Research on electric heating integrated system based on multi-factor game equilibrium

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Abstract: Taking the electric heating joint market as the research object, based on the standard Nash game model framework, a two-stage game model consisting of consumers, energy suppliers and electric heating joint trading center is established. It reveals the electric heating joint trading center and the consumer game mechanism, analyzes the game process, and proposes the overall structure of the game in the electric heating joint market, uses a distributed algorithm to solve the model, and establishes the optimal strategy for the interests of both parties. Finally, the model was simulated and verified, and the conclusion showed that the peak-to-average ratio decreased to 1.42 by using the method in this paper, which is lower than the value of 1.51 in the traditional method. The fluctuation range of electricity price is between 9.43~18.56 ¢/kWh, and its highest and lowest values are both smaller than the peak-valley price in the time-of-use tariff strategy.

1. Introduction
As the coupling of power and thermal systems continues to deepen, in order to realize the cascade utilization of energy and the improvement of overall efficiency, it is necessary to carry out research on joint planning and optimized operation control technology for power and thermal systems. As the capacity of combined heat and power units accounts for a large proportion in northern my country, it is a forward-looking and challenging task to optimize the integrated electric heating integrated energy system in the future.

Many scholars have also conducted research. Quanyan Zhu researched the game theory model and design mechanism of deception and anti-deception [¹]; Xiaotong Wu researched game theory about mobile location privacy [²]; Jing Yu, Hongbin Sun, Xinwei Shen. On the premise of fully studying the operating mechanism of the thermal storage tank, a day-ahead combined optimal dispatching model of thermoelectricity with the thermal storage tank is established [³]; Zepeng Gu, Chongqing Kang, Xinyu Chen and others have established an optimization model of an electric heating energy integrated system with heating network constraints. Although the temperature difference of the return water node is considered, the calculation model needs to establish a complex correlation solution matrix, which is slowly and computationally intensive [⁴]; Bozchalul MC, Hashmi SA, Hassen H proposed an intelligent intelligent decision system based on mathematical models [⁵]; Oneill R, Castillo A, Eldridge B proposed an axiomatic dual pricing method based on causality to determine price and cost allocation [⁶]; However, there are few studies on the optimization of the electric heating integrated system using game theory. This paper uses a two-stage game model to study the optimization of the electric heating
integrated system, which improves the energy utilization level and reduces the energy cost of consumers.

2. The overall structure of the two-stage game in electric heating joint market

Consider a smart electric heating integrated energy system with many consumers and multiple energy suppliers. The framework of the electric heating joint market is shown in Figure 1. CN represents a collection of consumers, and GN represents a collection of energy suppliers. Each consumer is equipped with a micro-energy management system that can automatically formulate energy consumption plans. Each micro-energy management system has a communication function and is connected to the electric heating joint trading center to form a communication local area network. Consumers, energy suppliers, and the electric heating joint trading center complete information exchange through the local area network. The electric heating joint trading center is responsible for sending real-time energy prices to the micro-energy management system. The micro-energy management system calculates and updates the energy consumption strategy and sends the energy demand to the electric heating joint trading center. The electric heating joint trading center collects the information after receiving the demand, and then calculates the total demand, the amount is sent to the energy supplier, and the supply side and the demand side maximize their own interests during the entire game process.

This paper uses a distributed algorithm to solve the model. Consumer revenue equals "user utility" minus the total cost of "purchasing electrical energy and heat", and "energy supplier revenue" equals "total revenue" minus "energy production cost".

\[
\sum_{i \in CN} h_{it} = \sum_{j \in GN} HL_{jt},
\]

\[
\sum_{i \in CN} p_{it} + \sum_{j \in GN} ph_{jt} = \sum_{j \in GN} PL_{jt},
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The price functions of electricity and heat are as follows:

\[
price_{eit} = price_{eit0} \left( \sum_{i \in CN} ph_{it} - \lambda_{eit0} \sum_{j \in GN} PL_{jt} \right)
\]

\[
price_{hit} = price_{hit0} \left( \sum_{i \in CN} h_{it} - \lambda_{hit0} \sum_{j \in GN} HL_{jt} \right)
\]
Among them, $price_{h0}$ and $price_{p0}$ are to guide electricity prices and heat prices, respectively. $\lambda^p_i$ and $\lambda^h_i$ are to achieve flexible pricing while ensuring the balance of market supply and demand.

Based on the price information broadcast at time $t$ in the combined electric and heating transaction, consumer $i$ adjusts his energy use plan $e_{i,t} = \{p_{i,t}, h_{i,t}, ph_{i,t}\}$ to reduce energy cost, let $e_{-i,t}$ denote the set of other consumer strategies except consumer $i$. Consumer income = user utility-total cost of purchasing electrical and thermal energy:

$$U^c_{i,t}(e_{i,t}, e_{-i,t}) = U^p_{i,t}(p_{i,t}) + U^h_{i,t}(h_{i,t}) + U^{p2h}_{i,t}(ph_{i,t}) - price_{p_j} * (p_{i,t} + ph_{i,t}) - price_{h_j} * h_{i,t}$$

(5)

This article divides household appliances into two categories: power-to-heat (P2H) equipment and non-electric-to-heat (non-P2H) equipment.

- $p_{i,t}$ ——Electric power consumed by consumers on non-P2H equipment;
- $ph_{i,t}$ ——Electric power consumed by P2H equipment;
- $h_{i,t}$ ——Thermal energy purchased directly by consumers from energy suppliers;
- $U^p_{i,t}$ ——The utility of consumers using non-P2H equipment;
- $U^h_{i,t}$ ——The utility obtained by consumers using heat energy purchased from energy suppliers;
- $U^{p2h}_{i,t}$ ——The utility of consumers using P2H equipment;

According to the total energy information broadcast at time $t$, each supplier $j$ makes its own production plan $E_{j,t} = \{PL_{j,t}, HL_{j,t}\}$, and let $E_{-j,t}$ denote the collection of production plans of all suppliers except energy supplier $j$. Total revenue of energy supplier $j$ = total revenue-energy production cost.

$$U^G_{j,t}(PL_{j,t}, HL_{j,t}) = price_{p_j} * PL_{j,t} + price_{h_j} * HL_{j,t} - C^p_{j}(PL_{j,t}) - C^h_{j}(HL_{j,t})$$

(6)

- $PL_{j,t}$ ——Electricity produced by energy suppliers;
- $HL_{j,t}$ ——Heat produced by energy suppliers;
- $C^p_{j}(PL_{j,t})$ ——The cost of electricity produced by energy suppliers;
- $C^h_{j}(HL_{j,t})$ ——Energy suppliers produce thermal energy;

The two-stage game model process is as follows:

The first stage: The micro-energy management system receives energy price information from the electric heating joint trading center through the local area network, formulating the latest energy strategy, and then separately sending the demand information to the electric heating joint trading center.

The second stage: The electric heating joint trading center summarizes the demand, sends the demand to the energy supplier, and the supplier competes and competes for the market, and arranges the energy production plan according to the Nash equilibrium solution. The energy producer sends the production plan to the electric heating joint trading center, and then the trading center calculates the price, and the trading center announces the latest energy prices to consumers.

3. Simulation analysis

The simulation analysis of the proposed two-stage game model for the electric heating joint market is carried out. The input conditions of this example are: a small case constructed by 2 energy suppliers and 500 consumers. The indoor temperature is considered to be a known parameter that can be measured in real time, $h_j$ can be based on consumption Set by the user, the guide electricity price $price_{p0}=15 \ $/kWh, and the guide heat price $price_{h0}=10 \ $/kWh, all energy suppliers can
supply energy to any consumer. In order to show the effect of the two-stage game model, the price of time-sharing energy is used as a comparative example. The peak price under the time-of-use tariff is 20¢/kWh, the trough price is 10¢/kWh, and the peak-to-average ratio is 1.51. The peak heat price under the time-of-use heat price is 15¢/kWh, and the trough price is 5¢/kWh, and the peak-to-average ratio is 1.39.

Using the two-stage game model, the peak electricity price is 18.56¢/kWh, and the trough price is 9.43¢/kWh, peak-to-average ratio is 1.42. The upper and lower limits of the peak-valley price under the two-stage game model are smaller than the upper and lower limits of the time-of-use tariff, and the peak-to-average ratio is reduced from the original 1.51 to 1.42, which effectively reduces the energy cost of users. The simulation results of 24-hour power demand are shown in Figure 2.

![Figure 2. Electricity demand and electricity price changes in different time periods](image)

Using the two-stage game model, the peak heat price is 13.9¢/kWh, the trough heat price is 4.3¢/kWh, and the peak-to-average ratio is 1.26. The upper and lower limits of the peak-valley heat price under the two-stage game model are all smaller than the upper and lower limits of the time-of-use heat price, and the peak-to-average ratio is reduced from 1.39 to 1.26. The simulation result of the 24-hour heat demand is shown in Figure 3.

![Figure 3. Heat demand and heat price changes in different time periods](image)
4. Conclusion
This paper takes the electric heating joint market as the research object, based on the standard Nash game model framework, and establishes a two-stage game model composed of consumers, energy suppliers and electric heating joint trading centers. The electric heating joint trading center summarizes energy demand and releases energy demand information to energy suppliers. The suppliers play games with each other and the trading center calculates the price and releases it to the consumer. Consumers adjust energy use strategies based on the released price information and send them separately trading center. After repeated iterations, the Nash equilibrium point of the market, that is, the optimal energy supply plan, is obtained. The energy price obtained by adopting the two-stage game model effectively reduces the peak electricity price and heat price, reduces the energy cost of consumers, improves the distribution time of the system load, promotes the scientific and orderly use of energy by residents, improves the energy utilization rate, and guarantees sustainable economic and social development.

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