

Pricing and Energy Management Optimization of Combined Heating and Power Integrated Energy System Based on Stackelberg Game

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ABSTRACT

Combined heating and power integrated energy system (CHP-IES) enables efficient coordination and dispatch of multiple energy sources, enhancing renewable energy utilization and overall efficiency, thus serving as a key technical approach to support the low-carbon transition under the dual carbon goals. First, the paper develops a detailed model of key components in the system, including gas turbines, gas-fired boilers, electrical energy storage, and thermal energy storage, thereby capturing the multi-energy flow coupling relationships within CHP-IES. Second, a pricing mechanism based on the Stackelberg game is established, in which the distributed energy resource (DER) operator acts as the leader and the users serve as followers. The CHP-IES dynamically determines electricity and heat prices based on market signals, while users adjust their flexible electricity and heat loads in response to price signals. Finally, the proposed method is validated through a case study.

Keywords: CHP-IES, multi-energy flow coupling, pricing and energy management optimization, Stackelberg game

NONMENCLATURE

Abbreviations

| | |
|---------|---|
| CHP-IES | Combined heating and power integrated energy system |
| DER | Distributed energy resource |

Symbols

| | |
|--------------|--|
| $P_{chr}(t)$ | The charging power of energy storage |
| $U_{chr}(t)$ | The charging state variable of energy storage |
| $U_{dis}(t)$ | The discharging state variable of energy storage |
| $SOC(t)$ | The state of charge of energy storage |
| η_{chr} | The charging efficiency of energy storage |

| | |
|----------------|--|
| η_{dis} | The discharging efficiency of energy storage |
| γ_H | The energy loss rate of heat storage |
| η_{Hchr} | The efficiency of heat storage |
| η_{Hdis} | The efficiency of heat release |
| $H_{chr}(t)$ | The power of heat storage |
| $H_{dis}(t)$ | The power of heat release |
| $W(t)$ | The total thermal energy |
| $U_{Hchr}(t)$ | The heat storage state variable |
| $U_{Hdis}(t)$ | The heat release state variable |
| $G_{GT}(t)$ | The consumption of natural gas |
| $P_{GT}(t)$ | The output of gas turbine |
| $H_{HE}(t)$ | The heat recovery power of gas turbine |
| η_{GT} | The heat recovery efficiency of gas turbine |
| λ_{GT} | The output electric heating power ratio of gas turbine |
| $H_{GB}(t)$ | The output thermal power of gas-fired boiler |
| $G_{GB}(t)$ | The input gas power of gas-fired boiler |
| η_{GB} | The thermal efficiency |
| $P_B(t)$ | The purchasing power of CHP-IES |
| $P_S(t)$ | The selling power of CHP-IES |
| C_{sell} | The income from energy supply |
| $C_{grid}(t)$ | The grid interaction costs |
| $C_{chp}(t)$ | The fuel cost of CHP-IES |
| $C_h(t)$ | The operation and maintenance costs of CHP-IES |
| $P_{el}(t)$ | The electrical load of users |
| $Q_{hl}(t)$ | The heat load of users |
| $c_{e,s}(t)$ | The CHP-IES's electricity selling price to users |
| $c_{h,s}(t)$ | The CHP-IES's heat selling price to users |

| | |
|---------------------|--|
| $c_{g,s}(t)$ | The CHP-IES's electricity selling price to upper grid |
| $c_{g,b}(t)$ | The CHP-IES's heat selling price to upper grid |
| $f_u(t)$ | The utility function of users |
| $P_{sel}(t)$ | The transferable electricity load of users |
| P_{sel}^{\max} | The transferable electricity load upper limit of users |
| W_{sel} | The total transferable electricity load of users |
| $Q_{fhl}(t)$ | The fixed heat load |
| $Q_{shl}(t)$ | The transferable heat load |
| $Q_{shl}^{\max}(t)$ | The transferable heat load upper limit of users |

1. INTRODUCTION

High efficiency, cleanliness, and low carbon have become the core objectives of the global energy transition [1]. To meet these goals, it is essential to promote the deep integration of energy systems with information technology, digital innovation, and other emerging technologies [2]. Building an integrated energy system that can flexibly accommodate distributed energy, diverse energy demands, and new service models is both a pressing requirement for system innovation and a key pathway to achieve strategic energy restructuring [3]. The combined heating and power integrated energy system (CHP-IES), with combined heating and power as its core structure, leverages the dynamic synergy of the entire "source-grid-load" chain [4]. Through multi-energy coupling and intelligent control mechanisms, CHP-IES significantly enhances the consumption of renewable energy and improves overall energy efficiency [5]. The structure of CHP-IES is illustrated in Fig. 1.

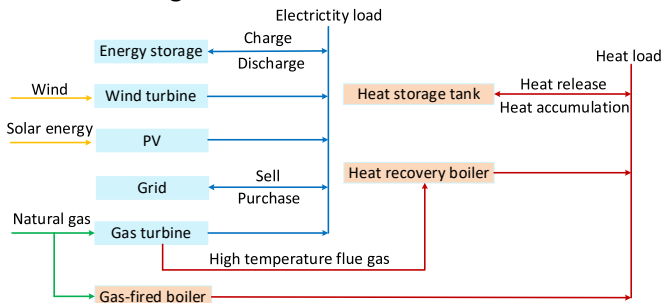


Fig. 1 The structure of CHP-IES

CHP-IES enables coordinated and optimized management of energy generation, transmission, conversion, consumption, and trading [6]. It features several new characteristics, including multi-energy flow coupling, multiple time scales, and diverse operating

conditions. These complexities make its optimal operation particularly challenging. Reference [7] proposes a multi-level Nash multi-stage robust optimization model for multi-integrated energy systems, achieving efficient and low-carbon operation under uncertainties in electricity prices and source-loads. Reference [8] proposes a robust state estimation method for electricity-gas-heat integrated energy systems based on dynamic modeling and kernel density-enhanced Kalman filtering, achieving high accuracy and resilience against bad data.

Therefore, we present a pricing and energy management optimization method for a (CHP-IES). A Stackelberg game-based pricing mechanism is designed to coordinate electricity and heat pricing between the system operator and users. Numerical results confirm the method's effectiveness in improving energy efficiency and supporting flexible, low-carbon system operation.

2. THE MODELING OF CHP-IES

2.1 The modeling of energy storage

To avoid the unfavorable effects of charging and discharging at low power and low charge state, the energy storage should be operated to satisfy the charging and discharging constraints and the charge state constraints.

$$U_{chr}(t)P_{chr}^{\min} \leq P_{chr}(t) \leq U_{chr}(t)P_{chr}^{\max} \quad (1)$$

$$U_{dis}(t)P_{dis}^{\min} \leq P_{dis}(t) \leq U_{dis}(t)P_{dis}^{\max} \quad (2)$$

$$SOC(t) = SOC(t-1) + [\eta_{chr}P_{chr}(t) - P_{dis}(t) / \eta_{dis}] \Delta t \quad (3)$$

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max} \quad (4)$$

2.2 The modeling of heat storage

Heat storage tanks can store heat when there is a surplus of heat and release heat when there is a shortage of heat or when the cost of heat production is high, improving the flexibility and economy of system operation.

$$W(t) = W(t-1)(1 - \gamma_H) + \eta_{Hchr}H_{chr}(t) - H_{dis}(t) / \eta_{Hdis} \quad (5)$$

$$W_{\min} \leq W(t) \leq W_{\max} \quad (6)$$

$$U_{Hchr}(t)H_{chr}^{\min} \leq H_{chr}(t) \leq U_{Hchr}(t)H_{chr}^{\max} \quad (7)$$

$$U_{Hdis}(t)H_{dis}^{\min} \leq H_{dis}(t) \leq U_{Hdis}(t)H_{dis}^{\max} \quad (8)$$

2.3 The modeling of gas turbine

The gas turbine in CHP-IES generates electricity while generating waste heat to output thermal power through a waste heat boiler, whose electrical and thermal output are as follow:

$$\begin{cases} G_{GT}(t) = a'P_{GT}^2(t) + b'P_{GT}(t) + c'I_{GT}(t) \\ H_{HE}(t) = \eta_{GT}P_{GT}(t) / \lambda_{GT} \end{cases} \quad (9)$$

$$\begin{cases} P_{GT}^{\min} \leq P_{GT}(t) \leq P_{GT}^{\max} \\ P_{GT}^{\text{down}} \leq P_{GT}(t) - P_{GT}(t-1) \leq P_{GT}^{\text{up}} \end{cases} \quad (10)$$

2.4 The modeling of gas-fired boiler

Gas boiler is the main heating equipment, through the combustion of natural gas to produce heat energy to supplement the heat load of the gas turbine heat production is insufficient.

$$\begin{cases} H_{GB}(t) = \eta_{GB}G_{GB}(t) \\ 0 \leq H_{GB}(t) \leq H_{GB}^{\max} \end{cases} \quad (11)$$

2.5 The modeling of CHP-IES interaction with upper grid

CHP-IES can purchase and sell power from upper grid to maintain electrical load balancing within the system.

$$\begin{cases} 0 \leq P_B(t) \leq P_B^{\max} \\ 0 \leq P_S(t) \leq P_S^{\max} \end{cases} \quad (12)$$

3. THE EARNINGS MODELING OF CHP-IES BASED ON STACKELBERG GAME

3.1 The revenue model of distributed energies

The DER operator is the leader in CHP-IES, assuming the responsibility of balancing the power of the system and playing the role of leaders in Stackelberg game. The optimization goal of DER is to maximize the revenue.

$$\max E_{\text{eso}} = \sum_{t=1}^T [C_{\text{sell}}(t) - C_{\text{grid}}(t) - C_{\text{chp}}(t) - C_h(t)] \quad (13)$$

$$C_{\text{sell}}(t) = [P_{\text{el}}(t)c_{e,s}(t) + Q_{\text{hl}}(t)c_{h,s}(t)]\Delta t \quad (14)$$

$$C_{\text{grid}}(t) = [\max(P_{\text{el}}(t) - P_{\text{es}}(t), 0)c_{g,s}(t) + \min(P_{\text{el}}(t) - P_{\text{es}}(t), 0)c_{g,b}(t)]\Delta t \quad (15)$$

$$C_{\text{chp}}(t) = a_e P_{GT}^2(t) + b_e P_{GT}(t) + c_e + a_h Q_{GB}^2(t) + b_h Q_{GB}(t) + c_h \quad (16)$$

3.2 The revenue model of users

Users optimize the power of their own electricity and heat loads for a given energy sales price with the aim of

maximizing the difference between the user's utility function and the cost of energy use.

$$\max F_{\text{user}} = \sum_{t=1}^T [f_u(t) - P_{\text{el}}(t)c_{e,s}(t) - Q_{\text{hl}}(t)c_{h,s}(t)]\Delta t \quad (17)$$

$$0 \leq P_{\text{sel}}(t) \leq P_{\text{sel}}^{\max} \quad (18)$$

$$\sum_{t=1}^T P_{\text{sel}}(t)\Delta t = W_{\text{sel}} \quad (19)$$

$$Q_{\text{hl}}(t) = Q_{\text{fhl}}(t) + Q_{\text{shl}}(t) \quad (20)$$

$$0 \leq Q_{\text{shl}}(t) \leq Q_{\text{shl}}^{\max} \quad (21)$$

3.3 CHP-IES balance constraints

Users optimize the power of their own electricity and heat loads for a given energy sales price with the aim of maximizing the difference between the user's utility function and the cost of energy use.

$$P_{\text{WT}}(t) + P_{\text{PV}}(t) + P_{\text{GT}}(t) + P_{\text{dis}}(t) = P_{\text{sel}}(t) + P_{\text{chr}}(t) \quad (22)$$

$$H_{HE}(t) + H_{GB}(t) + H_{\text{dis}}(t) = H_{\text{fhl}}(t) + H_{\text{shl}}(t) + H_{\text{chr}}(t) \quad (23)$$

$$P_{\text{grid.min}} \leq P_{\text{grid}}(t) \leq P_{\text{grid.max}} \quad (24)$$

$$P_{\text{grid.down}} \leq P_{\text{grid}}(t) - P_{\text{grid}}(t-1) \leq P_{\text{grid.up}} \quad (25)$$

3.4 The frame of Stackelberg game model

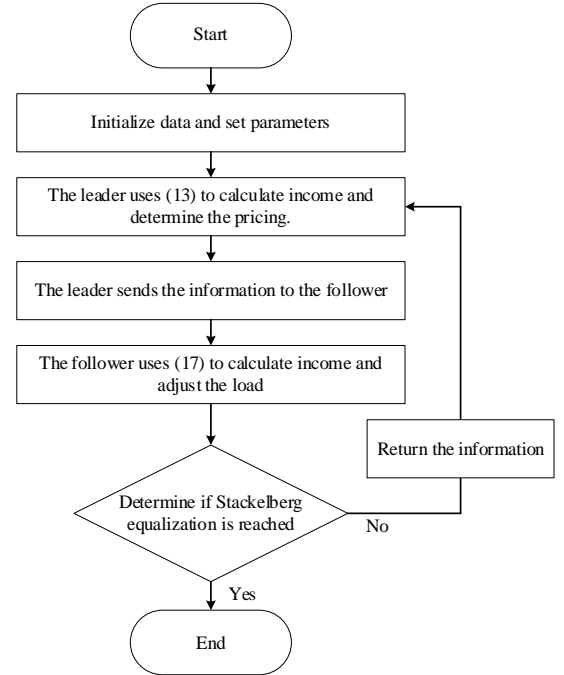


Fig. 2 The frame of Stackelberg game model

The Stackelberg game model of the CHP-IES consists of two stages: pricing decision and quantity decision. In this hierarchical structure, the DER operator acts as the leader, while the users act as the followers. The two stages are iterated until a game equilibrium is reached. In the first stage (pricing), the DER operator determines the electricity and heat prices based on supply–demand relationships and market information. In the second stage (quantity), users respond to the price signals by optimizing their load demand accordingly. The frame of Stackelberg game model is given by Fig.2.

4. CASE STUDY

In this study, a certain CHP-IES is selected as the case study. The predicted new energy output and the load curves are presented in Fig. 3.

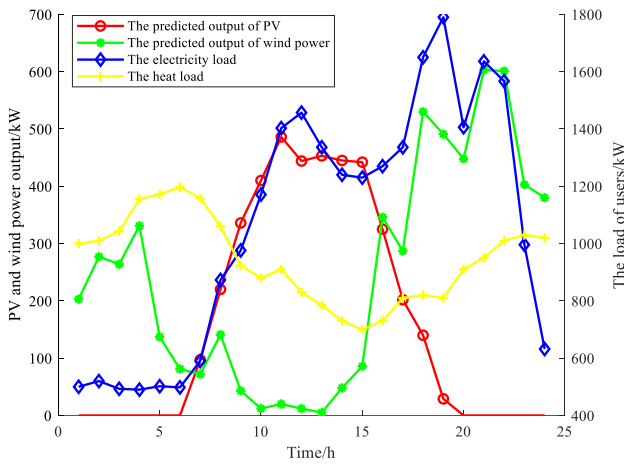


Fig. 3 The predicted new energy output and the load curves

Table 1 summarizes the new energy parameters of the CHP-IES.

Tab.1 The new energy parameters of the CHP-IES

| Parameter | Value |
|-----------------------------------|-------|
| Rated capacity of gas engine (kW) | 500 |
| Rated capacity of gas boiler (kW) | 800 |
| Power generation efficiency | 0.35 |
| Waste heat recovery efficiency | 0.83 |
| Heat exchanger efficiency | 0.80 |

4.1 Effectiveness analysis of CHP-IES pricing strategy

The pricing strategy of the DER operator is illustrated in Figs. 4 and 5. To prioritize the consumption of renewable energy within the system, the electricity pricing strategy is always maintained between the grid purchase price and the feed-in tariff, thereby offering more favorable prices to energy consumers. As shown in

Fig. 4, the fluctuation trend of the electricity sale price closely follows the time-of-use pricing of the main grid, aiming to incentivize users to actively purchase electricity. A similar pattern is observed in the heat pricing strategy, as shown in Fig. 5.

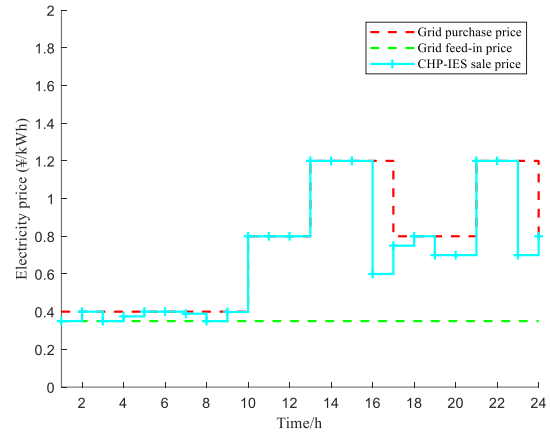


Fig. 4 Results of the CHP-IES electricity pricing strategy

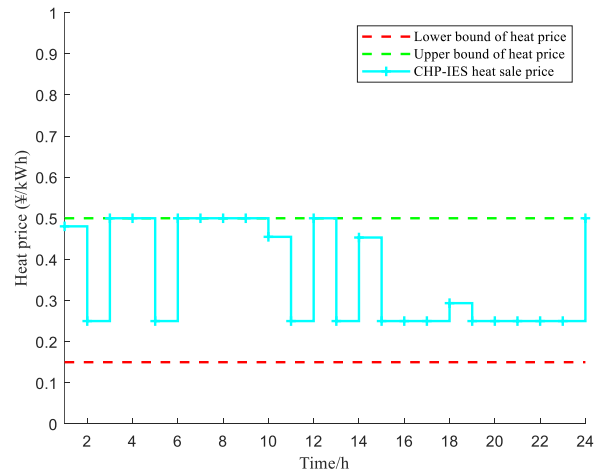


Fig. 5 Results of the CHP-IES heat pricing strategy

4.2 Effectiveness analysis of CHP-IES pricing strategy

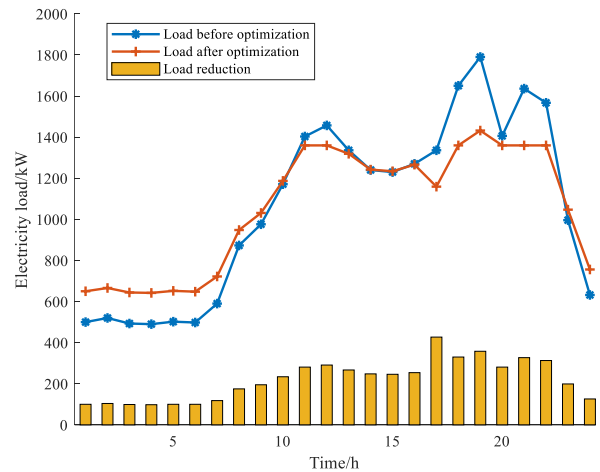


Fig. 6 Comparison of electricity load before and after optimization

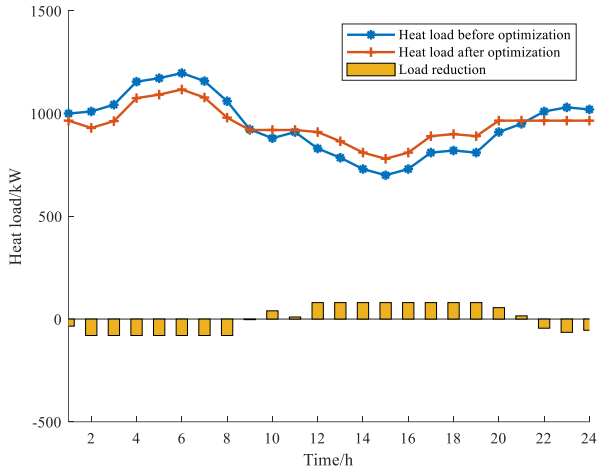


Fig. 7 Comparison of heat load before and after optimization

As illustrated in Fig. 6, under the incentive of time-of-use electricity pricing, the electricity load curve exhibits a clear "peak shaving and valley filling" effect after demand response optimization. The original peak loads occurred around 12:00 and 19:00, corresponding to periods with higher electricity prices. After optimization on the user side, these peak values are significantly reduced and shifted to off-peak periods with lower prices, such as 0:00–9:00 and 23:00–24:00. As a result, the overall fluctuation of the electricity load curve is notably smoothed. Fig. 7 presents the heat load profile before and after optimization. Similar to the electricity load, the heat load follows a comparable trend. However, to maintain user thermal comfort, the adjustment range of the heat load is relatively small. This indicates that while the electricity load is highly flexible under pricing incentives, the heat load has limited shiftability due to comfort constraints.

5. CONCLUSIONS

This research proposes a pricing optimization and energy management method for CHP-IES based on a Stackelberg game framework. The numerical results demonstrate that the proposed method enables cost-effective and flexible operation of CHP-IES by dynamically coordinating electricity and heat pricing. The pricing strategy effectively guides user-side load adjustments, achieving peak shaving and valley filling in electricity and heat consumption.

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