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Economic Efficiency Analysis of Micro Energy Grid Considering Time-of-Use Gas Pricing

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ABSTRACT The application of time-of-use (TOU) pricing in the electricity market has significant value, which can improve economic efficiency and promote effective management of resources. However, this pricing mechanism has not been applied and promoted in the gas market in China. In this paper, we propose a bi-level transaction model considering TOU gas pricing for analyzing the economic efficiency of micro energy grid (MEG) operation based on Game Theory. The multiple energies trading is conducted between the natural gas company (NGC), the MEG and energy users (EUs), which forms a hierarchical Stackelberg game model. We first analyze utilities and strategies of aforementioned participants, and derive the Stackelberg equilibrium (SE) analytically as a balanced solution that captures the equilibrium strategies of participants. Then, a mixed integer nonlinear programming is formulated to determine the optimal TOU gas prices delivering maximum NGC profit, the optimal energy sales prices corresponding to the MEG' SE utility, and the optimal load pattern for EUs. Finally, numerical experiments are conducted in two scenarios, which reveal that the TOU pricing can well balance the gas supply and demand, and has significant potential for improving the economic efficiency of the MEG.

INDEX TERMS Micro energy grid, Stackelberg game, economic efficiency, time-of-use pricing, equilibrium.

I. INTRODUCTION

By increasing the penetration level of combined cooling, heating and power (CCHP) systems in industrial, commercial and residential sectors, the interaction between energy-supplying entities and energy users (EUs) in the energy market becomes more complicated than before.

To analyze a system that integrates multiple energies and for considering its characteristics, the micro energy gird (MEG) is introduced [1]. The MEG is a multi-energy complementary system, where different types of energies are converted, stored and distributed in order to supply EUs with multiple energies, such as cooling, heating as well as electricity [2]. A variety of energy sources and the flexible structure make the MEG operation much more complicated [3]–[5]. Moreover, with the increasing number of MEGs, EUs and other market participants such as the natural gas company (NGC), participating in energy trading, the actions of them will influence the operation of the MEG. Energy prices are key elements for both energy suppliers and consumers. From an economic perspective, an efficient energy transaction considering energy pricing may be important not only to the MEG operation, but also to other participants [6].

A commonly used approach to tackle the MEG operation problem is based on traditional optimization. Li *et al.* [7] established a scenario-based optimal operation model for the integrated energy system to handle uncertainties in energy demand and renewable generation. In [8], an integrated energy management scheme was proposed to optimize the operation cost for a data center microgrid. An optimal scheduling model with unit commitment constraints was established to coordinate the complementary operation of different devices in the integrated energy system [9]. In [10] and [11], to augment the flexibility of energy management, Ma *et al.* discussed the energy hubs structure and the optimal energy management strategies for smart multi energy systems. A specific microgrid composed of CCHP units, photovoltaic (PV) and wind turbines (WT), was constructed in [12] and [13], as well as proposing an improved particle swarm optimization algorithm for solving the day-ahead

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multi-energy coordinated scheduling. Though the aforementioned references have made a significant contribution to the MEG optimal operation, it should be pointed out that some factors still need to be considered for the MEG operation in the energy market.

An energy trading model needs to take into account the interactions among different participants, without just pursuing one participant's objective [14]. Game theory is a suitable method to tackle this interactive problem [15], which has gained much attention in solving energy trading problems in recent years [16]–[18]. The application of game theory in MEG operation could be roughly divided into two aspects. One is focusing on the optimal operation of the MEG based on non-cooperative game theory. The problem of distributed home energy management system consisting of multiple microgrids and multiple customers was studied using the multiple-leader–multiple-follower game model in [19]. Paudel *et al.* [20] proposed a novel game-theoretic model for peer-to-peer energy trading among the prosumers in a community. Reference [21] formulated the energy management problem of different participants as a three-stage Stackelberg game, while reference [22] conducted energy management optimization of MEG based on hierarchical Stackelberg game. The other is to conduct the MEG trading based on cooperative game theory, such as [23]–[25]. The cooperative economic scheduling problem for multiple neighboring integrated energy systems on the basis of energy hubs was studied in [23]. A hybrid energy sharing framework with combined heat and power system and PV prosumers was proposed to facilitate the energy sharing in smart building cluster in [24]. The game-theoretic approach internalizes the decentralized structure of the MEG in the energy trading. Most of the aforementioned references put emphasis on the electrical energy trading, along with the total amounts of multiple energies for trading. Modeling of different types of EUs in transactions and the impact of energy pricing on transactions are not integrated enough into these studies.

Price is a key factor in the energy trading, for both producers and consumers. Gas is the main energy source for the MEG, whose price will influence the MEG operation. However, the current government-regulated gas pricing schemes may limit MEG's flexible scheduling based on purchase of gas, leading to financial losses for both MEG and NGC. Time-of-use (TOU) pricing is an efficient approach in the energy management, which plays an important role in improving economic and energy efficiency [26]. Some significant works have highlighted the potential abilities of TOU pricing in the energy management. Hung and Michailidis [27] discussed a general stochastic modeling framework for consumer's power demand based on which TOU contract characteristics can be selected to minimize the mean electricity price paid by the customer. An optimal TOU pricing in urban gas market based on an evolutionary game-theoretic perspective was proposed in [28]. All findings indicate that TOU pricing has vital and beneficial application value for energy management systems, which has remarkable potential for peak-shaving and load-shifting. Since the gas pricing reform progress in China is slowly going on, the theoretical research and the promotion on TOU gas pricing are still limited.

This paper proposes a bi-level transaction model considering TOU gas pricing for analyzing the economic efficiency of the MEG operation based on Game Theory. The multiple energies trading is conducted between the NGC, the MEG and EUs, which forms a hierarchical Stackelberg game model. The proposed model takes consideration of the coordination between different market participants, and holds the intention of treating all market participants in an unbiased way. The main contributions of this paper are summarized as follows:

- A bi-level transaction model is established for analyzing the energy trading problems between the NGC, the MEG and EUs, which can be transferred into a hierarchical Stackelberg game.
- The Stackelberg equilibrium (SE) is proven to exist uniquely, which can capture equilibrium strategies of the NGC, the MEG and EUs, simultaneously.
- The TOU gas pricing is evaluated in the transaction model and compared to the single gas pricing. This allows us to figure out the impact of TOU gas pricing on the MEG operation and its advantages in the energy market.
- By quantifying the experience of energy-usage and combining it with the energy expenditure in the fuzzy algorithm, the EU's model is constructed. Through configuring different parameters, different types of EUs are built and applied to the transaction model.

The rest of the paper is organized as follows: Section II introduces the transaction framework briefly. Section III presents the mathematical formulation of the transaction entities. Section IV analyzes the SE strategies of three participants theoretically. Section V presents the results from numerical examples in two scenarios, with detailed analysis. Section VI draws the conclusions.

II. TRANSACTION FRAMEWORK

The transaction model proposed in this paper consists of three types of participants: the NGC, the MEG and EUs. The NGC profits from selling gas to the MEG. Meanwhile, the MEG converts the purchased gas to multiple energies (electricity, heating and cooling energies) through internal coupled devices, and then sell these energies as products to its contract EUs. By setting different energy sales prices, the MEG incents EUs to adjust their loads according to the actual situation.

For different EUs, the habits of energy usage and the need for energies vary. For the sake of diversity, we extend the single type EU to three typical EUs: the industrial EU, the commercial EU and the residential EU. The industrial EU has the property of large energy consumption and high demand, and its load transferability characteristics make it highly sensitive to energy sales prices. Compared with the

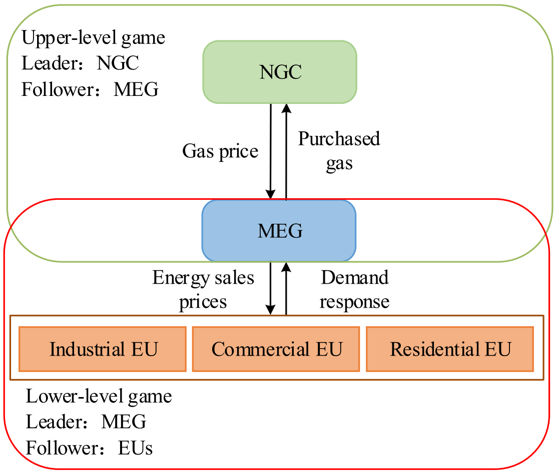


FIGURE 1. Framework of the transaction model.

industrial EU, the energy consumption of the commercial EU has continuous characteristics, which is not willing to adjust the load to affect commercial operations. For the residential EU, because of the relatively small and flexible energy consumption, the load can be better adjusted according to energy sales prices without affecting the experience of energy usage.

The framework of the proposed transaction model is presented in Fig.1. In the transaction, the NGC and the MEG form the upper-level game, while the MEG and EUs make up the lower-level game. The NGC incents the MEG to purchase gas by adjusting the gas price in the upper-level game, and the MEG encourages EUs to participate in demand response by adjusting energy sales prices in the lower-level game. It should be noted that the specific market design allows the market participants to make decisions a day ahead.

III. MODELS OF TRANSACTION ENTITIES

The transaction entities in this paper are mainly the NGC, the MEG and EUs. The mathematical models of different transaction entities will be described in detail below.

A. NGC MODELING

In gas trading, the NGC can provide the amount of gas the MEG needs at any time, due to the stable gas supply. By introducing a flexible gas pricing strategy, the NGC can stimulate the MEG to adjust and transfer the gas purchased volume according to its needs, so as to obtain better gas sales revenue. From the perspective of optimization, NGC's utility function is to maximize the benefits in energy trading, which is related to the gas prices, the gas volume purchased by the MEG. The expression is as follows:

$$\max I_{\mathrm{NGC}} = \sum_{t=1}^{24} (\varphi_t^{\mathrm{g}} v_t^{\mathrm{g}} - G_t^{\mathrm{emi}}) - F(v_t^{\mathrm{g}}) \tag{1}$$

where, φ_t^{g} is the NGC's gas price in period t, and v_t^{g} is the gas volume purchased by the MEG in period t. G_t^{emi} is the carbon emission cost. $F(v_t^{\mathrm{g}})$ is the cost caused by the deviation from the average gas sales volume of the NGC. The transaction model in this paper divides one day into 24 periods, and $\Delta t = 1\mathrm{h}$ is the basic unit to perform optimization.

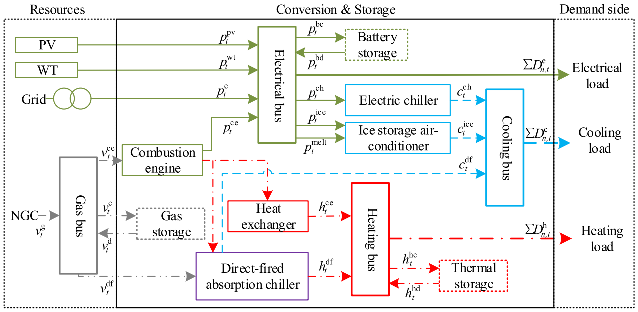


FIGURE 2. Structure of the MEG.

The carbon emission cost G_t^{emi} takes the following form:

$$G_t^{\mathrm{emi}} = \varphi_{\mathrm{emi}} \cdot \gamma_{\mathrm{g}} \cdot v_t^{\mathrm{g}} \tag{2}$$

where, φ_{emi} is the carbon emission unit cost, and γ_{g} is amount of exhaust gas corresponding to the production unit gas.

The last term $F(v_t^{\mathrm{g}})$ is the cost caused by the variation of the MEG demands within the optimization, which ensures the demand variation follows the historical pattern within a certain range. It is measured by the sum of squared generation deviations from the mean demand, multiplied by a coefficient μ [29]:

$$F(v_t^{\mathrm{g}}) = \mu \sum_{t=1}^{24} \sqrt{(v_t^{\mathrm{g}} - \bar{v})^2} \tag{3}$$

where, $\bar{v}$ is the mean gas purchased volume, and μ is the deviation cost coefficient.

B. MEG MODELING

According to the resources of the region and the demands of EUs, an MEG's structure can be flexibly planned and designed, which greatly improves economic and energy efficiency.

This paper takes the MEG which can meet the demands of EUs for various types of energies (electricity, heating and cooling energies) as the research entity. In terms of input resources, renewable energy devices (PV, WT), the power grid and the NGC provide energies for the MEG. The MEG converts and stores the input energies, and then provides electrical, heating and cooling products to EUs on the demand side. The structure of the MEG is shown in Fig.2.

1) UTILITY FUNCTION

In the transaction, the MEG maximizes its profits by managing outputs of devices and setting reasonable energy sales prices. The MEG has to meet EUs' actual energy loads, and take into account the NGC's gas price, distributed energy devices' characteristics. Accordingly, the utility function I_{MEG} for the MEG is as below.

$$\max I_{\mathrm{MEG}} = \sum_{t=1}^{24} (\varphi_t^{\mathrm{meg}} D_t \Delta t - C_t^{\mathrm{meg}} - \delta) \tag{4}$$

where, φ_t^{meg} is the energy sales price in period t, which contains electricity price φ_t^{e}, heating price φ_t^{h} and cooling price φ_t^{c}. D_t denotes the actual load of EUs in period t, including actual electrical load D_t^{e}, actual heating load D_t^{h} and actual cooling load D_t^{c}.

C_t^{meg} is the production cost of the MEG, which is composed of the cost of purchasing gas from the NGC, the cost of electricity purchased from the grid, and the operating and maintenance costs of distributed energy devices [30], [31]. The expression of C_t^{meg} is as below.

$$C_t^{\mathrm{meg}} = (\varphi_t^{\mathrm{g}} v_t^{\mathrm{g}} + \varphi_t^{\mathrm{ge}} p_t^{\mathrm{e}} \Delta t) + \sum_{k=1}^{K} r_k p_t^k \Delta t \tag{5}$$

where, φ_t^{ge} denotes the electricity sales price of the power grid in period t, and p_t^{e} represents the power of the grid injected into the MEG in period t. Moreover, r_k is the maintenance cost coefficient of the k-type device, and $pk\ t$ is the output of the k-type device in period t. K is the total number of devices in the MEG.

Regarding the penalty cost, δ represents the penalty for the deviation between the generation of renewable energies and the actual electrical load D_t^{e} in period t, which is given by the following:

$$\delta = \rho(D_t^{\mathrm{e}} - p_t^{\mathrm{pv}} - p_t^{\mathrm{wt}})\Delta t \tag{6}$$

where, ρ is the penalty price per kWh of electricity, and p_t^{pv}, p_t^{wt} denote outputs of PV and WT, respectively.

2) OPERATION CONSTRAINTS

a: ENERGY BALANCE EQUATIONS

$$v_t^{\mathrm{g}} + s_t^{\mathrm{gd}} v_t^{\mathrm{d}} = v_t^{\mathrm{ce}} + v_t^{\mathrm{df}} + s_t^{\mathrm{gc}} v_t^{\mathrm{c}} \tag{7a}$$

$$\begin{aligned} p_t^{\mathrm{e}} + p_t^{\mathrm{pv}} + p_t^{\mathrm{wt}} + p_t^{\mathrm{ce}} + s_t^{\mathrm{bd}} p_t^{\mathrm{bd}} &= D_t^{\mathrm{e}} + p_t^{\mathrm{ch}} + s_t^{\mathrm{cc}} p_t^{\mathrm{ice}} \\ &\quad + s_t^{\mathrm{cd}} p_t^{\mathrm{melt}} + s_t^{\mathrm{bc}} p_t^{\mathrm{bc}} \end{aligned} \tag{7b}$$

$$h_t^{\mathrm{he}} + h_t^{\mathrm{df}} + s_t^{\mathrm{hd}} h_t^{\mathrm{hd}} = D_t^{\mathrm{h}} + s_t^{\mathrm{hc}} h_t^{\mathrm{hc}} \tag{7c}$$

$$c_t^{\mathrm{df}} + c_t^{\mathrm{ch}} + c_t^{\mathrm{ice}} = D_t^{\mathrm{c}} \tag{7d}$$

where (7a), (7b), (7c) and (7d) are, respectively, the gas, electrical, heating and cooling energy balance equations.

In (7a), v_t^{ce} denotes the gas consumption of internal combustion engine, and v_t^{df} denotes the supplemental gas consumption of direct-fired absorption chiller. v_t^{c} and v_t^{d} are gas charging amount and discharging amount of gas storage, respectively. s_t^{gc} and s_t^{gd} represent on/off states of gas storage charging and discharging in period t (0/1, 0 stands for off and 1 stands for on).

In (7b), p_t^{ce} denotes the output of internal combustion engine. p_t^{bc} and p_t^{bd} are charging power and discharging power of battery storage, respectively. s_t^{bc} and s_t^{bd} represent on/off states of battery storage charging and discharging in period t. p_t^{ch} denotes the power consumption by electric chiller in cooling mode. p_t^{ice} and p_t^{melt} are power consumption by ice-storage air-conditioner in ice-making mode and in ice-melting mode. s_t^{cc} and s_t^{cd} are on/off states of ice-storage air-conditioner making and melting ice in period t.

In (7c), h_t^{he} and h_t^{df} denote heating outputs of heat exchanger and direct-fired absorption chiller, respectively. h_t^{hc} and h_t^{hd} are heating charging and discharging power of thermal storage. s_t^{hc} and s_t^{hd} represent on/off states of thermal storage charging and discharging in period t.

In (7d), c_t^{df}, c_t^{ch} and c_t^{ice} are cooling outputs of direct-fired absorption chiller, electric chiller and ice-storage air-conditioner, respectively.

b: OUTPUT LIMITS OF DEVICES

In the simulation horizon, not only the energy balance should be considered, but also the output limit of each device should be met. The output limit constraints are shown below.

$$\begin{cases} 0 \le p_t^i \le p_i^{\max} \\ 0 \le h_t^m \le h_m^{\max} \\ 0 \le c_t^l \le c_l^{\max} \end{cases} \tag{8}$$

where, p_t^i, h_t^m and c_t^l are electrical output of i-type device, heating output of m-type device, and cooling output of l-type device, respectively. $p_i^{\max}$, $p_m^{\max}$ and $p_l^{\max}$ are, respectively, the maximum output bounds for i-type device, m-type device, and l-type device. Hereon, the i type devices include internal combustion engine, PV and WT. The m type devices include heat exchanger and direct-fired absorption chiller. The l type devices include direct-fired absorption chiller, electric chiller and ice-storage air-conditioner.

c: STORAGE CONSTRAINTS

The MEG proposed in this paper contains four types of energy storage devices: battery storage, thermal storage, cooling storage and gas storage. Except the input and output limits, the constraints for state of charge should also be taken into account for energy storages. The specific constraints are shown below.

$$\begin{cases} 0 \le p_t^{\mathrm{cha}} \le p_{\mathrm{cha}}^{\max} \\ 0 \le p_t^{\mathrm{dis}} \le p_{\mathrm{dis}}^{\max} \\ SoC_{t+1} = SoC_t \\ \qquad + \dfrac{(\eta_{\mathrm{cha}} s_t^{\mathrm{cha}} p_t^{\mathrm{cha}} \Delta t - \frac{s_t^{\mathrm{dis}} p_t^{\mathrm{dis}} \Delta t}{\eta_{\mathrm{dis}}})}{S_{\mathrm{es}}} \\ SoC_{\min} \le SoC_t \le SoC_{\max} \\ s_t^{\mathrm{cha}} + s_t^{\mathrm{dis}} \in (0, 1) \end{cases} \tag{9}$$

where, p_t^{cha} and p_t^{dis} represent the charging and discharging power of energy storage systems in period t. $p_{\mathrm{cha}}^{\max}$ and $p_{\mathrm{dis}}^{\max}$ are the maximum charging and discharging power, respectively. SoC_t is the state of charge of the energy storage. η_{cha} and η_{dis} are charging and discharging efficiency. $SoC_{\min}$ and $SoC_{\max}$ are the lower and the upper bounds for SoC. s_t^{cha} and s_t^{dis} represent on/off states of the energy storage charging and discharging. S_{es} is the rated capacity of the energy storage.

C. EU MODELING

We assume that there is a flexible demand response environment, where EUs can optimize their utility function by adjusting energy consumption based on the energy sales prices issued by the MEG. For the sake of simplicity, one type of EU is chosen to describe the EU modeling problem. The EU is supposed to have a fixed demand before optimization. After receiving the updating energy sales prices, EUs will maximize their utility function by adjusting the energy consumption to a certain degree, with taking into account the experience of energy-usage.

Thus, EUs' utility function consists of two parts: the expenditure of purchasing energy and the experience of energy-usage. The formulation of the expenditure P is as below.

$$P = \sum_{t=1}^{24} \varphi_t^{\mathrm{meg}} D_t \Delta t \tag{10}$$

Through quantifying EU's dissatisfaction with the actual energy load, the experience of energy-usage can be characterized. The dissatisfaction function Q_t is constructed by taking the deviation between the EU's energy demand and the actual energy load as a variable. Referring to the concept of satisfaction function in [26], we construct the dissatisfaction function Q_t as below:

$$Q_t = b \cdot (a^{q(1-\frac{D_t}{N_t})} - 1) \tag{11}$$

where, a, b and q are related parameters of the dissatisfaction function. a is related to the magnitude of Q_t, and $a > 1$. b is the preset value, and $b > 0$. q is elastically related to the adjustment ratio of the energy load, and $q > 1$. N_t is the EU's nominal demand, including nominal electrical demand N_t^{e}, nominal heating demand N_t^{h} and nominal cooling demand N_t^{c}. The constructed dissatisfaction function Q_t has the following features:

(1) Q_t is positive when the actual energy load is less than the nominal demand, and it will increase as the actual energy load adjustment ratio increases.

(2) Q_t becomes 0 when the actual energy load meets the nominal demand.

(3) Q_t is negative when the actual energy load exceeds the nominal demand, which means it turns into satisfaction. However, EU satisfaction will tend to be flat as the actual energy load increases, and gradually approach the preset value.

Taking the electrical load as an example, under the nominal electrical demand N_t^{e}, with the adjustment of D_t^{e}, EU's dissatisfaction functions with different parameters are presented in Fig. 3.

In the daily energy transaction, dissatisfaction Q is the summation of EU's dissatisfaction values in all periods. The formulation is as below.

$$Q = \sum_{t=1}^{24} b \cdot (a^{q(1-\frac{D_t}{N_t})} - 1) \tag{12}$$

The dimensions of EU's two objectives are different. Thence, it is not suitable to conduct the simple weighted linear addition. We adopt the fuzzy solution method to deal with the bi-objective optimization problem [32]. The fuzzy solution method is to establish two mappings of objective function values to the optimal solution membership degree respectively. The specific steps are as follows:

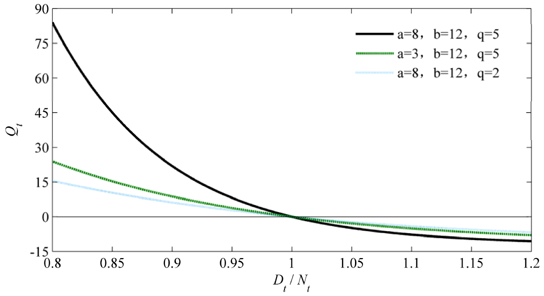


FIGURE 3. **Dissatisfaction functions with different parameters.**

Step 1: Take expenditure P as the objective to conduct optimization calculation. We can obtain the minimum expenditure P_{m} along with Q_{M} in this condition.

Step 2: Take dissatisfaction Q as the objective to conduct optimization calculation. We can obtain the minimum dissatisfaction Q_{m} along with P_{M} in this condition.

Step 3: Fuzz these two objective functions to establish the mapping from a single objective function value to membership degree. The membership degree is determined by linear rules. Equations (13) and (14) are the membership degree functions corresponding to EU's two objectives, respectively.

$$\gamma(P) = \frac{P_{\mathrm{M}} - P}{P_{\mathrm{M}} - P_{\mathrm{m}}} P_{\mathrm{m}} < P < P_{\mathrm{M}} \tag{13}$$

$$\gamma(Q) = \frac{Q_{\mathrm{M}} - Q}{Q_{\mathrm{M}} - Q_{\mathrm{m}}} Q_{\mathrm{m}} < Q < Q_{\mathrm{M}} \tag{14}$$

Step 4: Through adding the weighted membership degree functions linearly, the fuzzy bi-objective function for expenditure P and dissatisfaction Q can be obtained.

In summary, the EU's utility function I_{EU} is as below:

$$\max I_{\mathrm{EU}} = \max[\omega_1 \gamma(P) + \omega_2 \gamma(Q)] \tag{15}$$

where, ω_1 and ω_2 are the weight coefficients of expenditure P and dissatisfaction Q, respectively.

IV. THEORETICAL ANALYSIS OF EQUILIBRIUM STRATEGIES

A. GAME FORMULATION

When optimizing the utility functions (1), (4) and (15) of different participants in Section III, it will result in a tradeoff between different entities. For instance, maximizing the profits in (1) requires the NGC to increase the gas price and to sell more gas to the MEG, which in turn will affect the gas-purchasing amount of the MEG. Similarly, maximizing the MEG's utility function (4) requires the MEG to produce energies at a relatively low cost and to increase energy sales prices, which will affect both the NGC's revenues and the EU's expenditure. Besides, maximizing (15) will also need the EU to make a compromise between the energy-purchasing expenditure and the experience of energy usage. These factors lead to interactions between participants, who coordinate their interests by constantly adjusting strategies.

The interaction relationships between these three energy trading entities are leader-follower structures of typical Stackelberg game [33]. In this paper, a hierarchical Stackelberg game is proposed to simulate the energy trading process and to capture the equilibrium strategies. It is notable that the MEG plays a dual role in the hierarchical game, which has shown in Fig.1. For this Stackelberg game structure of energy trading, the mathematical model can be established as follows:

$$\boldsymbol{\Gamma} =< N, S, I > \tag{16}$$

where, Stackelberg game Γ consists of three basic game elements: Participant N, Strategy S and Utility I. The NGC, the MEG and EUs form the game participants N. The utility functions I of different participants have been presented in (1), (4) and (15). The strategy sets S are defined as follows:

$$\boldsymbol{\Psi}^{\mathrm{g}} = \left\{\varphi^{\mathrm{g}} | \varphi^{\mathrm{g}} \in \mathbb{R}^{N}, \varphi^{\mathrm{gdown}} \leq \varphi^{\mathrm{g}} \leq \varphi^{\mathrm{gup}}\right\} \tag{17}$$

$$\boldsymbol{V}^{\mathrm{g}} = \left\{v^{\mathrm{g}} | v^{\mathrm{g}} \in \mathbb{R}^{N}, v^{\mathrm{down}} \leq v^{\mathrm{g}}\right\} \tag{18}$$

$$\boldsymbol{\Psi}^{\mathrm{meg}} = \left\{\varphi^{\mathrm{meg}} | \varphi^{\mathrm{meg}} \in \mathbb{R}^{N}, \varphi^{\mathrm{megdown}} \leq \varphi^{\mathrm{meg}} \leq \varphi^{\mathrm{megup}}\right\} \tag{19}$$

$$\boldsymbol{D} = \left\{D | D \in \mathbb{R}^{N}, D^{\min} \leq D \leq D^{\max}\right\} \tag{20}$$

B. EQUILIBRIUM STATEGIES

In order to obtain the equilibrium results for game participants, a Stackelberg equilibrium (SE) is represented as the optimal result. Specifically, the SE (φ^{g*}, v^{g*}, $\varphi^{\mathrm{me}^{g*}}$, D^{*}) is achieved when the following conditions are satisfied:

$$I_{\mathrm{EU}}(D^{*}, \varphi^{\mathrm{meg}*}, v^{g*}, \varphi^{g*}) \geq I_{\mathrm{EU}}(D, \varphi^{\mathrm{meg}*}, v^{g*}, \varphi^{g*}) \tag{21}$$

$$I_{\mathrm{MEG}}(D^{*}, \varphi^{\mathrm{meg}*}, v^{g*}, \varphi^{g*}) \geq I_{\mathrm{MEG}}(D^{*}, \varphi^{\mathrm{meg}}, v^{\mathrm{g}}, \varphi^{g*}) \tag{22}$$

$$I_{\mathrm{NGC}}(D^{*}, \varphi^{\mathrm{meg}*}, v^{g*}, \varphi^{g*}) \geq I_{\mathrm{NGC}}(D^{*}, \varphi^{\mathrm{meg}*}, v^{g*}, \varphi^{g}) \tag{23}$$

where, $D^{*} = [D^{\mathrm{e}^{*}}, D^{\mathrm{h}^{*}}, D^{\mathrm{c}^{*}}]$ represents the equilibrium strategy for the EU; $\varphi^{\mathrm{me}^{g*}} = [\varphi^{\mathrm{e}^{*}}, \varphi^{\mathrm{h}^{*}}, \varphi^{\mathrm{c}^{*}}]$ and $v^{g*} = [v_{1}^{g*}, v_{2}^{g*}, \ldots, v_{24}^{g*}]$ represent the equilibrium strategies for the MEG; $\varphi^{g*} = [\varphi_{1}^{g*}, \varphi_{2}^{g*}, \ldots, \varphi_{24}^{g*}]$ represents the equilibrium strategy for the NGC. When the SE strategies are obtained, no participant can further increase its utility by choosing a different strategy other than the SE strategy.

Owing to the hierarchical structure of the Stackelberg game, SE can be deduced by using backward induction. First, we identify the equilibrium strategy of the EU in responding to the MEG's strategy in the lower-level game. Given EU's equilibrium response, we can find the MEG's equilibrium strategy. Upon the information revealed from the MEG, the existence and uniqueness of the equilibrium strategy for the NGC can be proved. The following theorem is proposed to verify that the SE of the hierarchical Stackelberg game exists uniquely.

Theorem 1: In a Stackelberg game, if (a) each participant's strategy set is a non-empty, closed, bounded convex set in the Euclid space; (b) for the leader's optimal strategy, the follower has the only optimal strategy; (c) for the follower's optimal strategy, the leader has the only optimal strategy; an SE exists uniquely.

Proof: (1) The NGC's, the MEG's, and the EU's strategy sets are both non-empty, closed, and bounded convex in the Euclid space. Hence the term (a) of Theorem 1 is satisfied.

(2) First, we identify the equilibrium strategy of the EU in responding to the MEG's optimal strategy.

Given the optimal strategy of the MEG (leader), we can deduce the optimal strategy of the EU (follower). According to the optimization rules, we take the derivative of the EU's utility function I_{EU} with respect to D_t as:

$$\frac{\partial I_{\mathrm{EU}}}{\partial D_{t}} = -\omega_{1} \frac{\varphi_{t}^{\mathrm{meg}}}{P_{0}} + \omega_{2} \frac{b \cdot a^{q(1-\frac{D_{t}}{N_{t}})} \cdot \ln a \cdot q}{Q_{0} \cdot N_{t}} \tag{24}$$

where, $P_0 = P_{\mathrm{M}} - P_{\mathrm{m}}$, and $Q_0 = Q_{\mathrm{M}} - Q_{\mathrm{m}}$. By taking (24) to be zero, we can obtain the optimal strategy of the EU:

$$D_{t}(\varphi_{t}^{\mathrm{meg}}) = N_{t}[1 - \frac{\log_{a}(\frac{\omega_{1} \cdot Q_{0} \cdot N_{t} \cdot \varphi_{t}^{\mathrm{meg}}}{\omega_{2} \cdot b \cdot \ln a \cdot q})}{q}] \tag{25}$$

The second-order derivatives of I_{EU} with respect to D_t and D_k is:

$$\frac{\partial^{2} I_{\mathrm{EU}}}{\partial D_{t} \partial D_{k}} = \begin{cases} -\dfrac{\omega_{2} \cdot b \cdot a^{q(1-\frac{D_{t}}{N_{t}})} \cdot (\ln a)^{2} \cdot q^{2}}{Q_{0} \cdot N_{t}^{2}} & t = k \\ 0 & t \neq k \end{cases} \tag{26}$$

Obviously, the diagonal elements of the Hessian matrix are all negative, and the off-diagonal elements are all zero. Therefore, the Hessian matrix of I_{EU} is negative definite, which indicates that the utility function of the EU is a concave function [34]. The EU's strategy for the given energy sales prices in terms of (25) is guaranteed to be optimal and unique. The term (b) of the Theorem 1 is satisfied.

According to the backward induction principle, the next step is to find MEG's equilibrium strategy in responding to the EU's optimal strategy in form of (25). By substituting the EU's optimal strategy into the MEG's utility function (4), I_{MEG} is transformed into:

$$\begin{aligned} I_{\mathrm{MEG}}(\varphi_{t}^{\mathrm{meg}}) = \sum_{t=1}^{24} (\varphi_{t}^{\mathrm{meg}} D_{t}(\varphi_{t}^{\mathrm{meg}}) \Delta t - C_{t}^{\mathrm{meg}}) \\ - \sum_{t=1}^{24} \rho(D_{t}(\varphi_{t}^{\mathrm{meg}}) - p_{t}^{\mathrm{pv}} - p_{t}^{\mathrm{wt}}) \Delta t \end{aligned} \tag{27}$$

C_{t}^{meg} is a non-linear function of v_{t}^{g} and would not change with the variable $\varphi_{t}^{\mathrm{meg}}$; thus, $C_{i,t}^{\mathrm{meg}}$ can be considered as a constant. We take the second-order derivatives of I_{MEG}, with respect to $\varphi_{t}^{\mathrm{meg}}$ and $\varphi_{k}^{\mathrm{meg}}$:

$$\frac{\partial^{2} I_{\mathrm{MEG}}}{\partial \varphi_{t}^{\mathrm{meg}} \partial \varphi_{k}^{\mathrm{meg}}} = \begin{cases} -\dfrac{N_{t} \cdot (\varphi_{t}^{\mathrm{meg}} + \rho)}{q \cdot \ln a \cdot (\varphi_{t}^{\mathrm{meg}})^{2}} & t = k \\ 0 & t \neq k \end{cases} \tag{28}$$

Similarly, the diagonal elements of the Hessian matrix are all negative, and the off-diagonal elements are all zero. Therefore, the Hessian matrix of I_{MEG} is negative definite, which indicates that the utility function of the MEG is a concave function. Thence, the MEG has a unique optimal strategy for the given EU strategy. The term (c) of the Theorem 1 is satisfied.

(3) Verify the existence of equilibrium strategies for the MEG and the NGC in the upper-level game.

The MEG's utility function I_{MEG} changes linearly in the feasible region of v_t^{g}. The linear function is also a kind of concave function. Consequently, I_{MEG} is proved to be a continuous quasi-concave function for the strategy v_t^{g}, indicating that for the optimal strategy of the NGC (leader), the MEG (follower) has the optimal strategy v^{g*}.

Similarly, the NGC's utility I_{NGC} changes linearly within the feasible region of φ_t^{g}, indicating that it is also a continuous quasi-concave function for the strategy φ_t^{g}. Hence, for the given optimal strategy of the MEG (follower), the NGC (leader)'s optimal gas price strategy exists.

Finally, the profile of strategies $(\varphi^{g*}, v^{g*}, \varphi^{\text{me}^{g*}}, D^*)$ constitutes the unique SE of the proposed hierarchical Stackelberg game, indicating that the proof of Theorem 1 is completed.

C. SOLUTION ALGORITHM

Generally, an overall optimization needs the global information, including utility functions and exact strategies of all participants. However, no participant is willing to disclose its private information to other participants. Considering this situation, we develop a solution algorithm that can deal with each participant's optimization problem separately. Algorithm 1 is proposed for this purpose, and its main steps are as below:

In the upper-level game, the NGC iteratively updates the gas price φ_t^{g} from φ_t^{gdown} to φ_t^{gup}, and issues it to the MEG.

For the given φ_t^{g}, the MEG launches its sub-program with contract EUs to determine its gas-purchasing strategy v_t^{g} and energy sales price strategy φ_t^{meg}. The constraint of v_t^{g} is as follows:

$$0 \leq v_t^{\text{g}} \tag{29}$$

In the lower-level game, the MEG sets the initial energy sales prices based on EUs' historical data and announce the prices to EUs. In addition, the MEG iteratively updates the energy sales price φ_t^{meg} from $\varphi_t^{\text{megdown}}$ to φ_t^{megup}.

After receiving the information of MEG's prices, EUs adjust their actual loads based on (25). The EUs' load strategies are constrained to:

$$\begin{cases} D_t^{\min} \leq D_t \leq D_t^{\max} \\ \sum_{t=1}^{24} D_t = \sum_{t=1}^{24} N_t \\ D_t^{\min} = 0.9 N_t \\ D_t^{\max} = D_t + 0.1 \max\{N\} \end{cases} \tag{30}$$

Algorithm 1 Solution Algorithm for Obtaining SE

```
Input: Parameters of the NGC, the MEG and EUs;
Output: SE $(\varphi^{g*}, v^{g*}, \varphi^{\text{me}^{g*}}, D^*)$ and corresponding utility function values.
for NGC sets gas price $\varphi_t^{\text{g}}$ from $\varphi_t^{\text{gdown}}$ to $\varphi_t^{\text{gup}}$, do
    for MEG sets energy sales price $\varphi_t^{\text{meg}}$ from $\varphi_t^{\text{megdown}}$ to $\varphi_t^{\text{megup}}$, do
        EU solves the $D_t^*$ for the given $\varphi_t^{\text{meg}}$, and calculates $I_{\text{EU}}$.
        According to the feedback demand loads of the EU, MEG optimizes the output of each device and selects the purchased gas amount.
        if condition (21) is satisfied, then
            break
        end if
    end for
    Calculate $I_{\text{MEG}}$ and $I_{\text{NGC}}$ according to the feedback information.
    if conditions (22) and (23) are satisfied, then
        break
    end if
end for
The SE $(\varphi^{g*}, v^{g*}, \varphi^{\text{me}^{g*}}, D^*)$ has been obtained.
```

where, $D_t^{\min}$ and $D_t^{\max}$ are the minimum load and the maximum load, respectively. We define that D_t can be cut or shifted, and the total amount of D_t equals to that of N_t in a day.

Afterwards, the MEG optimizes its outputs based on EUs' feedback energy loads. The MEG determines the purchased gas amount, and calculates its utility function I_{MEG}. The NGC calculates its utility function I_{NGC} according to the released information from the MEG. This process will continue until the conditions (21), (22) and (23) are satisfied, implying that the SE of the proposed hierarchical game model has been obtained. The pseudocode of the algorithm is shown in Algorithm 1.

V. NUMERICAL RESULTS AND ANALYSIS

A. SIMULATION SETTINGS

As stated in previous sections, a typical day is divided into 24 equal periods for the numerical simulation. The energy using-amount of EUs in each period is the basis of simulation. In addition, it is obvious that different EUs respond to the price change in different ways. Accordingly, EUs' price elasticity and energy demand in the optimization horizon are different. In the simulation, we adopt three typical types of EUs: the industrial EU, the commercial EU and the residential EU.

Specifically, the load fluctuations and nominal demands during a typical day of three types of EUs (industrial EU, commercial EU and residential EU) are demonstrated in Fig. 4, which consume about 50%, 30% and 20% of the total energy consumption, respectively. The dissatisfaction

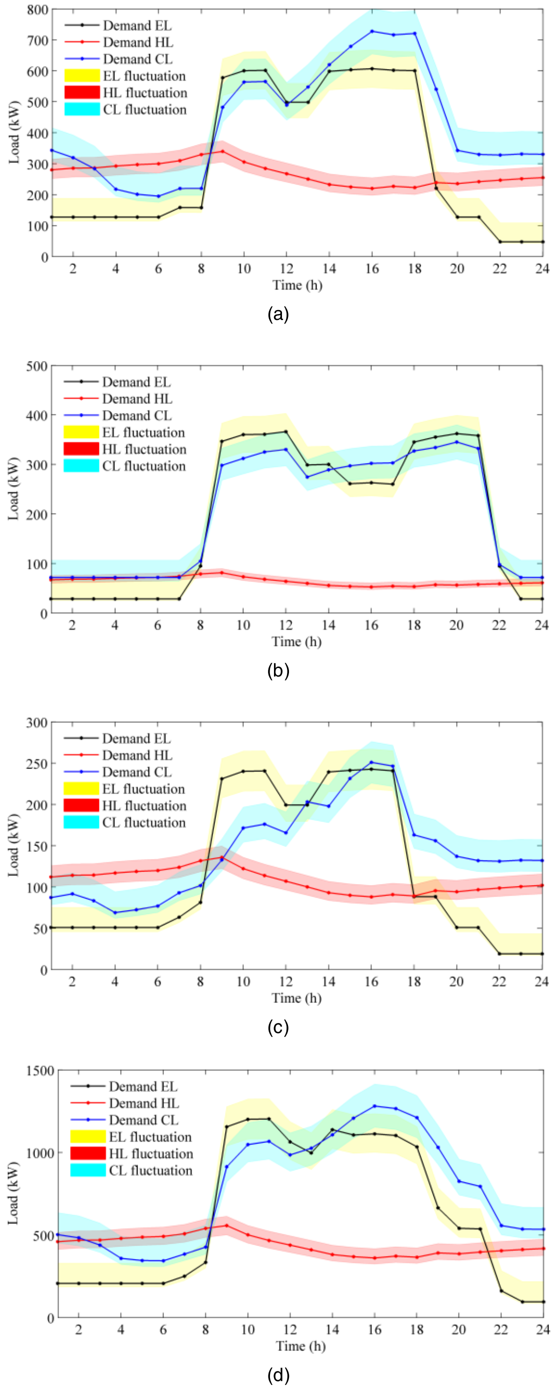


FIGURE 4. Different types of EUs' demand load and fluctuation in a typical day. (a) Industrial EU's data, (b) Commercial EU's data, (c) Residential EU's data, (d) Total EUs' data.

TABLE 1. The related parameters of different EUS.

Type	Industrial EU	Commercial EU	Residential EU
a	8	8	3
b	12	12	12
q	2	5	5
ω_1	0.8	0.4	0.5
ω_2	0.2	0.6	0.5

TABLE 2. The configurations of MEG's devices.

Device	Capacity (kW)	O&M Cost (Yuan/kWh)
Internal combustion engine	1200	0.025
Direct-fired absorption chiller	1500	0.007
Electric chiller	1000	0.01
WT	150	0.01
PV	400	0.0096

TABLE 3. The configurations of different energy storage systems.

Device	Battery Storage	Thermal Storage	Ice Tank	Gas Storage
Capacity (kWh)	1000	1000	1000	1000
Charge-discharge Efficiency	0.9	0.9	0.9	0.95
Maximum Charging Power (kW)	500	500	500	500
Maximum Discharging Power (kW)	500	500	500	500
$SoC_{\min}$	0.2	0.2	0.2	0
$SoC_{\max}$	1	1	1	1
O&M Cost (Yuan/kWh)	0.0018	0.0016	0.0016	0.0016

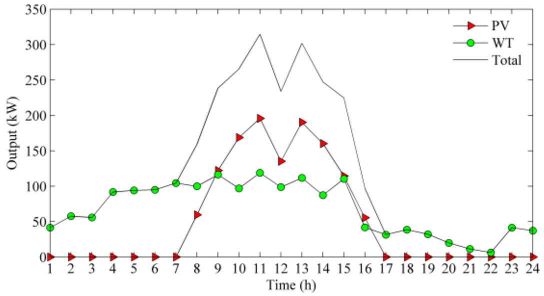


FIGURE 5. Renewable energy outputs of the typical day.

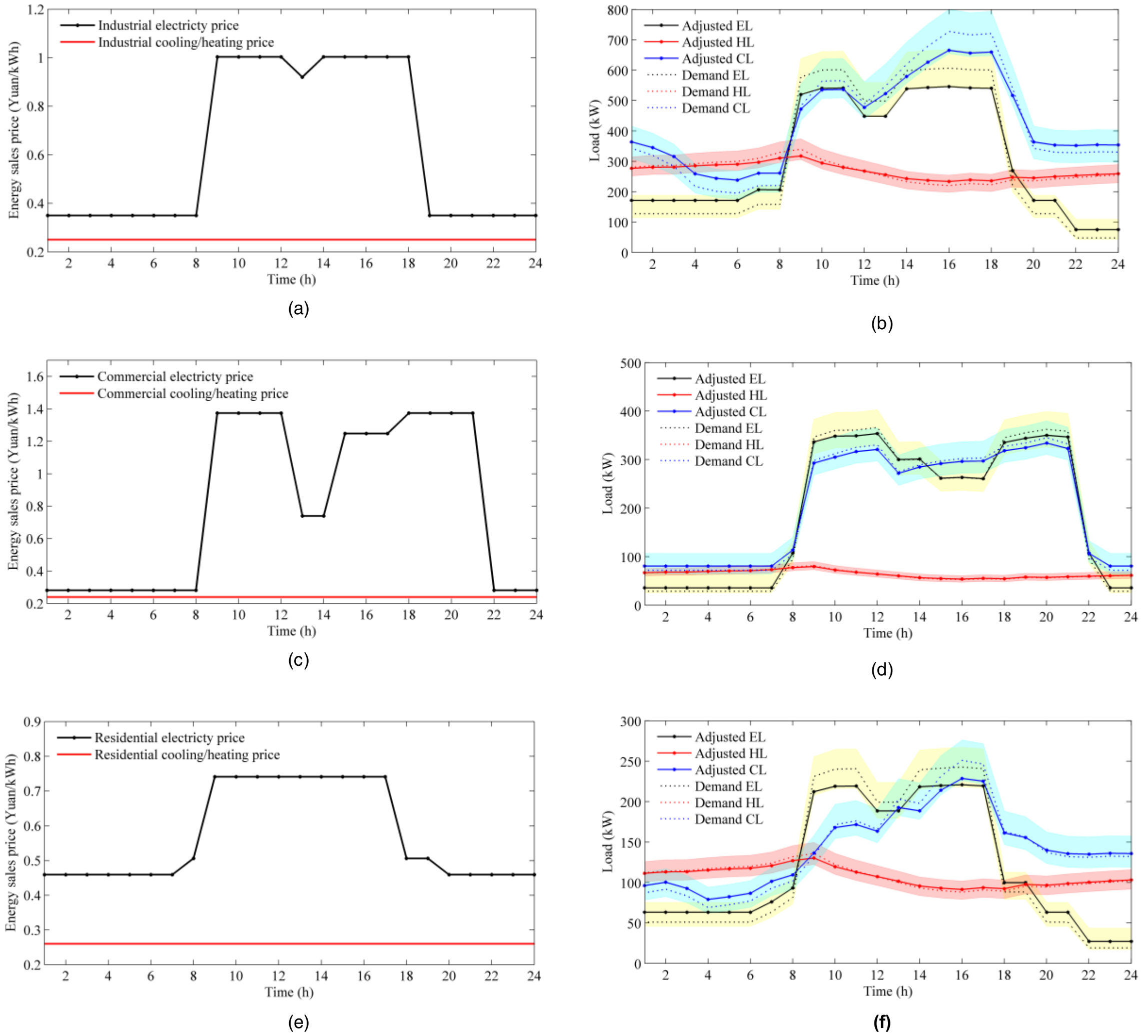
parameters and the weight coefficients of each EU are shown in Table 1.

In terms of the related parameters of the MEG, the configurations of MEG's devices are shown in Table 2, and the configurations of different energy storage systems are presented in Table 3 [18]. For the convenience of calculation, the capacity unit of gas storage is converted into kWh by gas heat value (GHV). The GHV takes 35.16 MJ/m^3, which equals to 9.77 kWh/m^3. According to [10], [12] and [18], the related energy devices coupled by the MEG are modeled. In addition, ρ is 0.01 Yuan/kWh, and the TOU electricity sales price φ_t^{ge} of the power grid is demonstrated in Table 4 [31]. Fig. 5 gives the renewable energy outputs of the typical day.

Regarding the NGC, γ_{g} is 0.968 kg/kWh, φ_{emi} is 0.02 Yuan/kg, and μ is selected to be 1.0 [28], [35].

B. NUMERICAL RESULTS ANALYSIS

In order to better analyze the impact of TOU gas pricing on the MEG operation, we adopt the single gas pricing as



(a) (b) (c) (d) (e) (f)

FIGURE 6. SE energy sales prices and adjusted loads for different EUs. (a) SE industrial prices, (b) SE industrial loads, (c) SE commercial prices, (d) SE commercial loads, (e) SE residential prices, (f) SE residential loads.

TABLE 4. TOU electricity sales price.

Periods	Duration	Price (Yuan/kWh)
High peak	11:00 - 13:00 20:00 - 21:00	1.44
Peak	10:00 - 15:00 18:00 - 21:00	1.32
Flat	7:00 - 10:00 15:00 - 18:00 21:00 - 23:00	0.84
Valley	23:00 - 7:00	0.38

a comparison experiment. Hence, we have two scenarios for optimal simulation:

Scenario 1: the NGC adopts the single gas pricing.

Scenario 2: the NGC adopts the TOU gas pricing.

Using the data mentioned above, we employ the proposed hierarchical transaction model to search the SE gas prices for the NGC. The transaction optimization problem could be solved by mixed integer nonlinear programming (MINLP) with the fmincon solution engine in Matlab platform.

TABLE 5. EUs' SE results in the transaction.

Type	I_{EU}	P (Yuan)	Q
Industrial EU	0.7080	10164.84	-93.59
Commercial EU	0.5201	6919.60	-131.81
Residential EU	0.6469	3424.31	-90.46

Through this approach, we can obtain the SE gas prices, along with SE strategies of both MEG and EUs. We analyze the numerical results of the transaction model according to different scenarios.

- MEG-EUs transaction results analysis

According to the proposed transaction model, the SE results of the MEG and EUs obtained through programming are demonstrated in Table 5 and Fig. 6.

Analyzing Table 5 and Fig. 6, we can draw the following conclusions:

(1) The energy sales prices are considerably different in different TOU periods. In TOU pricing situation, EUs prefer

to adjust the flexible loads in off-peak periods due to the low prices, especially for the industrial EU.

(2) The load adjustments of industrial and residential EUs are relatively larger because of their high economic weight coefficients and dissatisfaction parameters. It indicates these two types of EUs are sensitive to prices, and they adjust loads as possible as they can to balance the expenditure P and the dissatisfaction Q.

(3) The optimal dissatisfaction value Q of the commercial EU is -131.81, which is the minimum among three EUs. Despite the commercial TOU prices are the highest among the three, only a small part of the less urgent loads are shifted to other periods of the day. It implies that the commercial EU is most satisfied with the energy-usage in the typical day, and least sensitive to prices. This is consistent with the commercial EU's parameter settings.

(4) The industrial EU's expenditure P is higher than that of other EUs, and its dissatisfaction Q is also relatively higher. However, as the flexible loads and weight coefficient ω_1 of industrial EU are relatively larger, the industrial EU prefers to cut loads for reducing the expenditure. The industrial I_{EU} is larger than the other two, which illustrates the utility functions can be compared under different energy demands and dissatisfaction parameters through fuzzy optimization.

(5) Compared with the TOU electricity price, the cooling/heating price is a single price during the whole day, because of the stable supply of natural gas. In the transaction, the cooling demands of EUs are high, so the cooling strategy makes a certain change for reducing the expenditure. Conversely, the heating load change during all periods is not particularly obvious, due to the low heating demands, which will not have a great impact on the expenditure.

(6) In the lower-level transaction, EUs are more sensitive to MEG's electricity price, and can adapt to the TOU price with dynamic load balancing. Taking the industrial EU as an example, in the valley price periods (1-8, 19-24), the industrial EU shifts a certain loads from peak periods to these periods, which results in the lower dissatisfaction. In the peak price periods (9-13, 14-18), the electrical demands are large, so the industrial EU cuts the non-essential loads as possible as it can, for reducing the expenditure.

- NGC-MEG transaction results analysis

Table 6 presents the main SE results for the NGC and the MEG in different scenarios, including the NGC's utility, the MEG's utility, the production cost of the MEG and the total social welfare. From Table 6, we can see that:

(1) In the single gas pricing scenario, there is no economic incentive for the MEG to adjust its gas consumption according to the price signal issued by the NGC. In this situation, the gas is a single stable product without dynamic properties, which cannot promote MEG to consume. Without the adjustment, the production cost of the MEG tends to be relatively high, and the utility I_{MEG} is not so well.

(2) In the TOU gas pricing scenario, the gas prices are considerably different in different time-block periods, which are initially set according to the EUs' demand loads. In this situation, the MEG will adjust its gas consumption according to the TOU price signal, aiming at reducing the production cost. Compared with the SE results in scenario 1, the production cost of the MEG drops by 20.54% meanwhile the utility goes up to 5407.02 Yuan. It indicates that the MEG is more economical to operate in the TOU gas pricing scenario.

TABLE 6. The SE results for NGC and meg in the upper-level transaction.

Scenarios	I_{NGC} (Yuan)	I_{MEG} (Yuan)	C^{meg} (Yuan)	Social welfare (Yuan)
Scenario 1	10294.07	1818.79	17471.17	12112.86
Scenario 2	10293.06	5407.02	13882.94	15700.08

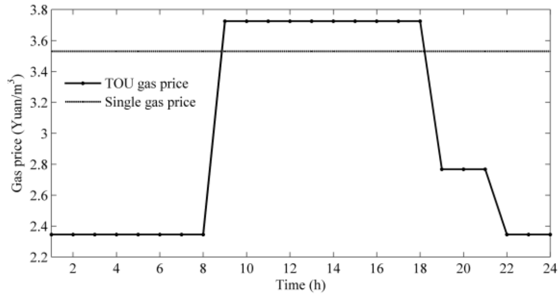


FIGURE 7. The SE gas prices of Scenario 1 and Scenario 2.

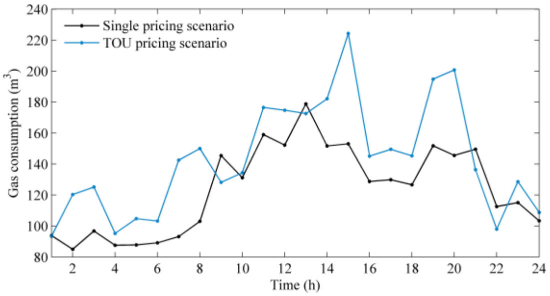


FIGURE 8. The gas consumption of Scenario 1 and Scenario 2.

(3) The total social welfare is calculated by adding the NGC's utility and the MEG's utility. It can be observed that TOU gas pricing achieves the higher social welfare than single gas pricing.

The SE gas prices of Scenario 1 and Scenario 2 are shown in Fig. 7, and the corresponding gas consumption is presented in Fig. 8. The optimal output results of the MEG in different scenarios at the SE point are demonstrated in Fig. 9 and Fig. 10, respectively. For the sake of brevity, the legends of Fig. 9 and Fig. 10 are shown in abbreviations. Please refer to the APPENDIX for details of the abbreviations.

By analyzing the optimal results from Fig. 7 to Fig. 10, the following conclusions can be drawn:

(1) In terms of gas pricing, the TOU pricing is better at shifting peak period loads to off-peak period than the single pricing, which could improve economic efficiency of the MEG operation. The single pricing usually causes inefficiencies in the open energy market, while the TOU pricing plays a leverage to balance the gas supply and demand. The TOU

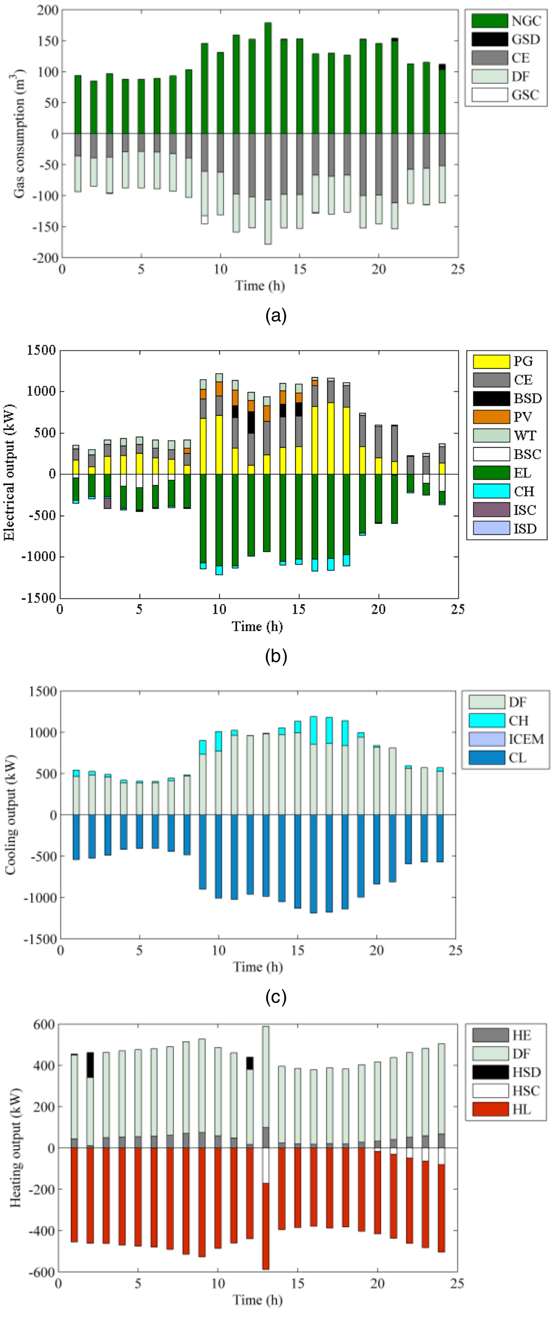


FIGURE 9. **The optimal output results of the MEG in Scenario 1. (a) The optimal gas consumption results, (b) The optimal electrical output results, (c) The optimal cooling output results, (d) The optimal heating output results.**

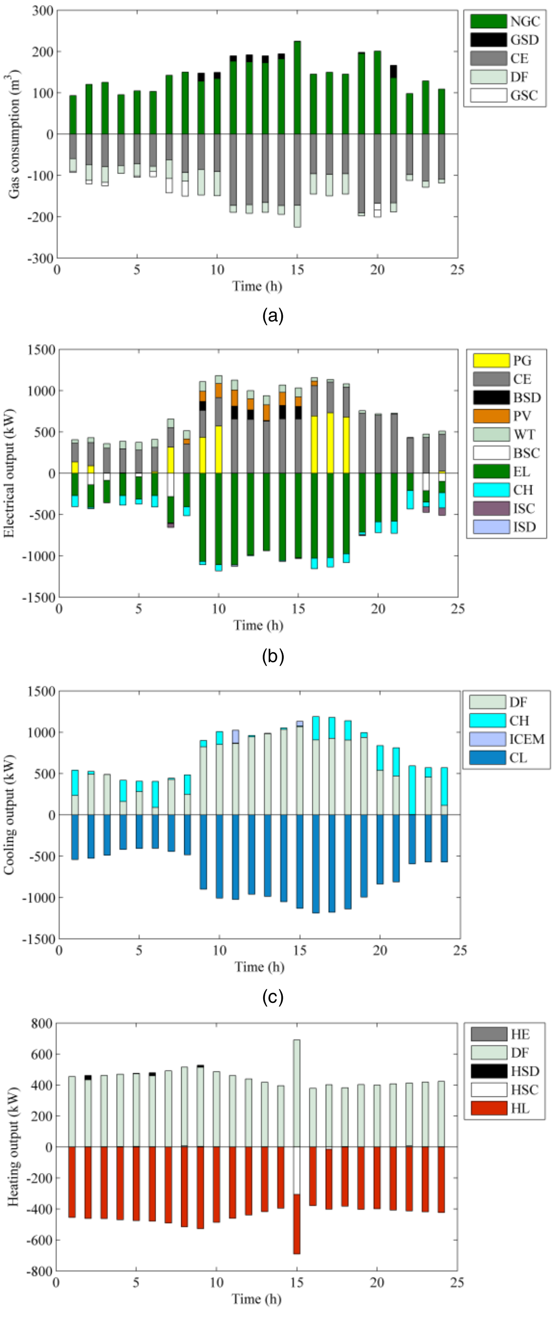


FIGURE 10. **The optimal output results of the MEG in Scenario 2. (a) The optimal gas consumption results, (b) The optimal electrical output results, (c) The optimal cooling output results, (d) The optimal heating output results.**

pricing could be an effective strategy to improve economic and energy efficiencies for both NGC and MEG.

(2) Compared with the gas consumption in Scenario 1, the total gas consumption has increased in Scenario 2. The MEG responses to the TOU gas prices and reschedules its gas consumption to a certain degree. In the off-peak periods (1-8, 19-24), the gas consumption has a certain growth, except periods 21 and 22. This may be due to the lower gas prices in these periods. In the peak periods (9-18), the gas price is higher than that in Scenario 1. Meanwhile, the corresponding gas consumption has both increased and decreased, which may be related to the operating strategy of the MEG. Although the utilities of the NGC are similar in two scenarios, the production cost of the MEG is falling by 20.54% with TOU pricing. It indicates that the TOU gas pricing has a significant effect on MEG's operation, which is more effective to reduce the production cost.

(3) Under TOU gas pricing, the gas storage can operate in a more flexible way. In the lower price periods, the gas storage

purchases a certain amount of gas to storage, preparing for discharging gas in the higher price periods. In the higher price periods (9-14, 21), the gas storage operates in discharging mode for reducing the gas-purchasing expenditure. However, when the gas prices are presented the same throughout the day, the MEG will consume the gas whenever it needs. Therefore, the gas storage is not so useful under single gas pricing.

(4) Since the SE results of the whole transaction are obtained by backward induction, the optimal results of the lower-level transaction in these two scenarios are the same. Hereon, the total EUs' expenditure is 20508.75 Yuan, which is the same as the revenue of the MEG.

(5) In terms of electrical output scheduling, when the gas prices are lower, the MEG prefers to use internal combustion engine to produce electricity, instead of purchasing electricity from the grid. Moreover, when both gas prices and electricity sales prices are high, the MEG will compare the efficiencies of the both and choose the proper way to generate electricity. The mixed application of TOU gas price and TOU electricity sales price would be of great value for improving economic and energy efficiency, which is of positive significance under the "electricity marketization trading" environment in China.

To summarize, TOU gas pricing is an effective measure in the energy market-opening environment. Though the market is still under construction, it is necessary to introduce the value and application scenarios of the TOU gas pricing.

VI. CONCLUSION

This paper has proposed an analytical bi-level transaction model considering TOU gas pricing in the energy market-opening environment based on Game Theory. The multiple energies trading is conducted between the NGC, the MEG and EUs, which forms a hierarchical Stackelberg game model. The SE of the proposed game model has been proved to be existed uniquely. For the coming energy market-opening transactions involving different entities, such a game framework can guarantee a unique market equilibrium. To explore the equilibrium strategies of all participants, a bi-level MINLP is formulated to solve the optimization problem for the proposed game structure of multiple energies trading.

To verify the feasibility and economic efficiency of the proposed transaction model, case studies are conducted in two different scenarios: the single gas pricing scenario and the TOU gas pricing scenario. SE results of respective scenarios are explored, revealing the following conclusions:

(1) The SE results indicate that the TOU pricing can well balance the gas supply and demand, which has significant potential for improving the economic efficiency of the MEG operation.

(2) In terms of the load adjustment, different types of EUs have different sensitivities to MEG's energy sales prices. The industrial EU is most sensitive, while the commercial EU is most insensitive, and the residential EU is in the middle.

(3) In the case of similar NGC utilities, TOU gas pricing can help the MEG meet EUs' demands at a lower production cost. In other words, TOU gas pricing raises MEG's profits in some degree. Moreover, we can observe that TOU gas pricing achieves the higher social welfare than single gas pricing.

The analysis in this paper provides effective advices for TOU gas pricing for the NGC, and economic operation for the MEG in the future energy market. Future extensions of the research can focus on multi-leader (the NGC, the power supply company) multi-follower (MEGs, EUs) transaction, and cooperative game among different participants. Moreover, in the future research, the real-time TOU gas pricing strategy could be introduced in the transaction.

APPENDIX

ABBREVIATIONS

TOU	time-of-use
MEG	micro energy grid
NGC	natural gas company
EU	energy user
SE	Stackelberg equilibrium
CCHP	combined cooling, heating and power
PV	photovoltaic
WT	wind turbines
EL	electrical load
HL	heating load
CL	cooling load
GSD	gas storage discharges
CE	internal combustion engine
DF	direct-fired absorption chiller
GSC	gas storage charges
PG	power grid
BSD	battery storage discharges
BSC	battery storage charges
CH	electric chiller
ISC	ice storage device charges
ISD	ice storage device discharges
ICEM	ice-storage air-conditioner melts ice
HE	heat exchanger
HSD	heating storage discharges
HSC	heating storage charges
GHV	gas heat value
MINLP	mixed integer nonlinear programming

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