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A novel alternative energy trading mechanism for different users considering value-added service and price competition

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ABSTRACT

In the context of integrated energy substitution and retail side liberalization, we develop a novel alternative energy trading mechanism in the presence of price competition and value-added service to study the purchase and sale strategies for integrated energy retailers. Under the mechanism, the retailer first joins a second-price sealed auction to make an optimal electricity purchase. If the retailer's purchase bid fails, the retailer procures natural gas from a natural gas company to generate electricity. The retailer then sells the electricity to different users who buy according to their own types, which is modeled a leader–follower game for multiple retailers and classified users. Using a computational data, we design a distributed algorithm to solve the leader–follower game. The simulation results verify the convergence of proposed algorithm. Moreover, our sensitivity analysis indicates that the natural gas distribution rate and its conversion rate with respect to electricity are important to the power retailer's profit in terms of energy loss rate and capacity rate. Compared with the non-demand response model, the novel alternative energy trading mechanism can help the power retailer reduce peaks and fill valleys to a certain extent, achieving an effective system balance of energy distribution and maximizing the power retailer's profit and users' utilities.

1. Introduction

Nowadays, building an environmentally friendly society is of great significance (Sun and Li 2021). In the past years, the research issues regarding the electricity market mainly focused on the power generation side. As a result of electricity market reform, the power production and operation begin to possess new characteristics, breaking the traditional vertically-integrated production-marketing system and carrying out the sustainable production and consumption (Guo et al. 2020). Especially, in the power generation process, the plant-grid separation system has made the traditional operation mode of plant-grid integration invalid. As an intermediary between power plants and users, the power retailers can resell to users the electricity purchased from power plants. Thus, the transform has changed the situation of power plants selling electricity directly to users, which separates power production from marketing. Then the research focus of electricity market has gradually transferred from the generation side to the retail side (Sun et al. 2016). Moreover, with new clean energy in, the electricity sources tend to be diversified (Yuan et al. 2021; Tao et al. 2019). In this case, the power retailers may compensate the lack of electricity procurement by purchasing other clean energy for environmental protection and sustainable development. On the other hand, the opening of electricity market means that the users have more independent options (Banshwar et al. 2018). Therefore, it is necessary to consider the users' utility and the influence of their options on the power retailers, which leads to an increasing competition among power retailers in power market. The competition includes not only retail price competition, but also non-price competition caused by providing service support mainly embodied in value-added service (Wang et al. 2017) and differentiated service.

At present, due to the substitution of different energy sources, the value-added service providers cannot deliver a single energy service only. To offer differentiated services, the firms categorize users into several groups according to their demands and preferences, and then provide different types of electricity plans and pricing schemes. A real example is about the E.ON (https://www.finder.com/uk/energy/eon), a subsidiary of German energy giant E.ON SE, which commits to supplying 5 million UK household and business customers with electricity from 100 % renewable sources. The power company not only sells electricity, purchases energy products from water and natural gas companies, but

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Nomenclature

Index

j	Number of power retailers
i	Type of different users
t	Number of time slots

Parameters Bidding for Electricity

v^*	Electricity purchase price of power retailers(yuan/MW)
v_j	Electricity purchase valuation of power retailer j (yuan/MW)
b_j	Electricity purchase quotation of power retailer j (yuan/MW)
B_1, B_2	Lower and upper limits of uniform distribution of the power retailers' valuation
P_{si}	Electricity powers' compensation for the shortage of users of three types in the failure of bidding (yuan/MW)
p_j	Probability of higher quotes from power retailer j
θ_j	Probability of power retailer j winning the bidding
$E(b_j)$	Expected profit of power retailer j to bid

Interruptible Tariff

δ	Probability of users performing interruption contracts
ΔQ	Interrupt quantity (MW)
$\Delta Q_{\max}, \Delta Q_{\min}$	Upper and lower limits of the interrupt quantity (MW)
P_{comp}	Interruption compensation price (yuan/MW)
R_c	Default compensation(yuan/MW)

High Reliable Pricing

β	Reliability
φ	Compensation coefficient

Natural Gas

α_i	Distribution ratio of natural gas replacement load
G^{in}	Amount of natural gas(kg)
$G^{in}_{\max}$	Upper limit of natural gas usage(kg)
α	Proportion of natural gas entering into micro turbine
η^e	Efficiency of natural gas transforming into electricity when passing through the micro turbine
ρ	Natural gas quality of one cubic meter under standard atmospheric pressure($\mathrm{MJ/m^3}$)
Q_{gas}	Load of natural gas power generation substitution(MW)
P_{gas}	Natural gas price(yuan/kg)
Δt	Unit time(h)

Electricity Service:

e_j	Cost coefficient of power service qualityinvestment
k_j	Level of power service quality investment
$G(k_j)$	Service cost of power retailer j

Social Welfare of Users:

$x_{ij}^{\max}, x_{ij}^{\min}$	Upper and lower limits of x_{ij}(MW)
ω_i	Variable parameter related to user types
γ	Predefined parameter

Iterative Step:

μ_j	Price adjustment step of power retailer j

Decision Variables

p_{ij}	Interruption tariff($i = 1$), high reliability price($i = 2$) and step tariff($i = 3$) formulated by power retailer j (yuan/MW)
x_{ij}	Electricity amount purchased by the users of three types from power retailer j for the implementation of interruption tariff($i = 1$), high reliability price($i = 2$) and step tariff($i = 3$)
Q_{ij}	Electricity purchased by class i from power retailer j
$E(C_j)$	Expected cost of electricity purchase of power retailer j
$E(R_j)$	Expected revenue of power retailer j
W_j	Profit of an integrated power retailer j
$\boldsymbol{x}_j^*$	Optimal resolution of user social welfare of power retailer j (MW)
$\boldsymbol{p}_j^*$	Optimal pricing strategies of power retailer j (yuan/MW)
u_{ij}	Utility of class i user purchasing electricity from power retailer j
U_{ij}	Social welfare function of class i user when purchasing electricity from the power retailer j
x_{ij}^*	Optimal solution of purchase electricity amount(MW)

Abbreviation

HR	Heat Rate
SI	International Unit Symbol
LHV	Lower Heating Value
CRECS	China's Residential Energy Consumption Survey
DR	Demand Response

also designs different collocation packages or discount schemes to attract users. For example, the authentic power generation and demand data from Texas in 2010 includes the power generation data from 144 conventional power plants and projected solar capacity from 79 weather observatories. The power retailers maximize their profits under different pricing policies by choosing renewable or conventional energy investment levels (Kök et al. 2018). In addition, the power retailers bid in the Eastern Denmark market region of NordPool, the Scandinavian power exchange, and participate in the electricity market with flexible demand (https://energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx).

Thus, there is a natural question about the power retailers' decision behaviors in the power market: How do the power retailers purchase different forms of energy sources? How to meet the demands of different types of users? Different purchase and sale behaviors may affect the integration and efficiency of power supply chain as well as the utilities of all power market participants.

Extant publications do not consider such electricity purchase and sale behaviors of power retailers. Therefore, we expect to contribute to the literature by analyzing energy-source purchases and sale strategies of power retailers for different types of users. The electricity purchase and sale strategies of power retailers fall into two stages. In the first stage, the integrated power retailers (can purchase different types of energy) obtain the optimal electricity purchase by participating in the second-price sealed auction, but when their bids fail, the power retailer can procure natural gas from the natural gas company and generate electricity. In the second stage, the power retailers resell the electricity to classified users considering price competition and value-added service. Then a leader–follower game is developed to describe the strategic interaction between multiple power retailers and multiple classified users, which is characterized by using the concept of Stackelberg equilibrium.

In fact, energy such as natural gas has become a necessary energy procurement supplement for power retailers, which enables the power retailers to choose more flexible power procurement channels. We design a two-price sealed auction power procurement mechanism supplemented by the purchase of natural gas to meet the users' energy demands. We also analyze the electricity retail decision for power retailers in the presence of price competition and added-value services. To our knowledge, the existing publications that jointly considered both power retailers' price competition and value-added services for different types of users did not contribute to the analysis of the power retail market. Kamyab et al. (2015) and Garcia et al. (2017) constructed non-cooperative game to investigate the interaction between multiple power retailers (who adopt a bidding mechanism to purchase electricity) and multiple users in smart grid, and used a distributed algorithm to solve their game model. Different from our paper, Kamyab et al. (2015) and Garcia et al. (2017) did not categorize the users under different pricing schemes.

The remainder of this paper is organized as follows. Section 2 reviews the relevant papers. Section 3 presents a leader–follower game model. In Section 4, we prove the existence and uniqueness of Stackelberg equilibrium, and also design a distributed algorithm to solve the proposed game model. In Section 5, we evaluate the performance of our approach and conduct a sensitivity analysis with a case study. This paper ends with a summary and concluding remarks of major results in Section 6.

2. Literature reviews

A number of relevant publications are concerned with the strategies of different power market participants and some factors for the outcomes of participants. For power retailers, the key issue is to ensure the stability of electricity sources and sustainable development. The electricity procurement has shown diversification and integration of sources in recent years (Rakipour et al. 2019, Wang et al. 2019), which promotes a new trend in the investment planning of electricity market (Egerer et al. 2021; Karatop et al. 2021). However, the existing works on electricity purchase and sale of integrated energy mainly analyze the interaction among integrated energy system and investment portfolio to the integrated energy, while the impact of integrated energy on the purchase and sale strategy of power retailer mainly focuses on the single influence of electricity purchase or sale strategy (see, e.g., Savelli et al. 2018, Dagoumas et al. 2017; Yoon et al. 2020). Although Luo et al. (2020) proposed an optimal energy schedule model for a three-level integrated energy system with multiple energy suppliers and end users, they focused on the interaction analysis of multiple single type of participants or the coalition of multiple users. As mentioned previously, the diversification of energy sources is bound to bring more choices for users. Therefore, from the user perspective, the establishment of multi-user differentiated pricing schemes according to a specific user demand is worth studying. With the explosive growth of smart grid users, user classification is essential to power grid planning, demand response and load forecasting. The traditional user classification model is based on empirical rules, and the classification results are not accurate, thereby, many researchers have been using a clustering method in data mining technology to classify users (see, e.g., Trotta et al. 2020; Wang et al. 2020). However, their studies did not address how retailers make pricing schemes for multi-class users in order to maximize their profits as well as social welfares.

In turn, the increase of user side research will inevitably affect the purchase and sale strategies of power retailers. The power retailers usually purchase electricity using bilateral contracts with power plants (Gilbert et al. 2015) or bidding (Bobo et al. 2021). The energy price stipulated in the contract market is preset, and the agreed amount of energy is traded at a specified price and designated time (Sheikh et al. 2015). An example of bidding for electricity purchase is from Swider (2020) who calculated the optimal bidding price relative to the given electricity quantity by maximizing the expected profit function. In the electricity retail market, the electricity is sold under the price competition, particularly, in the form of personalized pricing (Elmachtoub et al. 2021, Chen et al. 2020 and Le Cadre et al. 2020). Moreover, an increasing number of studies have begun to address the dynamic and overall analysis for power retailers and their upstream and downstream in a power supply chain. For example, Yu et al. (2016) developed an electricity trading leader–follower game between a power retailer and multiple users, and obtained the optimal power supply of a power retailer and the demand of users. Li et al. (2021) proposed a leader–follower game between the integrated energy operators (IEO) and users, and realized the IEO profit maximization and user cost minimization by transforming the game model to a mixed integer quadratic programming. Different from the above studies, our paper regards electricity purchase and sales as a whole rather than a unilateral analysis on contract or bidding for electricity purchase or price competition for electricity sales.

With the intense competition in electricity retail market, except for price factors, the competitive advantage of power retailers is their customized service or product and service innovation (Downward et al. 2016) based on user demand, which is called value-added service. Compared with the basic business mode of providing electricity services for users, value-added services are more common in practice as today's firms usually do not provide a single service only but offer a variety of services to meet the personalized and diversified demands of users (see, e.g., Banshwar et al. 2018, Boroumand et al. 2019; Mirza et al. 2014). Different from the above relevant publications, our paper is concerned with the combined use of value-added services and the changes in the cost of a power retailer and the user utility resulting from the services.

Based on the above analysis, it seems that the electricity market is changing from centralized energy system to distributed energy grid, from traditional products to service business mode, and the energy efficiency and integration of different energy in integrated energy system have attracted increasing attention. The existing studies on integrated energy of generation side, price competition of retailer side and classification of user side are rarely applied to the analysis on the unified mode of integrated energy scenarios, the purchase and sale strategy of power retailer, and the service as well.

Therefore, our paper will fill the gap by studying the purchase and sale strategy of integrated power retailer, which not only considers the substitution effect of integrated energy and the price and service competition among power retailers, but also takes into account the strategic interaction between the power retailers and classified users, so as to highly consider the impact of user utility and multi-class user differentiated pricing scheme on the electricity purchase and sale strategies of power retailers.

3. Problem description and model formulation

3.1. Electricity purchase and sale mode of integrated power retailers

Fig. 1 shows the electricity purchase and sale mode of integrated power retailers.

Moreover, all nomenclature used in the paper are presented in Nomenclature.

3.1.1. Electricity purchase mode of integrated power retailer

Since Vickrey auction (Cao et al. 2020) promotes the real bidding of power retailers and solves the problem of information asymmetry between the power retailers and power plants, it

is adopted by power retailers to bid for traditional electricity in our paper. Vickrey auction is strategy-proof, that is, all bidders' real bid is a Nash equilibrium (or even dominant equilibrium).

In an electricity purchase bidding involving n risk-neutral power retailers (bidders), the electricity value to the bidders is independent and subject to a uniform distribution on $[B_1, B_2]$ (Tadelis et al. 2013). Let the electricity value to the power retailer j as v_j and to the other

power retailers $h(h \neq j)$ as v_h. The bid of power retailer j and the other power retailers are respectively b_j and $b_h(h \neq j)$, which are also subject to the uniform distribution on $[B_1, B_2]$. The second highest bid is v^* (Tadelis et al. 2013). Next we consider the optimal purchasing

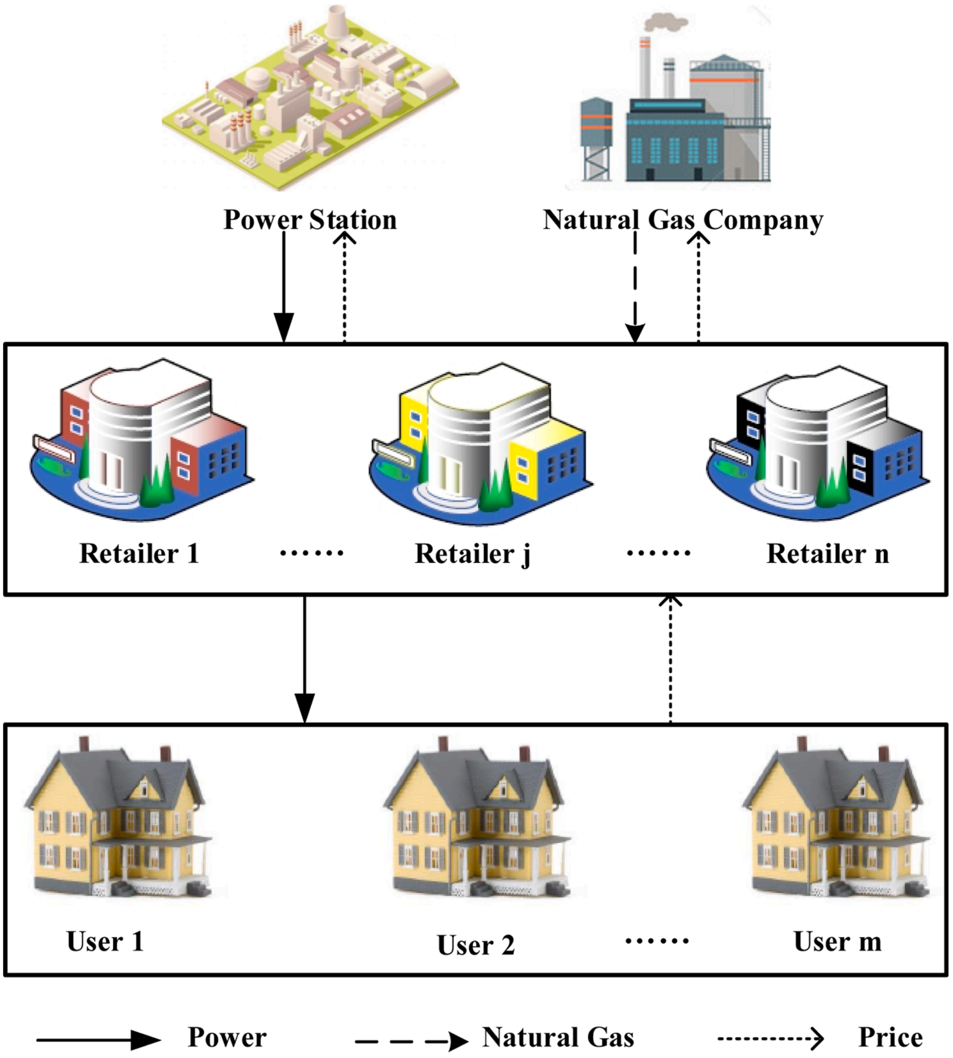

Fig. 1. Electricity purchase and sale structure of integrated power retailers.

strategy of power retailer$j$.

Obviously, when $B_1 > v_j$, power retailer j will lose the bid. The probability that the bid of power retailer h is lower than that of power retailer j is $\Pr(b_h < b_j) = \frac{b_j - B_1}{B_2 - B_1} = p_j,\ h \neq j$. Then power retailer$j$'s winning probability is $\theta_j = \prod_{h \neq j} \Pr(b_h < b_j) = p_j^{n-1}$, the expected revenue of power retailer j is denoted as$E(b_j) = (v_j - v^*)p_j^{n-1} = (v_j - v^*)\left(\frac{b_j - B_1}{B_2 - B_1}\right)^{n-1}$. It can be found that $E(b_j)$ increases with the growth of p_j, and $p_j = (b_j - B_1)/(B_2 - B_1)$ increases with the growth of b_j, then the expected revenue $E(b_j)$ is maximized when $b_j = v_j$. Therefore, when the two-price sealed auction applies to the bidding of power retailers, the optimal electricity purchase strategy of power retailer j is that the electricity purchase bid is equal to the valuation and the transaction price is v^*. The reason for optimal strategy can also be explained theoretically. If other power retailers offer the bids honestly, the bids of these power retailers only determine whether they obtain the electricity, regardless of the prices they actually pay, and lower bids are at risk of losing surplus values while higher bids face the risk of loss. Then in the two-price sealed auction, each power retailer's bid is his own real valuation, which means, the bid is equal to the valuation (Tadelis et al. 2013).

With the diversification of energy sources, the power retailers have more alternative energy procuring options, so when the power retailers fail to bid for traditional electricity, they can make up for the lack of energy by purchasing other substitution energy sources such as natural gas.

3.1.2. *Electricity sale mode of integrated power retailers*

Considering the different electricity consumption characteristics of users, we propose a multi-class user differentiated pricing scheme (Yin et al. 2018, Jahannoosh et al., 2021, Wang et al. 2020). In terms of the price competition among power retailers and the users' choices for power retailers, we take different electricity pricing schemes for three different user types into account. The existing user differentiated pricing schemes usually include interruptible tariff, high reliable pricing and step tariff, which correspond to three user types, respectively. The three pricing schemes are specified as follows:

(1) Interruptible Tariff. There is an interruption contract between power retailers and users. The users can reduce their electricity consumption in a timely and appropriate manner based on the interruption contract in the peak period of electricity consumption. Just as that be listed in following Table 4, the power retailers compensate the users in accordance with a step segment where the interrupted electricity is located. Meanwhile, if the users break the contract, they should also bear the corresponding default compensation.

(2) High Reliable Pricing. Under this scheme, power retailers need to provide electricity to users at an adequate reliability rate. The electricity price increases linearly with the reliability rate. However, if the electricity is unreliable due to some abnormal factors, the power retailers need to pay a high compensation.

(3) Step Tariff. Power retailers determine electricity quantity grades and an electricity price for each grade. For a higher electricity purchase grade, the electricity sale price is higher; see Table 2.

3.2. Formulation of leader–follower game

Under the price competition and multi-user differentiated pricing scheme, the users choose the power retailers to purchase electricity according to the rule of maximizing their own welfares, which affects the power retailers' electricity sales, and then affects the costs and revenues of power retailers. Thereupon, when the power retailers determine their own purchase and sale strategies, naturally, the impact of electricity price on the users is predicted. Conversely, the purchase and sale strategies of power retailers will be constrained by the users' response functions. Based on above analysis, a leader–follower game is developed for the strategic interaction between the power retailers and the users.

3.2.1. User's social welfare function

The quadratic function is often taken as utility function of user (Li et al. 2021, Yuan et al. 2021, Dai et al. 2017), which makes the user utility monotonically increase and the marginal utility gradually decrease with respect to the amount of electricity consumption. It is shown as follows:

$$u_{ij}(x_{ij},\omega_i) = \begin{cases} \omega_i x_{ij} - \dfrac{\gamma}{2}x_{ij}^2 \ , 0\leqslant x_{ij}\leqslant\dfrac{\omega_i}{\gamma}; \\ \dfrac{\omega_i^2}{2\gamma} \ , \ x_{ij}\geqslant\dfrac{\omega_i}{\gamma}. \end{cases} \tag{1}$$

where u_{ij} denotes the utility of class i user purchasing electricity from power retailer j, ω_i is a variable parameter related to user types, and x_{ij} is the electricity amount purchased by the users of three types from power retailer j for the implementation of interruption tariff ($i = 1$), high reliability price ($i = 2$) and step tariff ($i = 3$), respectively. γ is a predefined parameter. Usually, the utility function of class i user is taken as $u_{ij}(x_{ij},\omega_i) = \omega_i x_{ij} - \frac{\gamma}{2}x_{ij}^2$ since $\frac{\omega_i^2}{2\gamma}$ is a constant when $x_{ij}\geqslant\frac{\omega_i}{\gamma}$ (Yuan et al. 2021). Besides, we also assume that $x_{ij}^{\min}\leqslant x_{ij}\leqslant x_{ij}^{\max}$, where $x_{ij}^{\max}$ and $x_{ij}^{\min}$ are the upper and lower limits of x_{ij}, respectively. Therefore, considering the value-added service, the social welfare function of class i user when purchasing electricity from the power retailer j equals the utility of purchasing electricity minus the corresponding electricity cost and plus the utility of value-added service. It is shown as follows:

$$U_{ij}(x_{ij},\omega_i,k_j) \ = \ \omega_i x_{ij} - \frac{\gamma}{2}x_{ij}^2 - x_{ij}p_{ij} + \ln k_j \tag{2}$$

where p_{1j}, p_{2j}, p_{3j} are interruption tariff, high reliability price, and step tariff formulated by power retailer j, respectively, k_j denotes the investment level of power service quality, and the utility brought by service investment is $\ln k_j$ (Wang et al. 2020). Furthermore, the investment level of power service quality is only related to the value-added services provided by each power retailer and doesn't matter how much electricity the user purchases. According to the user types, x_{ij} can be expressed as the following form:

$$x_{ij} = \begin{cases} Q_{1j} - \delta\Delta Q \ , \ i = 1; \\ Q_{2j} \ , \ i = 2; \\ Q_{3j} \ , \ i = 3. \end{cases}$$

where $\Delta Q_{\min}\leqslant\Delta Q\leqslant\Delta Q_{\max}$, Q_{1j}, Q_{2j}, Q_{3j} are the electricity purchased by the users of three types from power retailer j before the implementation of interruptible price, high reliability price and step tariff. δ is the probability of performing an interruption contract for the user, ΔQ is the interrupt quantity, and $\Delta Q_{\max}$ and $\Delta Q_{\min}$ are the maximum and minimum of the interrupt quantity, respectively.

3.2.2. Profit of integrated power retailers

(1) Expected cost of integrated power retailer.

The expected cost of an integrated power retailer includes electricity purchase cost and service cost. When the power retailer bids successfully, his electricity purchase cost is the sum of electricity purchase costs of the users of three types and the additional purchase cost for natural gas to make up power shortage at peak time slots. When the bidding fails, the electricity purchase cost is the cost of natural gas purchased by the power retailer to compensate for his electricity shortage. Service cost refers to the retailer's investment cost for his value-added services with an aim to improve the retailer's competitiveness to meet the diverse demands of users. Thus, the expected cost of power retailer j is as follows:

(a) Expected cost of electricity purchase

$$\begin{aligned} E(C_j) &= \theta_j\left[(Q_{1j} - \delta\Delta Q - Q_{gas})v^* + G^{in}p_{gas} + Q_{2j}v^* + Q_{3j}v^*\right] + (1-\theta_j)G^{in}p_{gas} \\ &= \theta_j(Q_{1j} + Q_{2j} + Q_{3j} - \delta\Delta Q - Q_{gas})v^* + G^{in}p_{gas} \end{aligned}$$

where$0\leqslant G^{in}\leqslant G^{in}_{\max}$, θ_j is the successful bidding probability of power retailer j, Q_{gas} is the load of natural gas power generation substitution, v^* is the electricity purchase price of power retailer j after successful bidding, G^{in} is the amount of natural gas and $G^{in}_{\max}$ is the upper limit of natural gas usage, p_{gas} is the natural gas price and has a step-by-step increasing relationship with respect to the gas amount (Yin et al. 2018), is shown in Table 1.

Power retailer turns natural gas into electricity for users, i.e., natural gas power generation. Heat rate (HR) is the value measuring the gas-power generation efficiency, and its international unit symbol (SI) is MJ/MW · h. The relationship between the heat rate and power generation efficiency is $\eta^e(t) = \frac{3600}{HR}$ (Beér, 2007).

The conversion formula for natural gas generation (Zeng et al. 2016) is as follows:

$$Q_{gas}(t) = \frac{\alpha(t)\eta^e(t)G^{in}(t)LHV(t)}{3600\rho(t)\Delta t} \tag{4}$$

where $\alpha(t)$ is the proportion of natural gas entering into micro turbine, $\eta^e(t)$ is the efficiency of natural gas transforming into electricity when passing through the micro turbine, lower heating value (LHV) is the lower heating value taken as 37.26 MJ/m^3 (Zeng et al. 2016), $\rho(t)$ is the natural gas quality of one cubic meter under standard atmospheric pressure taken as 0.7192 MJ/m^3 (Wood et al. 2020), and Δt is the unit time often taken as one hour.

(b) Service cost

We denote the service cost function as $G(k_j) = \frac{1}{2}e_j k_j^2$ (Zhou et al. 2018), where e_j denotes the cost coefficient of power service quality investment, and k_j means the level of power service quality investment.

(2) Expected revenue of integrated power retailer.

The revenue of an integrated power retailer is dependent on whether his bidding is successful or not. When the bid is successful, the revenues include the revenue from electricity sales of interruptible users minus interruption compensation plus default compensation, the revenue from electricity sold to highly reliable users minus high compensation for them, and the revenue from electricity sold to step tariff price users. When the bidding fails, the revenue is the electricity revenue from natural gas power sold to the users minus the compensation for the lack

Table 1
Natural gas price.

Step segment (kg)	Price (yuan/kg)
0–200	1.2
200–400	1.4
400–600	1.8
600–800	2.2

of electricity when the users' electricity demand cannot be met. Therefore, the expected revenue is calculated as follows:

$$E(R_j) = \theta_j[(Q_{1j} - \delta\Delta Q)p_{1j} - \delta\Delta Qp_{comp} + (1-\delta)R_c + Q_{2j}p_{2j} - \varphi(1-\beta)Q_{2j}p_{2j} + Q_{3j}p_{3j}] \\ +(1-\theta_j)\sum_{i=1}^{3}[\alpha_i Q_{gas}p_{ij} - (Q_{ij} - \alpha_i Q_{gas})p_{si}]$$

where $0\leqslant\alpha_1\leqslant1,\ 0\leqslant\alpha_2\leqslant1,\ 0\leqslant\alpha_3\leqslant1$ and $\alpha_1+\alpha_2+\alpha_3 = 1$, p_{comp} is the interruption compensation price, R_c is the default compensation, β is the reliability rate, φ is the compensation coefficient, p_{si} is the compensation price of power retailer for the user's power supply gap when the bidding fails, and $\alpha_1, \alpha_2, \alpha_3$ are the proportions of natural gas replacement load allocated to the users of three types.

(3) Profit of integrated power retailer.

The profit of an integrated power retailer is the expected revenue minus the expected electricity purchase cost and the service cost. That is,

$$\begin{aligned} W_j &= E(R_j) - E(C_j) - G(k_j) \\ &= \theta_j\left[(Q_{1j}-\delta\Delta Q)p_{1j} - \delta\Delta Qp_{comp} + (1-\delta)R_c + Q_{2j}p_{2j} - \varphi(1-\beta)Q_{2j}p_{2j} + Q_{3j}p_{3j}\right] \\ &+ (1-\theta_j)\sum_{i=1}^{3}[\alpha_i Q_{gas}p_{ij} - (Q_{ij}-\alpha_i Q_{gas})p_{si}] - \theta_j\left(Q_{1j}+Q_{2j}+Q_{3j}-\delta\Delta Q - Q_{gas}\right)v^* \\ &- G^{in}p_{gas} - \frac{1}{2}e_j k_j^2 \end{aligned} \tag{5}$$

3.2.3. *Formulation of leader–follower game*

(1) User social welfare maximization model.

In the Leader-follower game between the power retailers and the users, when the class *i* user purchases electricity from power retailer *j*, in the case of sufficient power supply, the class *i* user needs to solve the following optimization problem to maximize his social welfare:

$$\begin{aligned} \max U_{ij}(x_{ij}, \omega_i, k_j) &= \omega_i x_{ij} - \frac{\gamma}{2}x_{ij}^2 - x_{ij}p_{ij} + \ln k_j \\ s.t.\ x_{ij}^{\min} &\leqslant x_{ij} \leqslant x_{ij}^{\max} \end{aligned} \tag{6}$$

where U_{ij}, x_{ij}, ω_i, γ, p_{ij}, k_j is shown in formula (2). According to first-order optimality condition, the optimal solution of problem (5) is obtained as follows:

$$x_{ij}^* = \begin{cases} x_{ij}^{\min}, & if\ \dfrac{\omega_i - p_{ij}}{\gamma} \leqslant x_{ij}^{\min}; \\ \dfrac{\omega_i - p_{ij}}{\gamma}, & if\ x_{ij}^{\min} < \dfrac{\omega_i - p_{ij}}{\gamma} < x_{ij}^{\max}; \\ x_{ij}^{\max}, & if\ \dfrac{\omega_i - p_{ij}}{\gamma} \geqslant x_{ij}^{\max}. \end{cases} \tag{7}$$

It can be seen from formula (7) that when the electricity quantity is less than or equal to its minimum value or greater than or equal to its maximum value, x_{ij}^* is a constant value, which is contrary to price competition among the power retailers, and is inconsistent with the preconditions of price competition and user classification studied in this paper. Therefore, we obtain the following proposition 1.

Proposition 1. *Given the value satisfies the range* $x_{ij}^{\min}\leqslant x_{ij}\leqslant x_{ij}^{\max}$, *the optimal electricity consumption of class i user from integrated power retailer j is*

$$x_{ij}^* = \frac{\omega_i - p_{ij}}{\gamma} \tag{8}$$

Proof. This proposition follows our arguments before it.

(2) Power retailer profit maximization model.

In Section 3.1.1, the optimal electricity purchase strategy of power retailer has been obtained. Next, the electricity sale price based on price competition need to be solved according to formula (8). By constructing the profit function of power retailer, the bid for electricity and the price competition for electricity are combined to analyze the optimal electricity purchase and sale strategy of integrated power retailers as a whole. Thus, specific problems need to be solved as follows:

$$\begin{aligned} &\max\ W_j \\ &s.t. \begin{cases} \Delta Q_{\min} \leqslant \Delta Q \leqslant \Delta Q_{\max}; \\ 0 \leqslant G^{in} \leqslant G_{\max}^{in}; \\ 0\leqslant\alpha_1\leqslant1,\ 0\leqslant\alpha_2\leqslant1,\ 0\leqslant\alpha_3\leqslant1; \\ \alpha_1+\alpha_2+\alpha_3 = 1. \end{cases} \end{aligned} \tag{9}$$

According to formula (5), the maximization of profit function is rewritten in the following form:

$$\begin{aligned} &\max\ W_j = E(R_j) - E(C_j) - G(k_j) \\ &= \theta_j\left[(Q_{1j}-\delta\Delta Q)p_{1j} - \delta\Delta Qp_{comp} + (1-\delta)R_c + Q_{2j}p_{2j} - \varphi(1-\beta)Q_{2j}p_{2j} + Q_{3j}p_{3j}\right] \\ &+(1-\theta_j)\sum_{i=1}^{3}[\alpha_i Q_{gas}p_{ij} - (Q_{ij}-\alpha_i Q_{gas})p_{si}] - \theta_j\left(Q_{1j}+Q_{2j}+Q_{3j}-\delta\Delta Q - Q_{gas}\right)v^* - \\ &G^{in}p_{gas} - \frac{1}{2}e_j k_j^2 \end{aligned} \tag{10}$$

Moreover, $\Pr(b_h < b_j) = p_j, h \neq j$ and formula $\theta_j = \prod_{h\neq j}\Pr(b_h < b_j) = p_j^{n-1}$ in Section 3.1.1 are substituted into formula (10), we obtain

$$\begin{aligned}&\max\ W_j\\ &= \left(\frac{b_j - B_1}{B_2 - B_1}\right)^{n-1}[(Q_{1j} - \delta\Delta Q)p_{1j} - \delta\Delta Q p_{comp}\\ &+(1-\delta)R_c + Q_{2j}p_{2j} - \varphi(1-\beta)Q_{2j}p_{2j} + Q_{3j}p_{3j}]\\ &+\left[1 - \left(\frac{b_j - B_1}{B_2 - B_1}\right)^{n-1}\right]\sum_{i=1}^{3}[\alpha_i Q_{gas}p_{ij} - (Q_{ij} - \alpha_i Q_{gas})p_{si}]\\ &-\left(\frac{b_j - B_1}{B_2 - B_1}\right)^{n-1}(Q_{1j} + Q_{2j} + Q_{3j} - \delta\Delta Q - Q_{gas})v^{*} - G^{in}p_{gas} - \frac{1}{2}e_j k_j^2\end{aligned} \tag{11}$$

(3) A leader–follower game.

We develop a game model to find the maximum profit of power retailers and optimal social welfares of users under constraints. The optimization problem is as follows:

Problem 1.

$$\max\ W_j$$

$$s.t.\begin{cases}\Delta Q_{\min}\leqslant\Delta Q\leqslant\Delta Q_{\max};\\ 0\leqslant G^{in}\leqslant G^{in}_{\max};\\ 0\leqslant\alpha_1\leqslant 1,\ 0\leqslant\alpha_2\leqslant 1,\ 0\leqslant\alpha_3\leqslant 1;\\ \alpha_1+\alpha_2+\alpha_3 = 1.\end{cases} \tag{12}$$

Problem 2.

$$\begin{aligned}&\max U_{ij}\\ &s.t.\ x_{ij}^{\min}\leqslant x_{ij}\leqslant x_{ij}^{\max}\end{aligned} \tag{13}$$

We consider a smart grid with n power retailers and m users (users of three types) as depicted in Fig. 1. Retailers and users can make interactions through a communication infrastructure such as a local power grid. Each user installs a smart meter to control the energy consumption and exchange information (Tao et al. 2019). The users are the followers and respond to the price information of the retailers, whose goals are to maximize their own utilities in problem (13). The constraint conditions are mainly to constrain the electricity consumption behaviors of multi-class users. As the leaders, the retailers update the electricity prices to maximize their profits in view of the user's different electricity consumption in problem (12). The constraint conditions also control the power supply behaviors, and make a full use of the power supply to avoid electricity waste.

4. Results and discussion

4.1. Stackelberg equilibrium

Since the leader–follower game can be solved by backward induction, firstly, when the strategies of power retailer are given, the users determine to find the optimal response to the power retailers' strategies in the lower game. Then, it will be proved that there exists Nash equilibrium in price competition game among electricity retailers when the optimal response of each user is known. Finally, the equilibrium of leader–follower game between the power retailers and the users is verified to exist. The existence and uniqueness of Stackelberg equilibrium are explained by the following theorem:

Theorem 1. *There exists unique Stackelberg equilibrium in the leader–follower game between the power retailers and the users.*

Proof. (***(a)***) When the power retailers' strategies (i.e. electricity prices) are given, the users' responses to the strategies of power retailers that must be determined in the lower game are optimal responses. The optimal response function of class i user can be obtained by solving the first-order derivative of social welfare function of class i user with respect to x_{ij} when class i user purchases electricity from the power retailer j.

Let $\partial U_{ij}/\partial x_{ij} = \omega_i - \gamma x_{ij} - p_{ij} = 0$, the optimal response function of the class i user can be obtained to be$x_{ij}^{*} = (\omega_i - p_{ij})/\gamma$, as is defined in formula (8). Continuing to calculate the second-order derivative of U_{ij} with respect to x_{ij}, we obtain $\partial^2 U_{ij}/\partial x_{ij}^2 = \partial(\omega_i - \gamma x_{ij} - p_{ij})/\partial x_{ij} = -\gamma < 0$. It shows that $U_{ij}(x_{ij}, \omega_i)$ is strictly concave in the feasible region of x_{ij}. Since each strictly concave game has unique equilibrium (Rosen et al. 1965), the best-response strategy in formula (8) is the unique optimal solution.

(b) Given the best-response strategies of classified users, next we will find the best strategies of power retailers according to the backward induction, and prove the existence of Nash equilibrium in price competition game among power retailers. Similarly, by calculating the second-order derivative of the power retailer$j$' profit function with respect to p_{ij}, we obtain $\partial^2\ W_j/\partial p_{ij}^2 = 0$, which shows that the profit function of power retailer j is the concave function with respect to p_{ij}. Therefore, according to the existence theorem of Nash equilibrium (MacKenzie et al. 2006), the unique Nash equilibrium exists, which confirms that the optimal strategies of power retailers are optimal and unique.

(c) The unique Stackelberg equilibrium exists in the leader–follower game between the power retailers and users. Given the optimal pricing strategies of power retailers, according to (a) and formula (8), the best response $\boldsymbol{x}_j^{*}:=\left\{x_{1j}^{*}, x_{2j}^{*}, x_{3j}^{*}\right\}$ of the users' social welfare functions exist uniquely. At this time, all power retailers obtain the optimal response strategies in terms of formula (10) according to formula (8), then the optimal solution $\boldsymbol{p}_j^{*}:=\left\{p_{1j}^{*}, p_{2j}^{*}, p_{3j}^{*}\right\}$ of profit function in the presence of price competition equilibrium can be obtained. Finally, the strategy profile constitutes the unique Stackelberg equilibrium of developed Leader-follower game (Yu et al. 2016).

4.2. Solving algorithm of Stackelberg equilibrium

In this subsection, a distributed algorithm is designed to obtain Stackelberg equilibrium. The power retailers adjust their prices step by step through iterative equation, and the price change rate can be expressed by marginal profit. The price iterative equation of power retailer is written as (Yuan et al.2021, Dai et al. 2017).

$$p_{ij}(t+1) = \begin{cases} p_{1j}(t) + \mu_j\dfrac{\partial\ W_j}{\partial p_{1j}(t)},\ i = 1;\\ p_{2j}(t) + \mu_j\dfrac{\partial\ W_j}{\partial p_{2j}(t)},\ i = 2;\\ \{547, 597, 847\},\ i = 3.\end{cases} \tag{14}$$

where $\mu_j > 0$ is the price adjustment step of power retailer$j$, for $i = 1$, 2,3. When $i = 1$,2, formula (14) is satisfied, but when $i = 3$, the value of step tariff should meet the step data in Table 2 (Du et al. 2015).

The iterative process of electricity price and quantity includes multiple time slices Δt. The final result of multiple iterations is that the user obtains the optimal electricity quantity $\boldsymbol{x}_j^{*}$, and power retailer j determines the optimal price strategy $\boldsymbol{p}_j^{*}$. The steps of distributed algorithm for solving the leader–follower game are depicted in Table 3.

As showed in Table 3, a loop body and a loop termination condition

Table 2
Step tariff.

Step segment (MW)	Price (yuan/MW)
0–210	547
211–400	597
greater than 400	847

Table 3
Distributed algorithm.

```
Distributed algorithm
1: Initialization: $t = 0$, $\varepsilon = 10^{-3}$, given $p_{ij}(t)$, $x_{ij}(t)$, $\forall j \in [1, n]$;
2: Given $p_{ij}(t)$, compute $p_{ij}(t+1)$ using formula (5), (14);
3: Compute $x_{ij}(t+1)$ using (8) according to $p_{ij}(t+1)$;
4: If $x_{ij}(t+1) - x_{ij}(t) \leqslant \varepsilon$, stop iteration, turn to Step 6;
5: If $x_{ij}(t+1) - x_{ij}(t) > \varepsilon$, set $t = t+1$, turn to Step 2;
6: Obtain the Stackelberg equilibrium solution $(x_j^*, p_j^*)$, end.
```

Table 4
Interruption compensation price data.

Step segment (MW)	Price (yuan/MW)
0–150	66
150–250	78
250–330	90
330–400	112

are involved. The power retailers and classified users interact with each other in the initial period to determine the optimal electricity sale price and optimal response. In the beginning, for any retailer j, the accuracy of ε is 10^{-3}, and the initial electricity purchase price and amount of class i user are given. First, we use an initial electricity purchase price and price iteration equation in formula (9) to update the electricity purchase price for the next period. Then, the optimal response in formula (8) is used to obtain the purchase electricity amount for the next period. Next, we test whether the difference of electricity purchase before and after the two periods meet the accuracy requirements. If it is satisfied, the equilibrium can be obtained. Otherwise, we continue to iterate until the accuracy condition is met. We then find the optimal solutions for optimization problems 1 and 2.

Furthermore, in the previous section, we have proved that the Stackelberg equilibrium is unique. Therefore, our algorithm converges to the equilibrium, and the users also choose the equilibrium strategies according to the retailers' electricity sale prices.

5. Case analysis

5.1. Parameter installation

In this section, a smart grid system consisting of three power retailers and the users of three types is designed, and one day is divided into 24 time slots. We use survey data from the China's Residential Energy Consumption Survey (CRECS), which covers ten provinces in China with different economy levels. These data show the bidding situation of power retailers, the investment in value-added services, as well as the average electricity consumption of multi-class users. The chosen parameter values are from Yin et al. (2018) and Du et al. (2015). It can be assumed that the valuation and bid of the power retailer are subject to the uniform distribution on [130,162]. In order to further control the scope of parameters, $v_j (j = 1, 2, 3)$ are set to 140 yuan/MW, 146 yuan/MW and 154 yuan/MW, respectively. The interruption compensation price data are shown as in Table 4. We learn from Yin et al. (2018) that the probability of users to perform contract will not have a great impact on the profit of power retailer, therefore, we assume $\delta = 0.5$, and α also does not affect the profit in a certain range, whose value is 80 %. According to their appendix, $G^{in} = 545$kg, $\alpha_1 = 19.37\%$, $\alpha_2 = 32.99\%$, $\alpha_3 = 47.64\%$, and $\Delta Q = 147$MW.

At the same time, when the bidding fails, $p_{si} (i = 1, 2, 3)$ are 50 yuan/MW, 60 yuan/MW and 55 yuan/MW, respectively. Under the interruption price scheme, p_{comp} is 66 yuan/MW according to the value of ΔQ and Table 4. We assume that R_c is double the compensation price, namely 132 yuan/MW. Next, thermoelectric ratio is taken as 0.4, which is in line with the requirements of "Management Method of Cogeneration" (Development and Reform Energy (2016) No. 617) (DRC et al. 2016) for industrial gas combined cycle projects with annual thermoelectric ratios no less than 40 percent, $\eta^e = 71\%$, and $Q_{gas} = 4.45$ MW according to formula (4). Under the high reliable price scheme, $\beta = 99.49\%$, here the compensation coefficient $\varphi = 1$. In the sensitivity analysis of the following section, the influence of compensation coefficient on the power retailer's profit will be considered. Taking into account the value-added services, $e_j (j = 1, 2, 3)$ are set to 1.2, 1.1 and 1, and $k_j (j = 1, 2, 3)$ are 400, 455 and 528, respectively. Like compensation coefficient, the profit changes caused by the change of service quality investment level will be discussed in the following section. In addition, $\omega_i (i = 1, 2, 3)$ are reasonably set as 800, 850 and 1200. Formula (8) means that the best response to electricity consumption of users should be greater than 0. If it is less than or equal to 0, the best response electricity is 0, which does not meet the expectation. Finally, we consider $\gamma = 0.5$.

5.2. Performance of proposed approach

According to the above parameter setting, the obtained parameters are substituted into formula (8) to obtain $x_{ij}^* = (\omega_i - p_{ij})/\gamma$, which is shown as follows:

$$x_{ij}(t) = \begin{cases} 1600 - 2p_{1j}(t), & i = 1; \\ 1700 - 2p_{2j}(t), & i = 2; \\ 2400 - 2p_{3j}(t), & i = 3. \end{cases}$$

Then, let the price adjustment step of each power retailer be 0.1, and update the above formulas according to the given values of b_j, e_j, k_j, as follows:

When $j = 1$, the value of b_1, e_1, k_1 is 140, 1.2 and 400, respectively, then

U_{i1}, p_{i1}, W_1 can be expressed as

$$U_{i1}(x_{i1}, p_{i1}) = \begin{cases} 800x_{11} - 0.25x_{11}^2 - x_{11}p_{11} + \ln 400, & i = 1; \\ 850x_{21} - 0.25x_{21}^2 - x_{21}p_{21} + \ln 400, & i = 2; \\ 1200x_{31} - 0.25x_{31}^2 - x_{31}p_{31} + \ln 400, & i = 3. \end{cases}$$

$$p_{i1}(t+1) = \begin{cases} 0.96p_{11}(t) + 27.64\ , & i = 1; \\ 0.96p_{21}(t) + 30.39, & i = 2; \\ \{547, 597, 847\}, & i = 3. \end{cases}$$

$$W_1 = 276.4p_{11} - 0.2p_{11}^2 + 303.94p_{21} - 0.2p_{21}^2 + 325.75p_{31} - 0.2p_{31}^2 - 439366.99$$

When $j = 2$, the value of b_2, e_2, k_2 is 146, 1.1 and 455, respectively, then

U_{i2}, p_{i2}, W_2 can be expressed as

$$U_{i2}(x_{i2}, p_{i2}) = \begin{cases} 800x_{12} - 0.25x_{12}^2 - x_{12}p_{12} + \ln 455, & i = 1; \\ 850x_{22} - 0.25x_{22}^2 - x_{22}p_{22} + \ln 455, & i = 2; \\ 1200x_{32} - 0.25x_{32}^2 - x_{32}p_{32} + \ln 455, & i = 3. \end{cases}$$

$$p_{i2}(t+1) = \begin{cases} 0.9p_{12}(t) + 54.87, & i = 1; \\ 0.9p_{22}(t) + 58.69, & i = 2; \\ \{547, 597, 847\}, & i = 3. \end{cases}$$

$$W_2 = 548.65p_{12} - 0.5p_{12}^2 + 586.93p_{22} - 0.5p_{22}^2 + 657.09p_{32} - 0.5p_{32}^2 - 530571.98$$

When $j = 3$, the value of b_3, e_3, k_3 is 154, 1 and 528, respectively, then U_{i3}, p_{i3}, W_3 can be expressed as

$$U_{i3}(x_{i3}, p_{i3}) = \begin{cases} 800x_{13} - 0.25x_{13}^2 - x_{13}p_{13} + \ln 528, & i = 1; \\ 850x_{23} - 0.25x_{23}^2 - x_{23}p_{23} + \ln 528, & i = 2; \\ 1200x_{33} - 0.25x_{33}^2 - x_{33}p_{33} + \ln 528, & i = 3. \end{cases}$$

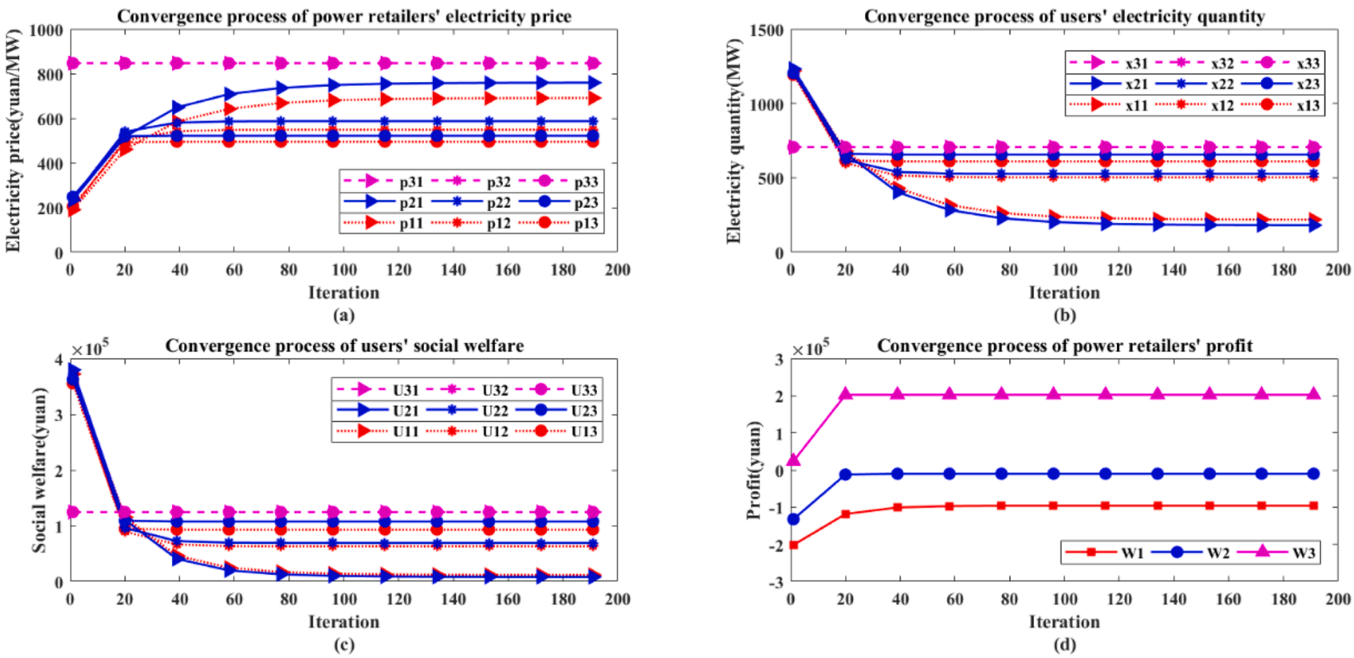

Fig. 2. Convergence process of distributed algorithm.

$$
p_{i3}(t+1)=\begin{cases}0.776p_{13}(t)+110.84, & i=1;\\ 0.776p_{23}(t)+116.88, & i=2;\\ \{547,597,847\}, & i=3.\end{cases}
$$

$$
W_3=1108.38p_{13}-1.12p_{13}^2+1168.77p_{23}-1.12p_{23}^2+1338.3p_{33}-1.12p_{33}^2-706884.01.
$$

The initial interruptible price is 50 yuan/MW higher than the electricity bid of power retailer, and the high reliability price is multiplied by its reliability rate on the basis of 95 yuan/MW higher electricity purchase bid (Yin et al. 2018). The step tariff is determined by the data located in Table 2, and it is assumed that the purchase of electricity by the third category of user in the three power retailers is greater than 400 MW, since the users using step tariff pricing scheme are the most common and account for the largest proportion of all types of users.

It can be seen from Fig. 2 whether the electricity price, user demand, user social welfare or the power retailer profit converge to a certain value in one time slot, which verifies the convergence of designed algorithm.

Fig. 2 (a) and (d) show the trend diagrams of electricity price and profit of the power retailer. It can be seen from the figures that, taking the first and second types of users for example, the change trend of electricity price and profit of power retailers is similar, which increase

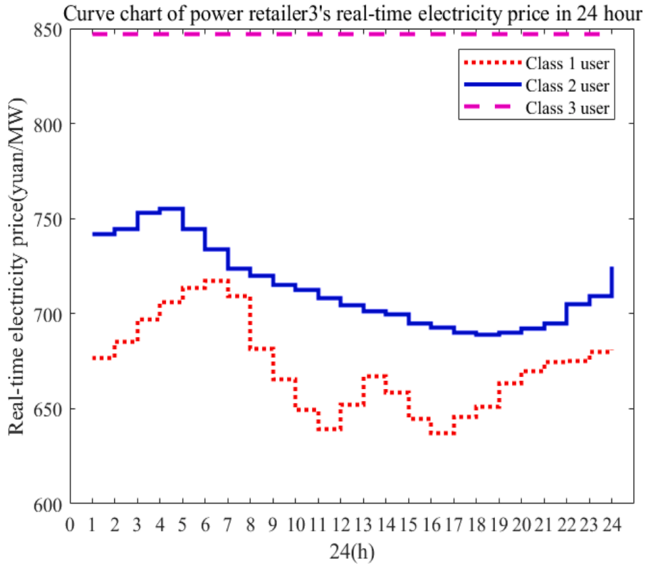

Fig. 3. Curve of power retailer3′s real-time electricity price in 24 h.

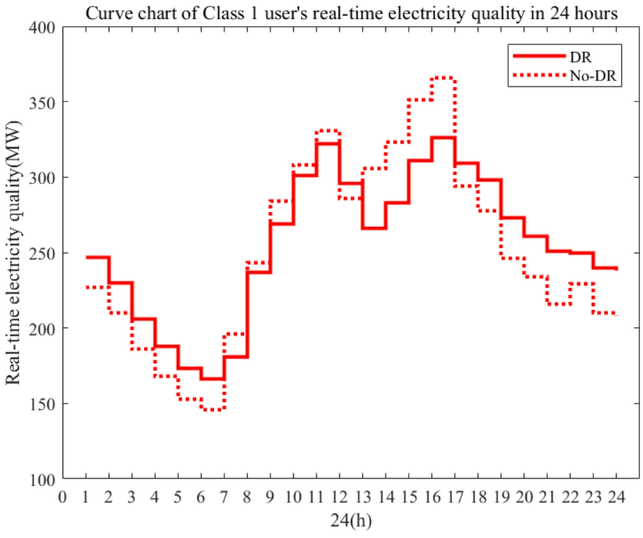

Fig. 4a. Curve chart of Class 1 user′s real-time electricity quality in 24 h.

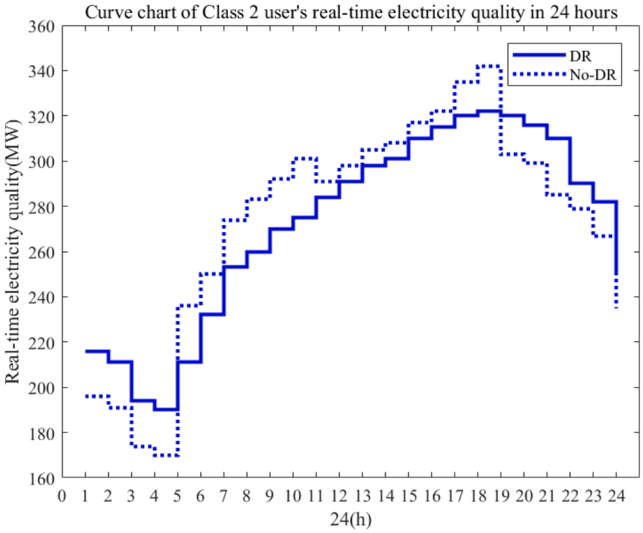

Fig. 4b. Curve chart of Class 2 user's real-time electricity quality in 24 h.

first but the amplification decreases gradually until a certain value is reached. This is because in the iterative equation of electricity price obtained according to the profit function of power retailer, the electricity price increases with the number of iterations, and finally tends to the level, reaching the Stackelberg equilibrium. At the same time, it can be found that there are significant differences in the profit magnitude and size of three power retailers under the equilibrium state, which is greatly affected by the electricity purchasing bids of power retailers.

Fig. 2(b) and (c) plot the change process of users' electricity quantity and welfare with the iterations, which are decreasing and finally tends to a constant value. This is because the optimal electricity quantity and electricity price obtained by maximizing the welfares of users change in the opposite direction. It can be seen from these two sub-graphs that, taking the power retailer 1 as an example, the optimal purchasing electricity of the users of three types is $x^*_{31} > x^*_{21} > x^*_{11}$, and the corresponding optimal social welfare$U^*_3 > U^*_2 > U^*_1$. This shows that the optimal social welfare increases with the increase of users' optimal purchasing electricity. The same result holds for power retailers 2 and 3.

There is an obvious horizontal line in Fig. 2 (a), (b), (c), i.e., the third category user has the same equilibrium electricity price, electricity quantity and welfare regrading to three power retailers. This is because for the step tariff users, given the initial same electricity price, the initial electricity quantity is still in the original step, and remains the same constant after iteration. According to Fig. 2(d), power retailer 3 has the largest profit in the equilibrium state. Therefore, Fig. 3 takes the third power retailer as an example to describe the real-time electricity price curve for different users under the equilibrium state in 24 h. We take one hour as a time slot and determine the peak and valley values according to different users' willingness to use electricity in different time periods, so as to obtain the trend of price change.

5.3. *Comparison analysis*

In order to evaluate the performance of our algorithm, we conduct another simulation analysis. It is worth noting that this paper applies the demand response scheme. Afterwards, we compare it with another model with no demand response, in which the power retailers keep the electricity price constant throughout the electricity sale process, as the traditional power grid. The users have no incentive to change their electricity consumption.

Figs. 4 shows the demand for electricity purchased by users throughout the day under two different models and different pricing schemes for retailer 3. The notable conclusion we can draw is that the DR scheme is effective in shaping the electricity demand. Because it can reduce peak load and demand during the peak consumption periods, whether for interrupted tariff users or high reliability tariff users. It thus follows that the DR model designed in this paper is of benefit to help the retailers reduce peaks and fill valleys to a certain extent.

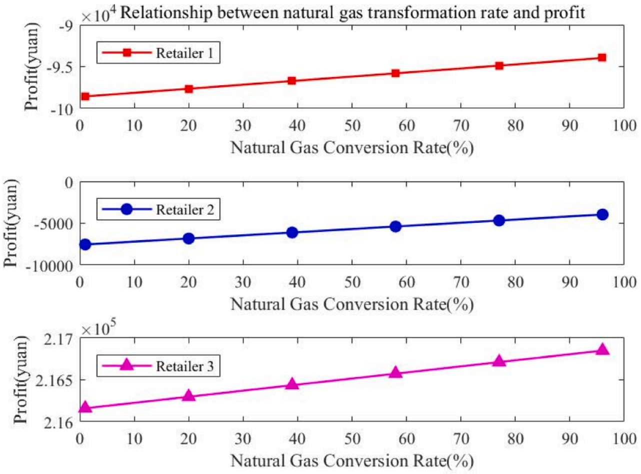

Fig. 5. Curve of power retailers' profit versus natural gas conversion rate.

Then, we compare our DR algorithm with that given by Chai et al. (2016). These two methods have the same performance in reducing peak load requirements. However, they have different load requirements in different time periods. The approach by Chai et al. (2016) is based on increasing or reducing load requirements in each time slot without considering other time slots. Differently, our DR algorithm shifts the load requirements from one time slot to other time slots. Moreover, by comparing our results with Figs. 4 of Chai et al. (2016), we learn that the iterative speeds of distributed algorithm in the two methods is similar. However, the algorithm in our paper is relatively more complex because we consider three power retailers and the users of three types. Nonetheless, the iterative effect of our method is still excellent.

In the last part of this section, we analyze and compare the proposed multi-class user differentiated pricing schemes and value-added services. Due to the price competition and service competition among power retailers, each retailer strives to attract more users and crowd out other companies. The efforts they can make themselves are mainly reflected in the technology innovation, especially the conversion rate of micro-turbines. Luo et al. (2020) considered plenty of smart energy hubs with same structure which can generate electricity and heat at the same time. The results of Figure 11 in Luo et al. (2020) show that when the natural gas conversion rate increases from 0.4 to 0.5 in steps of 0.01, the profit of power retailers increases evidently. However, they did not consider the multi-class user differentiated pricing schemes and different power retailers. Compared with previous studies, our paper involves interruptible tariff, high reliable pricing and step tariff respectively; and we comparatively analyze the impact of natural gas conversion rate on the profits of three power retailers. The simulation results in Fig. 5 show that the profit of power retailers increases by about 10 % with the unit change of natural gas conversion rate. Therefore, the pricing scheme proposed in our paper involving user characteristics has better performance.

5.4. *Sensitivity analysis*

The above simulation analysis verifies the existence and uniqueness of Stackelberg equilibrium as well as the convergence of designed algorithm. In this section, the sensitivity analysis of influence factors of three power retailers' Stackelberg equilibrium will be carried out to study the impact of natural gas distribution rate, probability of interrupting users to perform contract, reliability rate and compensation

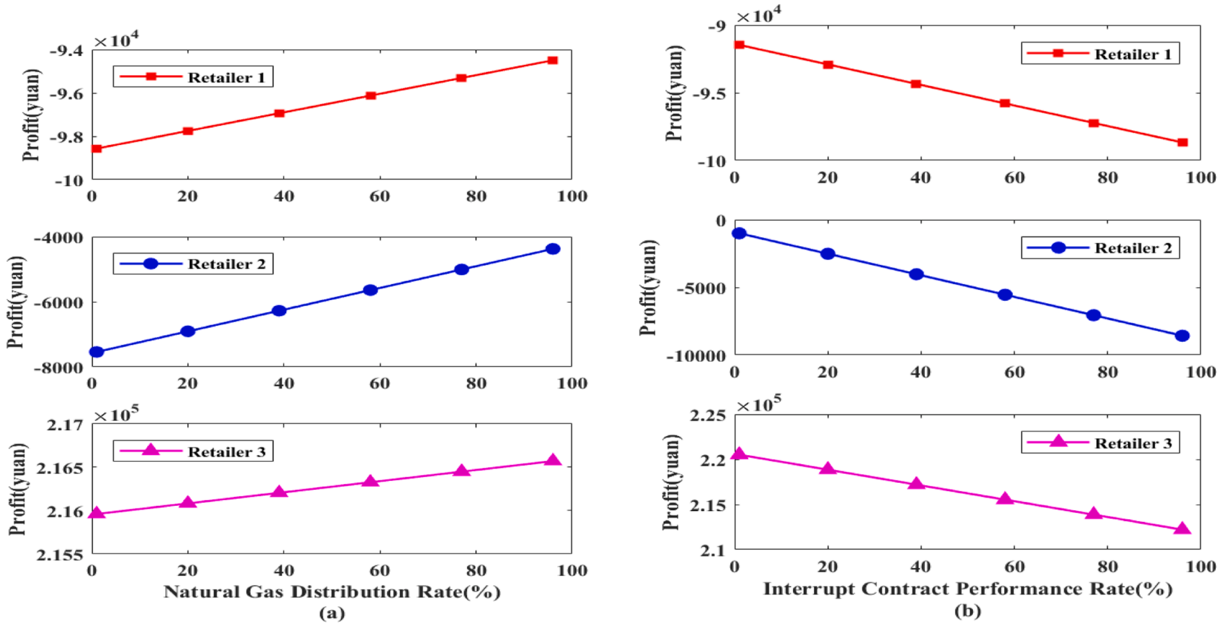

Fig. 6. Curve of power retailers' profit versus natural gas distribution rate and interruption contract performance rate.

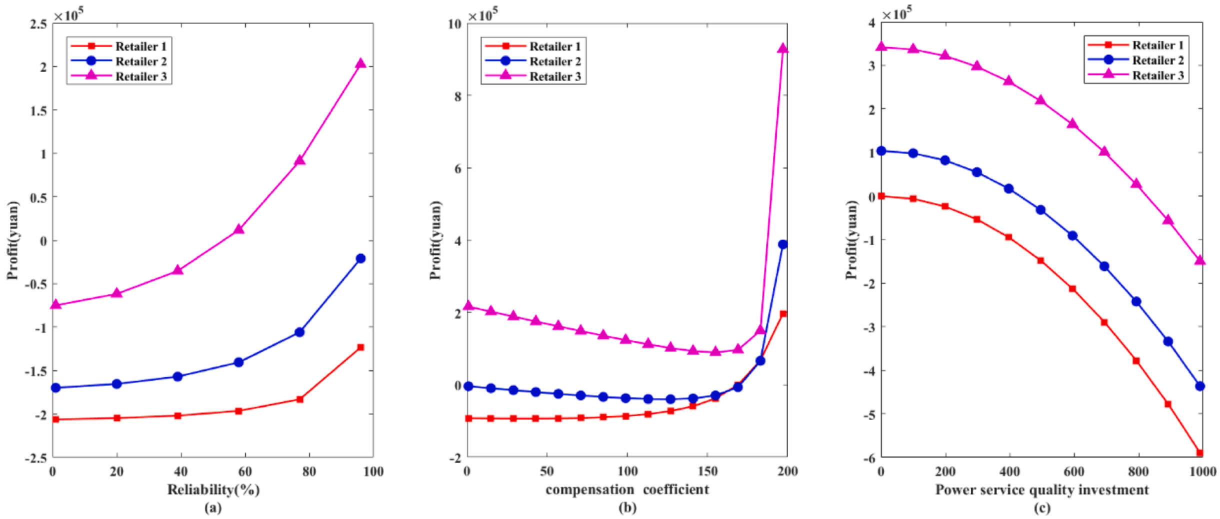

Fig. 7. Curve of power retailers' profit versus reliability, compensation coefficient and power service quality investment.

coefficient of highly reliable users, and power service quality investment level of power retailer on the profit of power retailer.

It can be seen from Figs. 6-7 that the natural gas distribution rate, the probability of interrupting users to perform contract, the reliability rate and compensation coefficient, and the power service quality investment level all have certain impacts on the profits of power retailers. Among them, the impact of natural gas distribution rate and the performance rate of interruption contract have linear change trends, and have negative impact on the profits of power retailers. With an increase in the proportion of natural gas entering the micro turbine, the profit of the power retailer increases linearly, because the increase in the load replaced by natural gas is sufficient to compensate the power shortage load. The higher the probability of the user to perform the interruption contract, the less profit the power retailer can obtain. The reason is that the retailer not only needs to provide the user interruption compensation but also incurs an opportunity loss of the user's default compensation.

Under the high-reliability pricing scheme, since the profit from reduced high compensation for increased reliability and increased maintenance costs are considered, the profit of power retailers increases with the increase of reliability rate and growth rate. With the increase of compensation coefficient in the outage compensation formula, the profits of power retailers show a trend of first decreasing and then increasing, and the profit minimum points of three power retailers move back and forth. At the same time, it can be seen that the improvement of power service quality investment will have a negative effect on profit increase, and the more investment, the faster the profit decreases.

6. Conclusions

This paper studies the purchase and sale strategy of integrated power retailer for sustainable development of energy. In the purchase of electricity, the power retailers centralize transactions in bidding form for obtaining traditional electricity, but can buy natural gas energy when the bids fail. In the sale of electricity, the power retailers adopt a multi-class user differentiated pricing scheme to trade with users. The bidding for electricity adopts the two-price sealed auction mechanism to obtain the optimal traditional electricity purchase, that is, the electricity purchase bid that equals the valuation and transaction price with the second highest bid. Under the price competition and multi-class user differentiated pricing scheme, a leader–follower game is developed to analyze the optimal electricity sale strategy between the power retailers and users, and a distributed algorithm is designed to solve the game. As to the factors that affect the retailer's profit, this paper mainly discusses the natural gas conversion and distribution rate, the probability of performing the contract of interruption price user, the reliability rate and compensation coefficient of user with a high reliable price, and the investment level of power service quality of a power retailer. Moreover, we compare the demand response model with the non-demand response model applied in our paper, and find that the former can be effective in helping retailers reduce peaks and fill valleys, which further proves the practical significance of the model developed in our paper. Finally, we conduct a comparative analysis on the performance of proposed distributed algorithms with other demand response models. It turns out that our model considers more specific real-world scenarios, and the final iteration works well. In the scenario based on the multi-class user differentiated pricing schemes and value-added services, our model also has better performance in improving the profit of power retailers compared with other literatures.

In this paper, we first construct the optimal electricity purchase strategies of power users and the optimal electricity sale strategies of power retailers. We find that the optimal purchasing electricity of users is positively correlated with the corresponding optimal social welfare. That is, our model can not only increase the social welfare of classified users but also increase the sales and profits of power retailers. In the context of integrated energy, natural gas conversion distribution rate is beneficial to improving the profit of power retailer to some extent. Therefore, more researches should be carried out on the structure and conversion rate of turbines in order to decrease the loss of energy and improve the productivity rate. At the same time, low-carbon and environmental protection should be encouraged, and clean energy should be introduced as much as possible. In this paper, it is assumed that the valuations and bids of the power retailers in the bidding process obey uniform distribution, and the accurate prediction of distribution pattern and distribution interval will have a great influence on the final purchase and sale strategy of power retailer. Power retailers should fully know the historical transaction data and make accurate forecasts before participating in the bidding. For the power retailers that implement the interruption price scheme, the performance rate of interruption contract has little effect on profits. Before signing the contract, the users should be coordinated as far as possible and the performance rate should be controlled within a reasonable range. For the power retailers that implement the high reliable pricing scheme, small changes in the reliability rate and compensation coefficient will affect profits. Therefore, the power retailer should prepare for both staff training and equipment maintenance to avoid large losses caused by operation errors or equipment failures, and the compensation coefficient should be controlled within a reasonable range. Although improving the investment level of power service quality will reduce the profits of power retailers, it should also be considered from the perspective of the users. The improvement of user's welfare can also promote the development of power retail market to a certain extent. As is evidenced by the above analysis, the following conclusions can be safely drawn:

(1) The developed leader–follower game in the presence of integrated energy manages to achieve the Stackelberg equilibrium of profits of power retailers and the welfare of users through the strategic interaction between the power retailers and classified users.

(2) The second-price sealed auction mechanism is used to purchase electricity, in the meanwhile, the price competition and multi-class user differentiated pricing schemes are adopted to sell electricity. These approaches are helpful to obtain the optimal electricity purchase and sale of integrated power retailers.

(3) A distributed algorithm is designed and has a stable and fast convergence speed to acquire the optimal solution of power retailers and classified users, which is suitable for applying to large-scale systems.

There are some limitations. Our original contribution is to incorporate value-added services into the costs of retailers and the utilities of classified users. However, the value-added services only aim at the investment level of power service quality of retailers without considering specific categories of users. Secondly, our paper is based on the deterministic assumptions of electricity market demand and integrated energy generation.

In future, one possible extension is to consider other power user classification methods, which can generate different user categories. Another future research direction would be to consider the uncertainty of electricity market demand and integrated energy generation, because the demand is affected by probability and the power generation has many uncontrollable external factors. Therefore, it is important for us to study the purchase and sale strategy for integrated power retailers when the user classification differs from ours in this paper and the random demand function is used.

CRediT authorship contribution statement

Yeming Dai: Conceptualization, Writing – review & editing. **Yuqing Yang:** Data curation, Writing – original draft. **Mingming Leng:** Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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