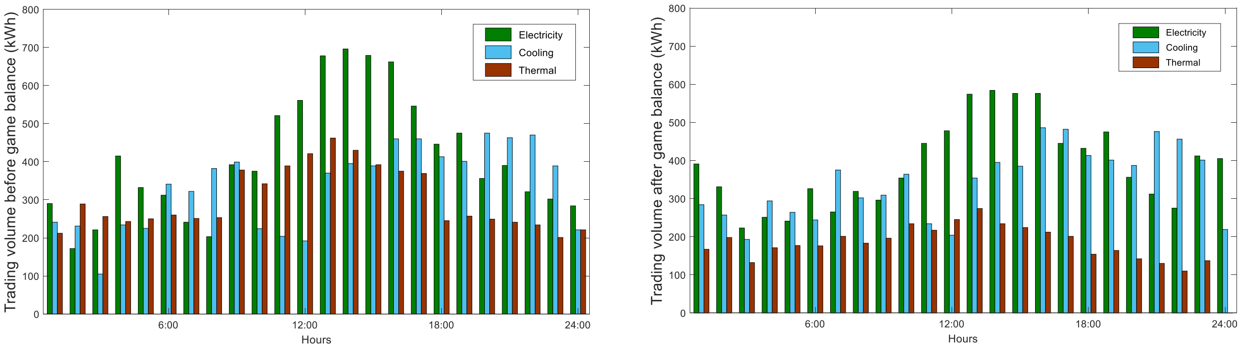


(**a**) (**b**)

Figure 8. Comparison of optimal unit electricity/cooling/thermal price before and after Nash equilibrium. (**a**) Optimal unit electricity/cooling/thermal price before Nash equilibrium. (**b**) Optimal unit electricity/cooling/thermal price after Nash equilibrium.

The IEU has a small demand for energy from 0:00 to 8:00, and the overall unit energy price is lower. The IEU's base load grows from 6:00 to 12:00. The IES maximizes profit by satisfying IEU's consumer demand satisfaction and increasing unit energy prices. During the period from 12:00 to 22:00, the IEU's energy demand is high, and IES maintains the balance between supply and demand by maintaining a high overall unit energy price during that period to maximize profit. During the period from 22:00 to 24:00, the IEU's base load gradually decreases, while the unit price of integrated energy gradually decreases and stabilizes. After the game reaches equilibrium, the unit-integrated energy price during the peak period of IEU demand rises, and the unit-integrated energy price during the low period of IEU demand declines.

Considering the demand for integrated energy and the base load of IEU in different time periods, IES adopts the strategy of time-of-use pricing to maximize profit. Figure 9 shows the integrated energy volume on a typical day before and after the game equilibrium.



(**a**) (**b**)

Figure 9. Comparison of integrated energy trading volume before and after Nash equilibrium. (**a**) Integrated energy trading volume before Nash equilibrium. (**b**) Integrated energy trading volume after Nash equilibrium.

In this case, the IEU's demand for electrical load is mainly concentrated in the period from 12:00 to 22:00. Due to the formulation of the time-of-use electricity price, the IEU changes the electricity demand of the low valley period, and the electricity volume decreases during the peak demand period.

The IEU's demand for thermal energy and cooling is mainly distributed between 11:00 and 24:00. During this period, the trading price of cooling/thermal energy has little fluctuation, and both sides of the game need to trade as much cooling/thermal energy as possible to balance the supply and demand. The IEU's cooling/thermal demand declines during the 0:00–11:00 time period, and the total trading volume of cooling/thermal energy also declines.

After the game balance, due to the low-price strategy incentives during the low demand period and the high price strategy during the peak demand period, on a typical day, the energy volume curves of IES and IEU are relatively smoother than before the game balance. After the game reached equilibrium, the peak-to-valley difference between electricity volume decreased by 44.3%, the peak-to-valley difference between cooling volume decreased by 36.9% and the peak-to-valley difference between thermal volume decreased by 49.5%, effectively achieving peak shaving and valley filling so that the energy supply in each period tends to be balanced.

In order to verify the impact of IEU's demand on economic benefits, the profits are compared before and after game equilibrium. Figure 10 is the hourly profit of IES in a typical day. Figure 11 is the hourly consumption of IEU in a typical day.

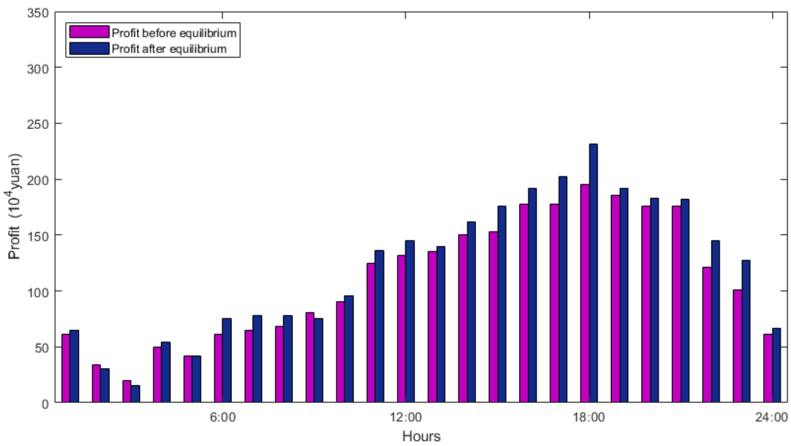


Figure 10. Comparison of IES profit before and after equilibrium in a typical day.

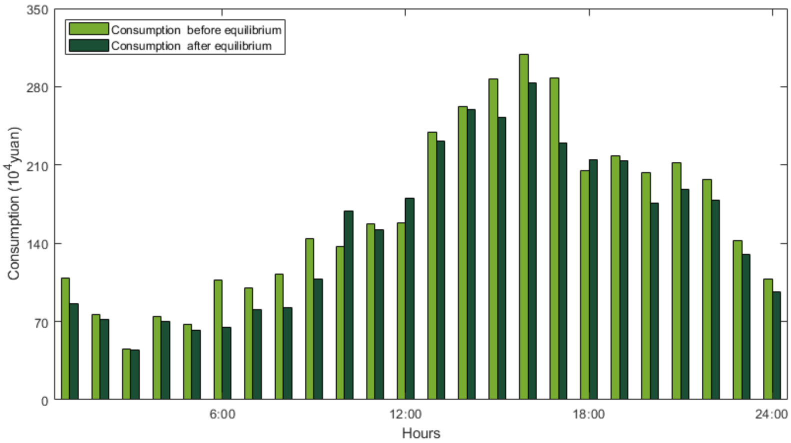


Figure 11. Comparison of IEU consumption before and after equilibrium in a typical day.

Before and after the game equilibrium considering IEU's behavior, and on the premise of meeting the IEU's energy demand, by implementing the time-of-use pricing strategy, IES improves the profit by 8.9% while smoothing the load distribution. IEUs reduce consumption by 11.4% while guaranteeing their own satisfaction.

4.3. Result Analysis in the Case of IES Target Profit

When the objective function of the integrated energy system is different, the equilibrium state of the game model will change. At the beginning of the game, the IES in the multi-subject game can also enlarge the market by reducing the unit energy price to gain a greater share in the market. At this time, the IES strategic objectives have changed, from maximizing profit to acquiring target profit to maintain daily operations. If the maximum daily target profit is set to 10 million yuan, Figure 12a,b show the changes in unit-integrated energy prices before and after the Nash equilibrium.

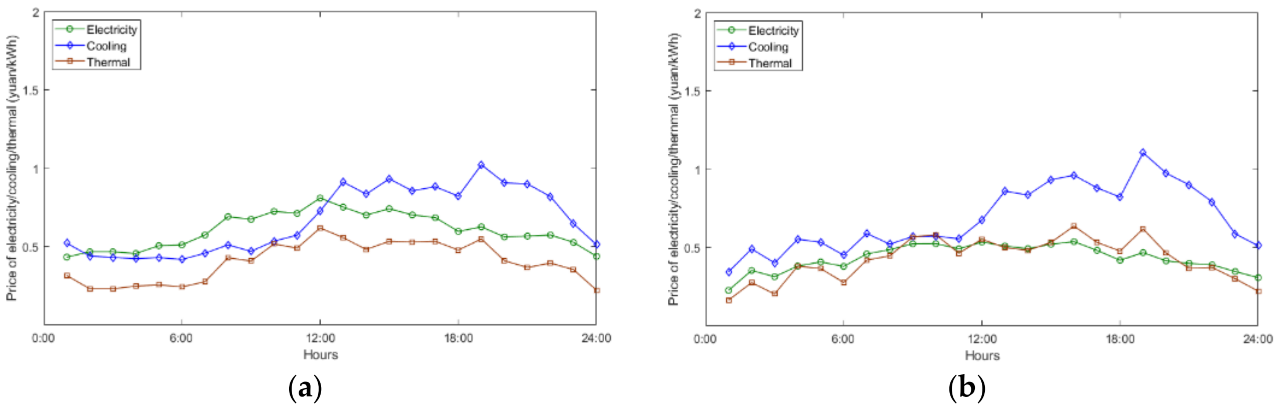


Figure 12. Comparison of optimal unit electricity/cold/thermal prices in the case of IES target profit. (**a**) Optimal unit electricity/cold/thermal prices before Nash equilibrium. (**b**) Optimal unit electricity/cold/thermal prices after Nash equilibrium.

After the game balance, the unit price of electric energy decreases, and the unit prices of cooling energy and thermal energy basically remain unchanged. There are two ways for IES to control profit by adjusting the integrated energy price, raising the integrated energy price or reducing it. For IEU, the decline in unit-integrated energy price means that more integrated energy can be traded at the same price. The increase in integrated energy trading volume helps IES to enlarge the market. Changes in integrated energy trading volume before and after the game balance are shown in Figure 13a,b.

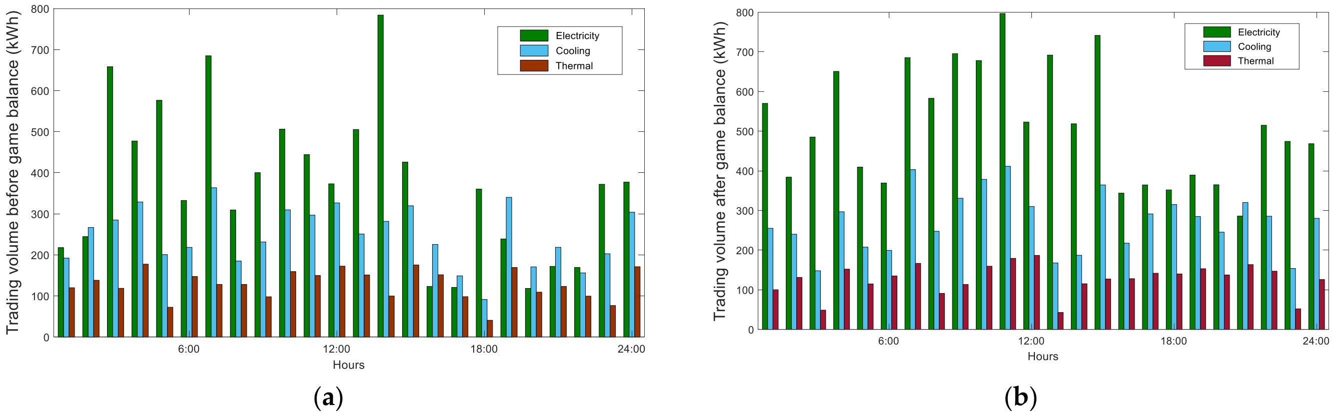


Figure 13. Comparison of integrated energy trading volume before and after Nash equilibrium. (**a**) Integrated energy trading volume before Nash equilibrium. (**b**) Integrated energy trading volume after Nash equilibrium.

IES reduces prices appropriately to increase integrated energy trading volume. After the game balance, the trading volume of electricity increased by 37.04%, the trading volume of cooling increased by 10.65% and the trading volume of thermal energy decreased by 0.6%. The price of electricity has a large reduction, the IEU's demand for electricity increased and more electricity was purchased in the interaction with IES. The prices of cooling and thermal have little changes, and the IEU only makes appropriate adjustments according to the corresponding prices and demand. After the game reached balance, the peak-to-valley difference between electricity volume decreased by 23.45%, the peak-to-valley difference between cooling volume decreased by 3.9% and the peak-to-valley difference between thermal volume decreased by 7.1%. The peak sharing and valley filling are not as effective as the strategy under the objective of maximizing profit, but they also have a certain effect.

The profit function of IES and the consumption function of IEU before and after the game balance are shown in Figures 14 and 15.

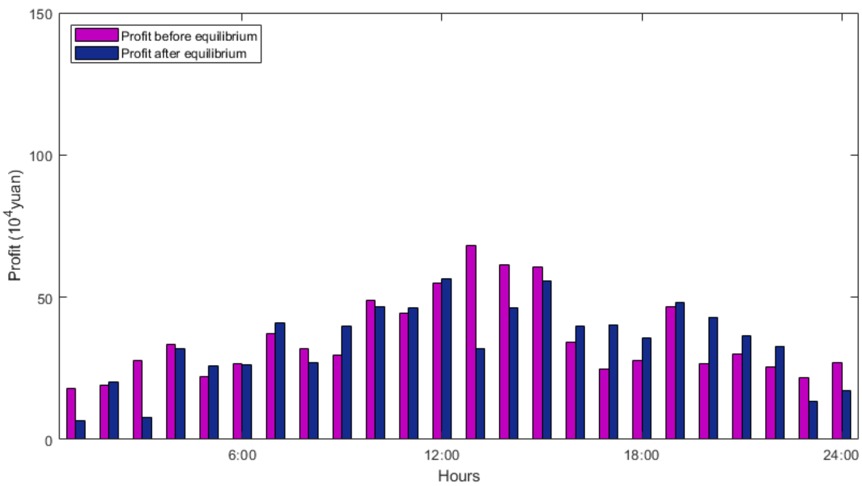


Figure 14. Comparison of IES profit before and after equilibrium.

While IES expanded the energy trading volume, the profit decreased by 3.5%. In the case of IES fixing the profit and reducing the price, IEUs reduce consumption by 17.5%.

The main purpose of the IES controlling profit is to expand the trading volume of integrated energy and become the target of energy purchase priority for users in the game. As the final trading volume is difficult to determine directly, IES participates in the game by controlling the target profit. Finally, the unit price of integrated energy decreased in each time period. Due to the target profit, the unit price of integrated energy and the trading volume mainly showed a negative correlation. Part of the trading volume of the integrated energy in the peak time period shifts to the valley time period.

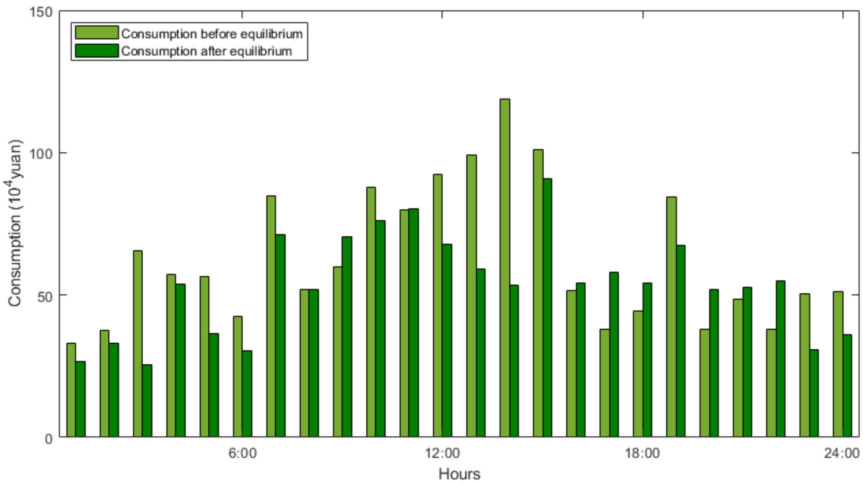


Figure 15. Comparison of IEU consumption before and after equilibrium.

Comparing Figures 8 and 9 with Figures 12 and 13, the unit electricity price, unit cooling price and unit thermal price after game balance under the objective of target profit are reduced by 58.54%, 46.37% and 60.09%, respectively, and the total energy trading volume is increased by 32.06% compared with the objective of maximum profit. It is obvious that the energy price of the game strategy aimed at maximizing profit is significantly higher than that of the game strategy aimed at target profit, and the energy trading volume is also significantly lower than the latter. It can be concluded that the IES with target profit as objective function of the game strategy can enlarge the market by limiting its own profit, and can obtain the purchase willingness of IEUs by reducing the energy price, so that it can have a larger market share, ensure its participation in market transactions for a long time and ensure reliable profit.

5. Conclusions

We analyzed and modeled the game linkage between IES and IEU, which are the participants in the integrated energy market, and constructed the objective functions with maximum profit and target profit of IES. It is proved that the equilibrium solution of the established game model exists in the process of multi-agent participation. Finally, the time-of-use pricing strategy is solved for different time periods under two different objective profits. Integrated energy trading volume and pricing curves are obtained under the two different profit objectives. According to the comparison and analysis of the game strategies under the two different objectives, several conclusions can be drawn.

(1) IES and IEU are linked by participating in the game. Typical energy equipment is used as the basic unit, and the energy input/output model of the IES is established. The time-of-use pricing strategy is the IES's strategy, and the objective function is to maximize its own profit. When the game reaches the Nash equilibrium, IES's operating profit significantly increases.
(2) As the main body of energy consumption, consumption function and utility function of IEU are considered to establish the IEU model. While satisfying the utility function, the IEU influences the time-of-use pricing strategy of IES by changing its own energy consumption behavior. When the game reaches the Nash equilibrium, the utility function of the IEU is satisfied and the consumption is reduced.
(3) Under the two objectives, the peak and valley difference in the electricity/cooling/thermal trading volume after the game balance decreased by 30–50%. It can be concluded

that time-of-use pricing will reduce peak load and fill valley load, smooth the load distribution and improve the stability of IES's energy supply.

(4) The game strategy aiming at target profit has a larger market share and user audience, and it has the potential to participate in the market operation for a long time and obtain reliable profit. The case results show that the energy trading volume of the game strategy with target profit is about 32.06% higher than that of the strategy with the maximum profit, and the pricing is also 54% lower than the latter. The IES can fix its own profit to improve market competitiveness.

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