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A two-stage energy management for heat-electricity integrated energy system considering dynamic pricing of Stackelberg game and operation strategy optimization

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A B S T R A C T

Considering the flexibility and adjustability value of integrated energy system (IES) with flexible energy units and multivariate adjustable load in urban energy market, this paper proposes a two-stage energy management method of heat-electricity integrated energy system (HE-IES) considering dynamic pricing of Stackelberg game and operation strategy optimization. Firstly, a general comprehensive energy efficiency considering the exergy properties of electric and thermal energy is established, on this basis, this paper put forward a two-stage energy management framework considering interactive relationship between energy service provider (ESP) and users. Secondly, a two-stage energy management model is established to improve the energy efficiency and operation economy of the system, which includes the multi-objective optimization model of day-ahead scheduling and Stackelberg game dynamic pricing model of real-time energy management based on the source-load interaction optimization for hybrid energy. Finally, in order to illustrate the effectiveness of the proposed energy management method in improving system energy efficiency and operation strategy, a typical HE-IES consisting of 6 users and 1 ESP is chosen to simulation. The simulation results demonstrate that the proposed approach can not only enhance renewable energy utilization and reduce the cost of both ESP and users, but helpful to promote the benign interaction between energy equipment and load in IES, which could improve the energy efficiency of system operation.

1. Introduction

With the increase of world population and the development of economy, when facing the deteriorating environment and ecology, human beings are increasingly discovering the damage of energy consumption to environment and ecology under the current development. Considering the long-term development in the future, low-carbon economy and carbon neutrality have been put forward and paid more and more attention. The proposal of carbon neutrality originates from scientists' expectation of climate change in the next 100 years, which means that the amount of carbon dioxide emitted by subjects (individuals, enterprises, collectives, countries, etc.) is balanced with the amount of carbon dioxide absorbed by them in a certain period, and the “net emission” of carbon dioxide is zero [1]. In recent years, traditional fossil energy shortage, energy security, environmental protection and other issues have attracted much attention. Renewable energy, including cooling, heat and electricity, has problems such as low energy conversion efficiency, decentralized distribution and high use cost. Therefore, it is an important issue to explore ways to optimize energy structure and improve the utilization efficiency of various energy sources [1,2]. At the same time, with the deepening coupling of various energy situations, the interaction between the energy system and the social system will be closer, and the game and decision-making behavior among the subjects will have a great impact on the development of the energy system [3]. Under this background, through energy conversion equipment, power, heat, natural gas and other energy systems are coupled together to form Regional Integrated Energy System (RIES), realizing horizontal co-ordination and complementary and vertical cascade utilization among multiple energy sources, which helps to reduce the cost of

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energy use, improve energy utilization efficiency and realize low-carbon operation of energy system [4,5].

Compared with the traditional power distribution system, IES has undergone great changes in physical field, cyber field and social field [6–8]. With the changes of social interaction forms and decision-making patterns, as well as the development of energy trading market and power auxiliary service market, there are more and more participants in energy trading, and their trading behaviors are characterized by random behavior, personalized utility and diversified business [9]. The above factors increase the flexibility and adjustability of IES, and make it have great potential to participate in the regulation of urban energy market.

Driven by the above factors, achievements in theoretical research and engineering practice have been made in energy management and system operation optimization. For the energy management problems, the key issues are the stable operation and optimal scheduling of equipment in energy system. Energy management aims to maintain the stability of voltage-frequency-load and the optimal control of power flow at the operation level, and ensure the economic operation goal of the system at the optimal level [10]. Energy management firstly meets the power demand and energy balance in the system. If renewable energy sources generate surplus power, the internal energy storage system can be charged first and then sold to other nearby IES or to the urban energy network [11]. When the internal energy supply of the system is insufficient, the power balance can be satisfied first by discharging the energy storage system or by purchasing power from other IES through a set communication protocol. When there is an emergency, such as insufficient power grid supply, energy management must first ensure the priority operation of internal critical loads, and at the same time reduce the load shedding rate as much as possible to ensure the comfort of users. Related researches put forward cooperative energy and reserve scheduling model [12], designed dynamic game framework, and proposed fast scheduling decision scheme for IES [13]. For instance, a method for improving household energy efficiency is proposed in Refs. [14,15]. Through the regulation of various types of household resources, the overall benefit of smart home is maximized to effectively improve the electricity utilization benefit of users while optimizing the load peak-valley difference. For multi-energy complementary user-side IES, there are researches and proposals on energy efficiency improvement framework suitable for user-side IES and efficiency improvement strategies [16]. The optimization process of different energy optimization strategies is analyzed in detail and implemented on embedded central controller and successfully applied to demonstration projects [17]. In addition, there are also studies on energy efficiency improvement methods for regional IES such as industrial parks, commercial buildings, residential quarters, etc. in combination with environmental policies and building energy efficiency methods [18].

In addition, with the development of energy markets, the behavior of users in social field is gradually considered in the energy management of IES. In the process of energy transaction, the energy supplier gives priority to formulating the price strategy according to the load demand, and the user side responds to the demand according to the price information. The ESP is regarded as a leader and users as followers in related studies. Based on the Stackelberg game model, the interaction mechanism between ESP and users in the electric heating market is analyzed. Wei W and Ma L established the pricing strategy of operators and the selection model of producer and consumer trading mode, and proposed a distributed energy management method based on the Stackelberg game theory [19,20]. Zhou C et al. combined economic operation with auxiliary services, and put forward an interactive optimization method of Stackelberg game for park integrated energy system [21]. Wu L et al. combined with thermal network, proposed an energy transaction model based on multi-master and multi-slave game, which was used to analyze the interaction between multiple distributed energy stations and users [22]. Yu M et al. regarded the seller as a leader and all kinds of loads as followers, and put forward a real-time demand-side response optimal control model based on Stackelberg game to obtain the optimal strategy of each participant [23]. Salyani P et al. established a two-tier Stackelberg game model in which electric vehicle operators and distributed generators cooperated in market transactions [24]. Yu M et al. established a two-stage Stackelberg model between the superior market, the power sales company and the users according to the operation level of the power market [25].

Regarding the literatures presented above, the energy management of IES is based on the energy balance, and the energy management and energy efficiency improvement of integrated energy system are only through equipment operation optimization and some studies have considered the game behavior between energy suppliers and users. In the existing studies, although the energy price is optimized by game theory, these studies mainly focus on the game behavior between ESP and users, and seldom do they consider the interaction between users and energy units, which leads to the poor flexibility of the operation mode of energy units such as CHP (Combined heating and power supply), resulting in poor flexibility and low operation efficiency of the system [26]. In general, the traditional energy management focuses on optimizing the operation of system equipment on the premise of meeting the load demand. System operation is usually carried out in a way of “Source Follows Load” (SFL,the energy unit is adjusted according to the fixed load demand, and finally the system power balance is realized.), with less information interaction and energy interaction between physical field and social field. Based on the existing research, this paper discusses the energy management and energy efficiency improvement problem of IES under the condition of increasingly frequent interaction between social field and physical field. Fig. 1 shows the interaction relationship highlighted in this article between information and energy from the cyber-physical-social system perspective (CPSS).

According to Fig. 1, the IES scheduling should be a complex energy management problem in the multi-dimensional field of CPSS. At the information system level, the information interaction between the social field and the physical field is more frequent, which includes not only the balance information of energy supply and demand, but also the benefit game information between users and equipment operators. At the level of energy system, the energy relationship between physical field and social field gradually changes from one-way transmission to two-way interaction [3,6]. And the system operation is usually carried out in a way of “Source Interacts Load” (SIL, the load demand is uncertain, which can be adjusted to the best load demand state through real-time optimization with the energy units, and finally realize the system power balance.), which effectively improves the flexibility of the system. To fill the above gap, this paper proposes a two-stage energy management method considering energy efficiency improvement and source-load interactive strategy. Compared with the existing similar works, main contributions of this work are summarized as follows:

(1) A comprehensive energy efficiency model and the hybrid energy management framework are established. The comprehensive energy efficiency model is defined by Exergy efficiency, which considers the Exergy equilibrium of solar energy, wind energy and gas in the IES. The hybrid energy management framework considers two stages of day-ahead scheduling and real-time optimization. Especially, in the

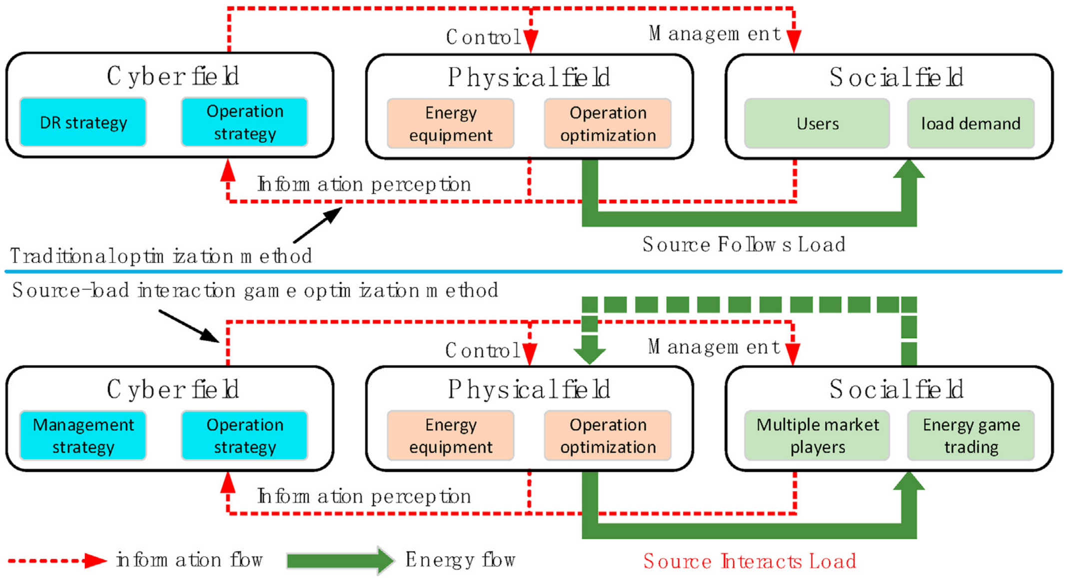

Fig. 1. Interaction relationship between information and energy from the CPSS perspective.

stage of real-time energy management, through the dynamic pricing of Stackelberg game between ESP and users from the perspective of game interaction optimization, the generators and load are cooperatively optimized, so as to respond to the peak shaving demand of urban energy system and improve the efficiency and economy of system.

(2) A two-stage energy management optimization model is designed, which includes operation optimization in the day-ahead scheduling stage and Stackelberg game in the real-time scheduling stage. In the day-ahead scheduling model, ESP cooperatively optimizes the energy equipment and user load in the system, and obtains the planned interactive power curve between IES and urban energy system, that is, the virtual load curve of IES. In the real-time optimal dispatching model, ESP considers its own benefits and users' interests, and optimizes and adjusts the planned unit output strategy and users' load curve by establishing a game relationship, so as to adjust the virtual load curve in the most economical and efficient way. Through the two-stage optimization model, the optimal dynamic pricing between ESP and users can be realized, and the economy and energy efficiency of system operation can be improved.

2. System structure and energy management framework

2.1. System Architecture

The hybrid energy conversion and coupling framework of multiple interconnected energy conversion equipment in a heat-electricity integrated energy system is shown in Fig. 2. The HE-IES can realize efficient and comprehensive utilization of electric energy, heat energy and gas through coupling between different energy conversion equipment, and directly improve the efficiency of different energy sources in the whole life cycle. Typical HE-IES may be composed of DGs system (Distributed Generations), CHP, P2G-CCS system (Power to gas, Carbon capture and storage system), different loads and energy management system. From the point view of energy conversion and comprehensive utilization, HE-IES can be regarded as a low-carbon, economical and efficient energy self-balancing system [27]. The CHP system can not only generate electric energy and participate in electricity market transactions together with electric energy generated by WT (Wind turbine) and PV (Photovoltaic power generation), but also meet the demand of thermal load and cooling load. The P2G-CCS system can use a small amount of energy of the system to capture and store carbon emissions to reduce carbon transaction cost, and actively cooperate with other peaking equipment in the system to provide auxiliary services for the utility energy network. The users in HE-IES are assumed to have a certain amount of adjustable loads, which enable them to participate in integrated demand response (IDR, Electrical load and heat load are both adjusted according to the price stimulus signal of electricity and heat respectively).

2.2. Modeling of comprehensive energy efficiency

In this paper, comprehensive energy efficiency is expressed by Exergy efficiency, and the comprehensive energy efficiency of the system is analyzed and modeled by fuel specific consumption analysis theory. According to the first law of thermodynamics, the energy conversion process should satisfy the Exergy equilibrium [28].

$$\sum_{i}^{n} E_{loss}^{EXE-i}(t) = \sum_{i}^{n} E_{in}^{EXE-i}(t) - \sum_{i}^{n} E_{out}^{EXE-i}(t) \tag{1}$$

where E_{loss}^{EXE-i} is the irreversible Exergy loss, kJ/h; E_{in}^{EXE-i} is the Exergy input system, kJ/h; E_{out}^{EXE-i} is the Exergy output system, kJ/h.

According to fuel specific consumption analysis theory, the Exergy equilibrium equations of distributed generation, CHP system and P2G-CCS system can be obtained [29–31].

$$\eta_{DGs}^{EXE} = \frac{P_{pv}(t)\cdot\Phi_E}{E_{solar}(t)} + \frac{P_{wt}(t)\cdot\Phi_E}{E_{wind}(t)} \tag{2a}$$

$$\begin{aligned} E_{solar}(t) &= Q_{solar}(t)\left(1 - T_0(t)\cdot(T_{STC}(t))^{-1}\right) \\ &= DNI\cdot S\cdot\cos(\theta)\cdot LAM\cdot\left(1 - T_0(t)\cdot(T_{STC}(t))^{-1}\right) \end{aligned} \tag{2b}$$

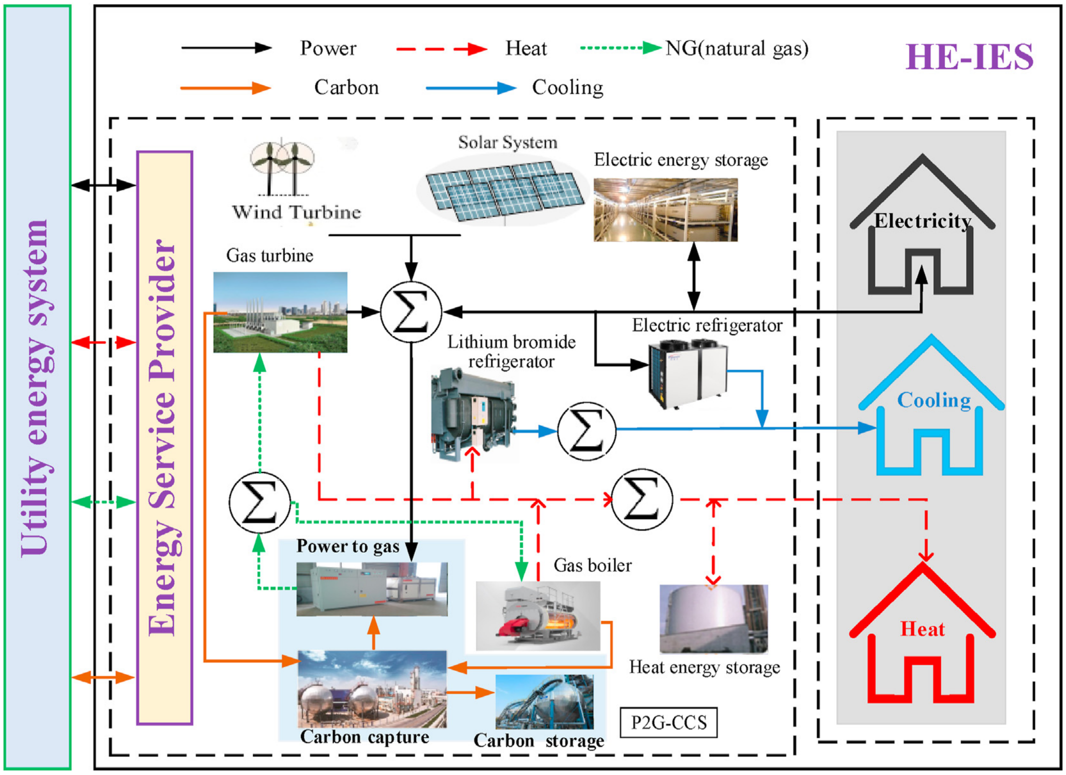

Fig. 2. Energy conversion and coupling framework of typical HE-IES.

$$E_{wind}(t) = \frac{\rho \times \pi \times R^2}{2} \times (v_{wind}(t))^3 \tag{2c}$$

where η_{DGs}^{EXE} is the Exergy efficiency of the DGs system; $P_{pv}(t)$ is the output of PV, kW; Φ_E is the Exergy value of electricity, kJ/kW; $P_{wt}(t)$ is the output of WT, kW; $E_{solar}(t)$ is the Exergy value of solar, kJ; $E_{wind}(t)$ is the Exergy value of wind, kJ; $T_{STC}(t)$ is the surface temperature of photovoltaic battery pack,°C; $T_0(t)$ is the temperature in standard test environment, °C; $DNI(t)$ is the solar radiation, kJ/m^2; S is the total area of photovoltaic panel, m^2; θ is the angle of incidence; LAM is the correction factor; ρ is the air density,kg/m^3; R is the ratio of peak speed and wind speed of blades; $v_{wind}(t)$ is the wind speed, m/s.

$$\eta_{chp}^{EXE} = \frac{P_{chp}(t) \cdot (\Phi_E + \Phi_H)}{E_{gas,chp}(t)} \tag{3a}$$

$$\eta_{gb}^{EXE} = \frac{P_{gb}(t) \cdot \Phi_H}{E_{gas,chp}(t)} \tag{3b}$$

$$E_{gas}(t) = q_{net}\left(1.0064 + 0.1519\frac{W(H)}{W(C)} + 0.0616\frac{W(O)}{W(C)} + 0.0429\frac{W(N)}{W(C)}\right) \tag{3c}$$

where η_{chp}^{EXE} is the Exergy efficiency of the CHP; η_{gb}^{EXE} is the Exergy efficiency of the GB; $P_{chp}(t)$ is the output of CHP,kW; $P_{gb}(t)$ is the output of GB, kW; Φ_H is the Exergy value of hot water for thermal system, kJ/kW; Φ_C is the Exergy value of air conditioning for cooling system, kJ/kW; $E_{gas}(t)$ is the Exergy value of gas, kJ; q_{net} is the calorific power of gas, kJ/kg; $W(C), W(H), W(N), W(O)$ are mass fractions of carbon, hydrogen, nitrogen and oxygen in gas respectively [32].

$$\eta_{p2g-ccs}^{EXE} = \frac{P_{p2g}(t)\mu_{gas}\Phi_{gas}}{\Phi_E(P_{p2g}(t) + P_{ccs}(t)) + \Phi_c P_{p2g}(t)} \tag{4}$$

where $\eta_{p2g-ccs}^{EXE}$ is the Exergy efficiency of the P2G-CCS system; $P_{p2g}(t)$ is the output of P2G, kW; $P_{ccs}(t)$ is the output of CCS,kW; μ_{gas} is the gas conversion factor of P2G, m^3/kW;Φ_c is the Exergy value of carbon resources, kJ/kW.

$$\begin{aligned}\eta^{EXE} &= \sum_i^n E_{out}^{EXE-i}\left(t\right) \cdot \left(\sum_i^n E_{in}^{EXE-i}\left(t\right)\right)^{-1} \\ &= \eta_{DGs}^{EXE} + \eta_{chp}^{EXE} + \eta_{gb}^{EXE} + \eta_{p2g-ccs}^{EXE}\end{aligned} \tag{5}$$

where η^{EXE} is the Exergy efficiency of the HE-IES.

2.3. Two-stage energy management framework

The members integrated by IES can be roughly divided into two categories: schedulable members and non-schedulable members.

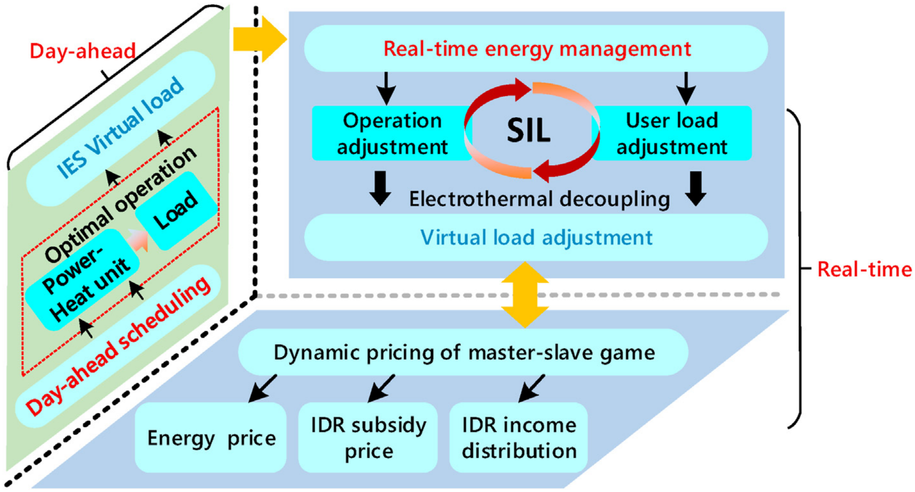

Fig. 3. Two-stage energy management framework.

Among them, the schedulable members include CHP, energy storage units and flexible loads, while the non-schedulable members include random generating units such as WT and PV. Adjustable resources in the system participate in the energy market interaction through alliance under the guidance of price mechanism. Fig. 3 is the two-stage energy management framework.

Firstly, with the release of urban energy trading information, ESP plans to participate in the day-ahead energy market transactions under the joint influence of economy and energy efficiency by coordinating the power supply, heating units and energy storage equipment while meeting the load demand of users in the system. The virtual load curve interacting with urban energy network is generated through optimal operation, which represents the planned trading mode and trading volume of IES with the urban energy system.

Secondly, stimulated by peak shaving demand and demand response (DR) subsidy of urban energy system in the real-time energy market, ESP adjusts the virtual load curve to respond to the demand of electricity-heat peak shaving in urban energy system. However, because the economy and energy efficiency of operation have been comprehensively considered in day-ahead output plan, the adjustment capacity of energy units that can be used for ESP adjustment is limited. Therefore, this paper constructs the game relationship between ESP and users, and mobilizes the collaborative optimization between energy units and loads in the physical field through the game in the social field. In this process, the CHP units in the system are decoupled and cooperated with the energy storage system to participate in the collaborative optimization with user load. In the cyber field, ESP sends out electrical load and thermal load collaborative optimization signals to users (Internal energy price and DR subsidy allocation strategy), and the user feeds back the load adjustment strategy to ESP as a response according to their own interests and preferences.

3. Two-stage energy management model

3.1. Multi-objective optimization model for day-ahead scheduling

1) Optimization objective functions

Objective Function of minimum economic cost: IES takes minimizing total cost as the economic optimization objective.

$$\min F_C = C_M + C_F + C_C + C_E \tag{6a}$$

where F_C is the total cost in scheduling period, CNY; C_M is the operation and maintenance cost, yuan; C_F is the fuel cost, CNY; C_C is the carbon treatment and transaction cost, CNY; C_E is the virtual load cost, CNY.

The details of C_M are given as follows:

$$C_M = \sum_{t=1}^{T}\sum_{k=1}^{w} P_k(t)\vartheta_{M,k} \tag{6b}$$

where T is the total time periods in scheduling period; $\vartheta_{M,k}$ is the unit maintenance cost of equipment k, CNY/kW.

The details of C_F are given as follows [33]:

$$C_F = \sum_{t=1}^{T}\left(\sum_{k=1}^{w}\Big(P_{chp}(t)+P_{gb}(t)\Big)\gamma_{gas}^{k} - V_{gas}^{p2g}(t)\right)\cdot\beta_{gas} \tag{6c}$$

$$V_{gas}^{p2g}(t) = P_{p2g}(t)\cdot\omega_{p2g}^{co_2}\cdot\varsigma_{gas}^{co_2} \tag{6d}$$

where γ_{gas}^{k} is the gas consumed per unit power of equipment k; $V_{gas}^{p2g}(t)$ is the volume of gas produced by P2G, m^3; β_{gas} is the market price of gas, CNY/m^3; $P_{p2g}(t)$ is the output power of P2G, kW; $\omega_{p2g}^{co_2}$ is the carbon dioxide conversion per unit power of P2G, kg/kW; $\varsigma_{gas}^{co_2}$ is the volume of carbon dioxide converted into gas per unit mass, m^3/kg.

The details of C_C are given as follows [34]:

$$C_c = \sum_{t=1}^{T}\left(\sum_{k=1}^{w} P_k(t)\delta_{E,co_2} - Q_{co_2}^{quota,e+h}(t)\right)\cdot\beta_{co_2} \tag{6e}$$

$$Q_{co_2}^{quota,e+h}(t) = P_{load,e}(t)\cdot\pi_e^{co_2}\cdot a\cdot b\cdot c + P_{load,h}(t)\cdot\pi_h^{co_2} \tag{6f}$$

where δ_{E,co_2} is the emission parameter of CO_2, kg/kW; $Q_{co_2}^{quota,e+h}(t)$ is the carbon quota of different loads, kg/kW; β_{co_2} is the market price of carbon quota trading, CNY/kg; $P_{load,e}(t)$ and $P_{load,h}(t)$ are the electric load and heat load respectively, kW; $\pi_e^{co_2}$ and $\pi_h^{co_2}$ are the emission standards for electrical and heat loads respectively, kg/kW; a,b and $c$are the cooling mode correction coefficient, heat supply correction coefficient and fuel calorific value correction coefficient respectively.

The details of$C_E$are given as follows:

$$C_E = \sum_{t=1}^{T}\left\{\beta_{net}^{e}(t)P_{grid-VE}(t)+\beta_{net}^{h}(t)P_{grid-VH}(t)\right\} \tag{6g}$$

where $P_{grid-VE}(t)$ is the virtual electrical load between IES and utility energy grid, kW;$P_{grid-VH}(t)$ is the virtual heat load between IES and utility energy grid, kW; $\beta_{net}^{e}(t)$ and $\beta_{net}^{h}(t)$ are the price of power supply and heat supply of urban energy system, CNY/kW.

Objective Function of maximum energy efficiency: comprehensive energy utilization efficiency is one of the important indicators of HE-IES operating conditions. In this paper, Exergy efficiency is introduced to reflect the comprehensive energy efficiency of the system [28].

$$\begin{aligned}\max F_\eta &= \sum_{i}^{n} E_{out}^{EXE-i}\left(t\right)\times\left(\sum_{i}^{n} E_{in}^{EXE-i}\left(t\right)\right)^{-1}\\ &= \eta_{DGs}^{EXE}+\eta_{chp}^{EXE}+\eta_{gb}^{EXE}+\eta_{p2g-ccs}^{EXE}\end{aligned} \tag{7}$$

where F_η is the objective function of energy efficiency.

2) Optimization constraints

a) Power supply system operation constraint: consists of equations (8a)-(8d) [35,36].

$$\begin{aligned}&P_{grid}(t)+P_{DGs}(t)+P_{chp}(t)\bullet\eta_{chp}^{e}+P_{dis}(t)\\ &=P_{e-load}(t)+P_{char}(t)+P_{p2g-ccs}(t)+P_{eb}(t)\end{aligned} \tag{8a}$$

$$P_{e\_\min}\le\left|P_{grid}(t)\right|\le P_{e\_\max} \tag{8b}$$

where$P_{grid}(t)$is the interactive power between IES and power grid, kW; $P_{DGs}(t)$is the distributed generation output, kw; $P_{e-load}(t)$ is the user electrical load after the demand response, kW; $P_{eb}(t)$ is the output of electric boiler, kw; η_{chp}^{e} is power generation efficiency of CHP; $P_{e\_\min}$ and $P_{e\_\max}$ are the upper and lower limits of interactive power between IES and power grid, kW.

$$\begin{cases}SOC_{\min}\le SOC(t)\le SOC_{\max}\\ 0\le P_{char}(t)\le P_{char\_\max}\varpi_{e\_s}\\ 0\le P_{dis}(t)\le P_{dis\_\max}\varpi_{e\_r}\\ \varpi_{e\_s}+\varpi_{e\_r}\le 1\\ SOC_{start}(t)=SOC_{end}(t)\end{cases} \tag{8c}$$

$$\begin{cases}SOC(t+1)=SOC(t)-\varpi_{e\_s}\dfrac{P_{char}(t)}{E_{ees}}\\ SOC(t+1)=SOC(t)-\varpi_{e\_r}\dfrac{P_{dis}(t)}{E_{ees}}\end{cases} \tag{8d}$$

whereSOC is the state of charge of energy storage; $P_{char}$is the charging power, kW; $P_{dis}$is the discharge power,kW; $\varpi_{e_s}$is the charging efficiency; $\varpi_{e_r}$is the discharge efficiency; E_{ees} is the maximum capacity of energy storage battery before attenuation.

b) Heating supply system operation constraint: consists of equations (9a)-(9c) [37].

$$P_{h.grid}(t)+P_{eb}(t)\eta_{eb}^{t}+P_{chp}(t)\eta_{chp}^{t}+P_{h.re}(t)=P_{h-load}(t)+P_{h.st}(t) \tag{9a}$$

$$P_{h\_\min}\le\left|P_{h\_grid}(t)\right|\le P_{h\_\max} \tag{9b}$$

where $P_{h_grid}(t)$is the interactive power between IES and heat grid, kW; $P_{h_re}(t)$is the heat energy release power, kW; $P_{h-load}(t)$ is the user heat load after the demand response, kW; η_{eb}^{t} is heat efficiency of electric boiler; $P_{h\_\min}$ and $P_{h\_\max}$ are the upper and lower limits of interactive power between IES and heat grid, kW.

$$\begin{cases}0\le P_{h\_re}(t)\le P_{h\_re\_\max}\varpi_{h\_r}\\ \varpi_{h\_s}+\varpi_{h\_r}\le 1\\ P_{h\_st\_start}(t)=P_{h\_st\_end}(t)\end{cases} \tag{9c}$$

where $P_{h_st}$is the heat energy storage power,kW; P_{h_re} is the energy release power,kW; $\varpi_{h_r}$is the release efficiency; $\varpi_{h_s}$is the heat storage efficiency; $P_{h\_st\_\max}$ is the maximum storage power,kW; $P_{h\_re\_\max}$ is the maximum release power,kW; η_{chp}^{t} is heat efficiency of CHP.

c) ***Carbon conversion system constraint: consists of equations (10a)-(11e)*** [38–40].

$$P^{ccs,\min}\le P_{ccs}(t)\le P^{ccs,\max} \tag{10a}$$

$$\lambda(t)=(e^{c}P_{ccs}(t))^{-1}E(t)^{2} \tag{10b}$$

$$0\le P_{ccs}^{chp}(t)+P_{ccs}^{DGs}(t)+P_{ccs}^{ES}(t)\le P_{ccs}^{c,\max}(t) \tag{10c}$$

$$|P_{ccs}(t)-P_{ccs}(t-1)|\le\Delta P_{ccs}(t) \tag{10d}$$

$$P^{p2g,\min}\le P_{p2g}(t)\le P^{p2g,\max} \tag{11a}$$

$$Q_{ng}(t)=Q_{ng}(t-1)+Q_{ng}^{in}(t)-Q_{ng}^{out}(t) \tag{11b}$$

$$Q_{ng}^{\min}\le Q_{ng}(t)\le Q_{ng}^{\max} \tag{11c}$$

$$|P_{p2g}(t)-P_{p2g}(t-1)|\le\Delta P_{p2g}(t) \tag{11d}$$

$$\left|\sum_{t=1}^{T}\left(\sum_{k=1}^{w}P_k(t)\delta_{E,co_2}-Q_{co_2}^{quota,e+h}(t)\right)\right|\le Q_{co_2}^{trade,\max} \tag{11e}$$

where$P_{ccs}(t)$ is the carbon capture power, kW; $\lambda(t)$is the flue gas split ratio of carbon capture system; $E(t)$is the amount of CO2 treated by the regeneration tower, t; $e^{c}$is the amount of CO2 generated per unit equivalent power generation output, t; $P_{ccs}^{chp}(t)$, $P_{ccs}^{DGs}(t)$and $P_{ccs}^{ES}(t)$are the carbon capture energy consumption of CHP, DG units and ES respectively, kW; $P_{ccs}^{c,\max}(t)$is the maximum power of CCS unit, kW;$\Delta P_{ccs}(t)$ is the CCS unit climbing rate, kW; $P_{p2g}(t)$ is the output power of P2G, kW; $Q_{ng}(t)$and $Q_{ng}(t-1)$ are the gas storage capacity of P2G system in adjacent periods,m^3; $Q_{ng}^{max}(t)$ and $Q_{ng}^{min}(t)$ are the upper and lower limits of gas storage capacity respectively, kW;$\Delta P_{p2g}(t)$ is the P2G unit climbing rate, kW;$P_k(t)$ is the output of carbon emission source equipment, kW; $Q_{co_2}^{trade,\max}$ is the maximum carbon trading quota, t.

d) System Exergy efficiency constraint: consists of equations (12a)-(12e).

The system Exergy efficiency constraint mainly considers the balance of energy input and output in the system, including Exergy balance of solar, wind, natural gas (NG) and carbon [30–32].

$$\sum_{t=1}^{T} E_{solar}(t) = \Phi_E \sum_{t=1}^{T} P_{pv}(t) + \sum_{t=1}^{T} E_{solar}^{loss}(t) \tag{12a}$$

$$\sum_{t=1}^{T} E_{wind}(t) = \Phi_E \sum_{t=1}^{T} P_{wt}(t) + \sum_{t=1}^{T} E_{wind}^{loss}(t) \tag{12b}$$

$$\sum_{t=1}^{T} E_{gas,chp}(t) = (\Phi_E + \Phi_H) \sum_{t=1}^{T} P_{chp}(t) + \sum_{t=1}^{T} E_{gas,chp}^{loss}(t) \tag{12c}$$

$$\sum_{t=1}^{T} E_{gas,gb}(t) = \Phi_H \sum_{t=1}^{T} P_{gb}(t) + \sum_{t=1}^{T} E_{gas,gb}^{loss}(t) \tag{12d}$$

$$\sum_{t=1}^{T} \{\Phi_E(P_{p2g}(t) + P_{ccs}(t)) + \Phi_C P_{p2g}(t)\} = \mu_{gas}\Phi_{gas} \sum_{t=1}^{T} P_{p2g}(t) \tag{12e}$$

where $E_{solar}^{loss}(t)$,$E_{wind}^{loss}(t)$,$E_{gas,chp}^{loss}(t)$and$E_{gas,gb}^{loss}(t)$ represent the Exergy loss of solar, wind and gas, kJ/h.

3.2. ***Stackelberg game*** *model for real-time energy management*

In the real-time energy management stage, ESP optimizes the energy units and load in IES based on the peak shaving signal of urban energy system to realize the adjustment of virtual load. Where, a Stackelberg game-based energy optimization mode is proposed to realize energy management and energy efficiency improvement of IES, in which the ESP works as a leader who chooses proper interactive price to guide the adjustment of the energy use strategy on the consumer side while the user serves as a follower who optimize its energy consumption strategy and maximize total energy benefits in response to the interactive price set by ESP.

1) ESP game strategy model

ESP benefits include power supply benefits, heating benefits, DR benefits and system operating costs. Its benefit model can be expressed as follows:

$$F_{ESP}^{game} = F_{ESP}^{H} + F_{ESP}^{E} + F_{ESP-R}^{IDR} - F_{ESP-C}^{IDR} - F_C \tag{13a}$$

When ESP guides users to participate in the market demand response of computer users, it will set an internal DR compensation price according to the market subsidy price and guide users to participate in DR program. ESP can directly obtain DR subsidies paid by urban energy systems, but it also needs to pay users a certain amount of internal DR subsidies [41].

$$F_{ESP-R}^{IDR} = \sum_{t=1}^{T} \left\{ \left(\sum_{l=1}^{L} P_l^{dr,ve}(t)\beta_l^{dr,e} + \sum_{z=1}^{Z} P_z^{dr,vh}(t)\beta_z^{dr,h} \right) \right\} \tag{13b}$$

where $F_{ESP-R}^{IDR}$is the DR subsidies of ESP obtain from urban energy systems,yuan; $P_l^{dr,ve}(t)$ is adjustment of virtual electric load, kW; $P_z^{dr,vh}(t)$ is adjustment of virtual heat load, kW; $\beta_l^{dr,e}$ is the urban energy system subsidy price of electrical load adjustment,yuan/kW; $\beta_z^{dr,h}$ is the urban energy system subsidy price of heat load adjustment,CNY/kW.

$$F_{ESP-C}^{IDR} = \sum_{l=1}^{L} P_l^{dr,e}(t)p_{IDR}^{e}(t) + \sum_{z=1}^{Z} P_z^{dr,h}(t)p_{IDR}^{h}(t) \tag{13e}$$

where F_{ESP-C}^{IDR} is the DR subsidy expenditure to users, yuan; $p_{IDR}^{e}(t)$and $p_{IDR}^{h}(t)$ are the DR subsidy price of ESP to users, CNY/kW.

ESP not only guides users to carry out DR, but also charges users for power supply and heating [42].

$$F_{ESP}^{E} = \sum_{i=1}^{T} \left\{ \left(P_{load}^{e}(t) - \sum_{l=1}^{L} P_l^{dr,e}(t) \right) p_l^{e}(t) \right\} \tag{13c}$$

$$F_{ESP}^{H} = \sum_{i=1}^{T} \left\{ \left(P_{load}^{h}(t) - \sum_{z=1}^{Z} P_z^{dr,h}(t) \right) p_l^{h}(t) \right\} \tag{13d}$$

where F_{ESP}^{E} and $F_{ESP}^{H}$are the benefits of electrical supply and heat supply to users, yuan;$P_{load}^{e}(t)$ and $P_{load}^{h}(t)$are the original user electrical load and thermal load of users, kW; $P_z^{dr,e}(t)$and $P_z^{dr,h}(t)$ are the load adjustment capacity of users, kW; $p_l^{e}(t)$and $p_l^{h}(t)$ are the price of electrical supply and heat supply to users, CNY/kW.

$$\underline{p_l^e} \le p_l^e(t) \le \overline{p_l^e} \tag{13e}$$

$$\underline{p_l^h} \le p_l^h(t) \le \overline{p_l^h} \tag{13f}$$

Constraint (13e) and (13f) enforce the interactive price of electrical supply and heat supply to users at time slot t to be within prespecified limits, i.e., within the interval $[\underline{p_l^e}, \overline{p_l^e}]$ and $[\underline{p_l^h}, \overline{p_l^h}]$.

In addition, users also need to pay a certain cost for the normal operation of the location system, ESP costs are expressed by equations (6a)-(6g).

2) Users game strategy model

The user benefit model includes five aspects, namely, electricity utilization income, DR benefit, electricity purchase cost, heat purchase cost and temperature satisfaction cost. Its benefit model can be expressed as follows [43,44]:

$$F_{UES}^{game} = F_{UES}^{U} + F_{ESP-C}^{IDR} - F_{ESP}^{H} - F_{ESP}^{E} - F_{UES}^{T} \tag{14a}$$

Equation (14b) represents the energy consumption of the user, k is the user preference coefficient, and the application of logarithmic function model can effectively represent the change of the benefit of the DR with its power usage [45].

$$F_{UES}^{U} = k \cdot \ln\left(1 + \sum_{l=1}^{L} P_l^{dr,e}(t)\right) \tag{14b}$$

where F_{UES}^{U} represents the users energy consumption utility.

Through the response of heat load demand, the temperature comfort will be reduced. However, from an economic point of view, as long as this discomfort can offset the reduction of the heat purchase cost, the user will be willing to participate in the reduction of heat load. Equations (14c) and (14d) represent user DR benefits and temperature comfort costs, respectively [45,46].

$$F_{ESP-C}^{IDR} = \sum_{l=1}^{L} P_l^{dr,e}(t) p_{IDR}^{e}(t) + \sum_{z=1}^{Z} P_z^{dr,h}(t) p_{IDR}^{h}(t) \tag{14c}$$

$$F_{UES}^{T} = \alpha_i \cdot \left[\sum_{z=1}^{Z} P_z^{dr,h}(t) \right]^2 \tag{14d}$$

where F_{UES}^{T} represents the cost of temperature comfort; α_i represents the comfort coefficient of the users.

3) Stackelberg game model between ESP and users

In this article, the interaction between ESP and users are described as a Non-cooperative Stackelberg Game. In this game model, ESP, as the manager of the integrated energy system, has the priority to make decisions and acts as a leader in the game. ESP can set its own internal electricity price, heat price and DR price to guide users to make consumption and obtain maximum profits. As a follower in the game, users can flexibly adjust their heat/electricity load according to the price information set by the operators, obtain DR subsidies, reduce the corresponding heat/electricity purchase costs, and thus pursue their maximum benefits [47]. Fig. 4 shows the dynamic pricing game relationship between ESP and users in real-time energy management stage.

According to the above game framework shown in the Fig. 4, the game between ESP and users can be described as follows [48]:

$$\boldsymbol{G} = \left\{ (USER \cup ESP); \left\{ P_{l-i}^{dr,e} \right\}; \left\{ P_{z-i}^{dr,h} \right\}; p_{IDR}^{e}; p_{IDR}^{h}; p_l^{e}; p_l^{h}; \left\{ F_{UES-i}^{game} \right\}; F_{ESP}^{game} \right\} \tag{15a}$$

where $\{P_{l-i}^{dr,e}\}$and $\{P_{z-i}^{dr,h}\}$ represent the set of power and heat consumption strategy for each user; F_{UES-i}^{game} represents the user benefit function; F_{ESP}^{game} represents the ESP benefit function.

In game model $\boldsymbol{G}$, neither ESP nor users can maximize their profits by unilaterally changing their strategy. Subsequently, the following theorem is employed to proof the existence and uniqueness of the Stackelberg equilibrium in the proposed game. In the proposed Stackelberg game, a unique Stackelberg equilibrium exists if the following conditions are satisfied [48,49].

1) The strategy set of each player is nonempty, convex, and compact. Because the strategy sets of $\boldsymbol{p}_{coup}\boldsymbol{p}_{coup}$ ESP price and user load adjustment defined in the paper are sets of linear inequality constraints, i.e., (13e), (13f) and linear equality constraint, i.e., (8a), (9a), these sets are readily defined as nonempty, convex, and compact.
2) Users have unique optimal best-response strategy once informed of the ESP's interactive price strategy and ESP has a unique optimal strategy given the identified load adjustment strategy of users. The above conditions can be proved by the method of reference [49].

3.3. Algorithm for solving energy management model

This section mainly introduces the solving algorithm for two-stage energy management model. And Fig. 5 shows the solution flow chart for two-stage energy management model.

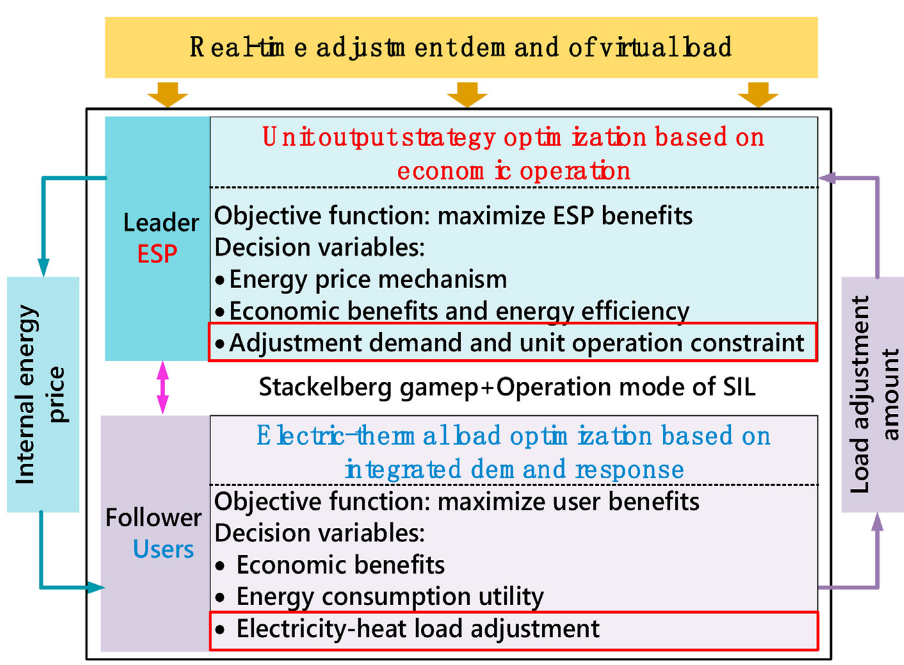

Fig. 4. Game relationship between ESP and users in real-time energy management stage.

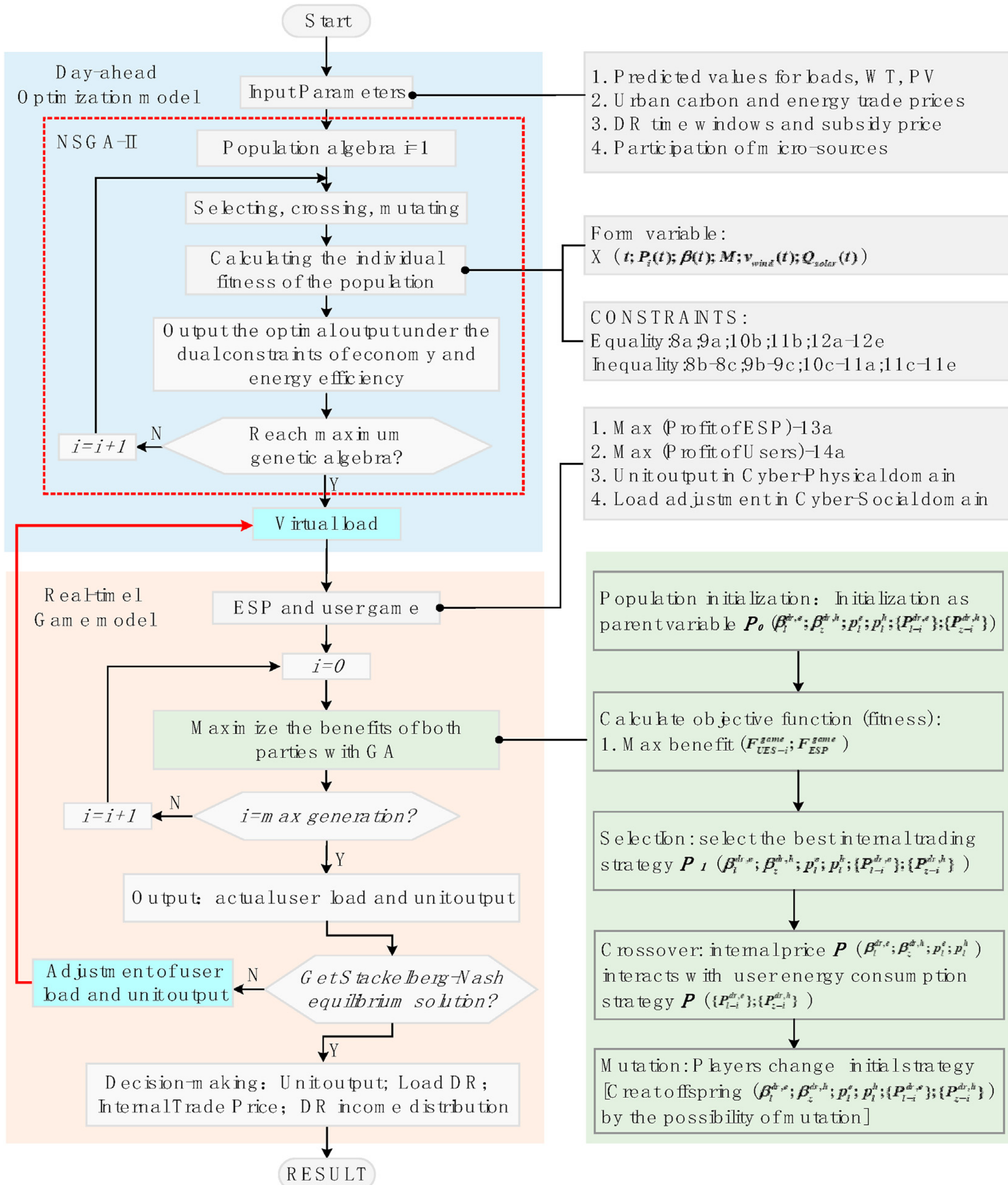

Fig. 5. Solution flow chart for two-stage energy management model.

In the process of day-ahead scheduling, the Non-dominated sorting genetic algorithm II (NSGA-II) is used to achieve multi-objective optimization. And the optimal strategy of energy exchange between IES and urban energy system is obtained by optimizing the internal operation of IES, which is reported to the superior energy system as the virtual load curve of IES. Before calculating the problem, the parameters of urban carbon and energy trade prices, DR time windows and subsidy price, participation of micro-sources and the predicted values for loads, WT, PV are imported. Then, the NSGA-II algorithm is used to solve the double objective optimization problem of economy and energy efficiency. Optimized variables include scheduling time, wind and light parameters, output of energy storage, real-time carbon trading price and energy price, and power of electric heating unit units. Constraints involved in the calculation process include equality constraints and inequality constraints. Then the optimization results under the dual constraints of economy and energy efficiency are exported. Finally, when the calculation results meet the balance of energy supply and demand under the dual constraints of economy and environment, the calculated virtual load will be transmitted to the real-time game model as the input value.

The process of real-time energy management emphasizes that through the game optimization between ESP and users, the interests of all parties are balanced, and IES adjusts the virtual load curve to participate in the demand response of urban energy system. The focus of the game lies in the price strategy of electricity and heat supply and the revenue sharing strategy of DR between ESP and users. And in the second game optimization problem, the genetic algorithm (GA) is used to maximize the profits of both parties. In this process, ESP price strategy and user energy consumption strategy are used as initialization variables for genetic operations of crossover, mutation and selection. Once the generation reaches the maximum generation, the optimal number will be found in population based on the benefit function of ESP and users. At this time, the actual load of users and the actual output of units in the system will be obtained. If the results meet the requirements of game equilibrium, the final game decision will be made. If not, the virtual load curve will be readjusted for the next round of calculation.

4. Simulation

4.1. Basic data

In this paper, a typical HE-IES consisting of 6 Users and 1 ESP is chosen as the case study. ESP has a variety of electricity-heat supply resources such as GT, EB, P2G and PV. Fig. 6 and Fig. 7 are the original electrical load and heat load of 6 users. Time-of-use electricity price is adopted in urban energy grid, as shown in Table 1. The heat load price is taken as 0.25CNY/kWh [45], and the natural gas price is 3.5CNY/m^3 with reference to the market price of a certain day [50]. Parameters of ESP equipment are presented in Tables 1 and 2, respectively. The energy price parameters is listed in Table 3. The simulation is conducted using MATLAB 2018a. The optimal time period of optimal scheduling is 24 h, and the time interval for each optimization is 1 h.

4.2. Day-ahead scheduling results

In the day-ahead scheduling stage, IES as a whole determines the virtual load curve interacting with urban energy network under the joint action of economic goals and energy efficiency goals. By solving the two-objective optimization, the Pareto optimal solution of the system economy-energy efficiency objective can be obtained. At the same time, the output plan of ESP units and the virtual electricity-heat load curve reported by IES to the urban energy system can also be worked out through system operation optimization. Fig. 8 shows the Pareto optimal solution space based on NSGA-II.

Under the dual constraints of operating cost and system energy efficiency, ESP optimizes the unit output in the system and obtains the optimal output strategy of electric-heat units. According to the results shown in Fig. 8, there is a positive correlation between the total operating cost and energy efficiency. At the same time, due to the mutual restriction between the economic goal and the energy efficiency goal, it is difficult to find a solution that meets both goals at the same time in some cases, which is the reason why the Pareto curve is composed of many scattered points and appears discontinuous. Under the optimal output strategy, the minimum operating cost of the system reaches 113245.48 CNY, and the maximum energy efficiency of the system reaches 0.573. Fig. 9 and Fig. 10 show the output strategies of electric-heat units and PV respectively, and the planned output strategies of ES systems are shown in Fig. 11.

It can be seen from the above output results that even under the optimal energy efficiency level, the average utilization level of PV units is 0.79, and the output of CHP unit is completely determined by heat load, which leads to the serious suppression of the adjustable capacity of CHP. Under this strong constraint, CHP unit have low operating efficiency when the heat load demand is low. Through calculation, it can be found that the average load rate of CHP unit is less than 50% from 0: 00 to 5: 00, which seriously affects the operation efficiency of the system, and is one of the key factors restricting the energy efficiency level of the system.

According to the above analysis, ESP can meet part of the energy demand by dispatching the units in the system. However, under the two strong constraints of operating cost and system energy efficiency, it is still necessary to interact with the urban energy system to achieve system energy balance. As shown by the virtual load curve in Fig. 12, the system needs to purchase electricity and heat from urban energy system that can be used to meet the demand for most of the day.

4.3. Real-time energy management results based on SIL

1) ESP action in real-time energy management

In the first stage of optimization, IES reported the virtual load curve participating in the scheduling to the urban energy system through optimization. With the start of daily dispatching of urban energy system, DR information will be released to the energy market in time, including load demand response capacity, energy price and subsidy policy. In this case, ESP first perceives DR information, and participates in DR planning of urban energy network by adjusting equipment output and guiding users to adjust load. Fig. 13 and Fig. 14 show the output strategies of electric-heat units

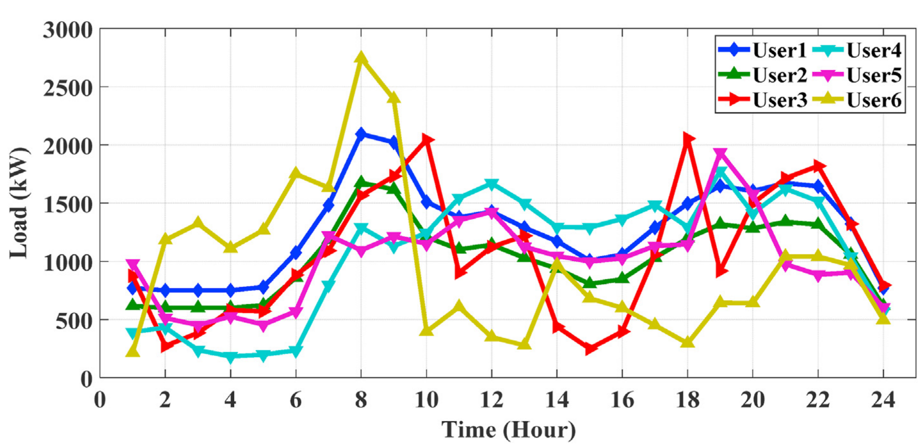

Fig. 6. Original electrical load of 6 users.

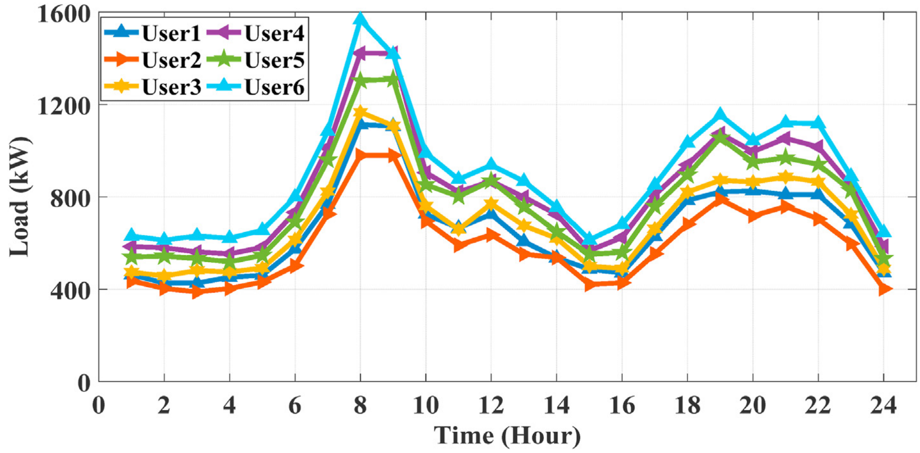

Fig. 7. Original heat load of 6 users.

Table 1
Technical parameters of energy storage system [51].

ES type	Capacity/kW	SOC_{max}	SOC_{min}	Discharge efficiency	Charging efficiency
EES	2000	100%	10%	95%	100%
TES	1500	100%	0	95%	100%

Table 2
Technical and economic parameters of units in the system [49,51].

Unit type	Capacity/kW	Output power/kW		Operation Cost CNY/kW
		Lower limit	Upper limit	
PV	5000	0	5000	0.42
GT	6000	0	6000	0.17
EB	2000	0	2000	0.15
EES	2000	−2000	2000	0.81
TES	1000	−1000	1000	0.22
P2G	1000	0	1000	0.14

and PV respectively, and the planned output strategies of ES systems are shown in Fig. 15.

Through the way of generator-load interaction and collaborative optimization, ESP makes game strategy with users according to market information, and participates in DR of urban energy system by changing the intra-day dispatching plan and guiding users to adjust load. In this case, ESP adjusts the unit operation strategy in order to increase its own interests and improve the system operation efficiency. CHP units are decoupled and P2G operation mode is more flexible. As shown in Fig. 13, the output of CHP is obviously improved from 0: 00 to 5: 00, and the average load rate exceeds 60%. At the same time, with the coordination and adjustment of ES system, the utilization level of photovoltaic has been raised to over 85%. Through the operation strategy optimization, ESP has more flexibility when playing games with users, which greatly improves the energy conversion and utilization of the IES, and realizes the dynamic collaborative optimization of generators and loads.

2) User action in real-time energy management

Under the condition of balancing the game benefits between ESP and users, users adjust the load by losing a part of comfort within the acceptable range, and get economic compensation. At the same time, ESP guided users to complete load adjustment and completed DR plan under the condition of providing excellent price to users. Table 4 shows the hourly adjustment of electric load and heat load of users, and the indoor temperature and satisfaction curves of 6 users are shown in the Fig. 16.

3) Real-time energy management results

Through the collaborative optimization of user load and ESP unit output, the virtual load curve is quickly adjusted to respond to DR scheduling of urban energy system. The DR results of virtual electric and heat load are show in the Fig. 17 and Fig. 18, respectively.

Table 3
Different energy prices on a typical day.

Energy type	Price type	Price	Time windows
Electricity CNY/kW	Peak Price	1.35	12:00–15:00 20:00–22:00
	Normal Price	0.86	9:00–11:00 16:00–17:00 23:00–24:00
	Lower Price	0.45	1:00–8:00
Carbon trading [43] CNY/*t*	Selling Price	200	1:00–24:00
	Buying Price	200	1:00–24:00

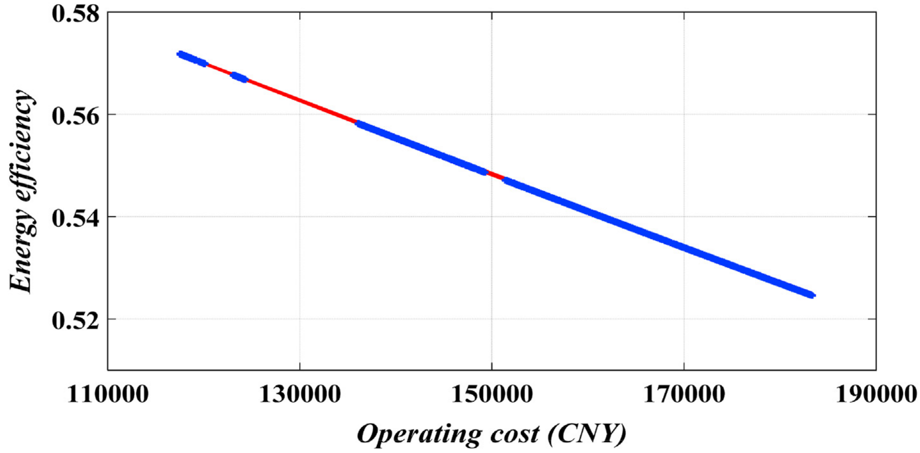

Fig. 8. Pareto optimal solution space based on NSGA-II.

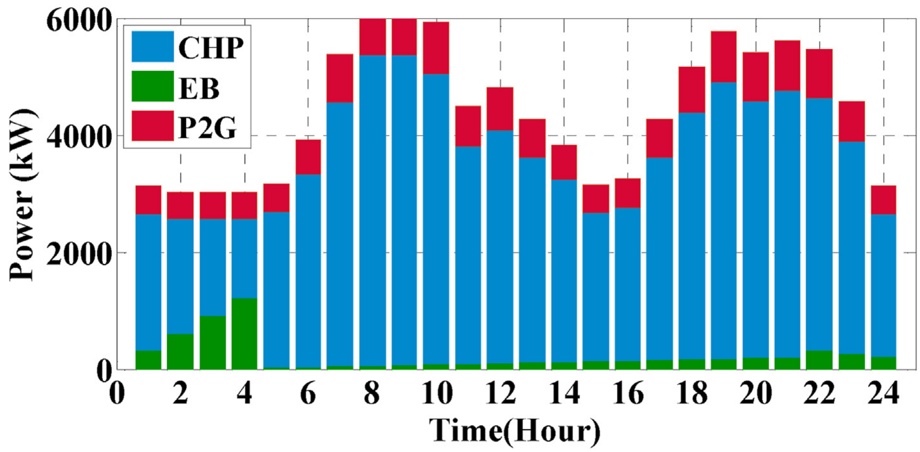

Fig. 9. Optimization results of Electric-heat unit.

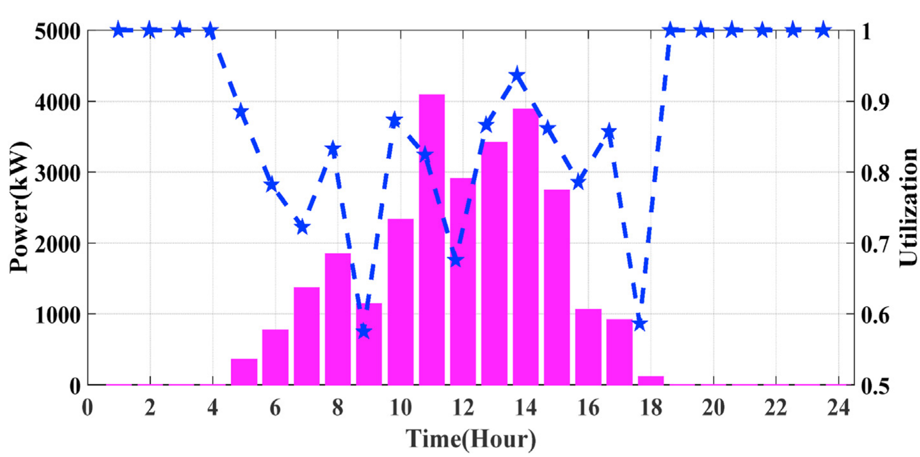

Fig. 10. Output and utilization efficiency of photovoltaic unit.

As shown in Figs. 17 and 18, the virtual electric load is adjusted more in the valley section (1:00–8:00) and peak section of urban electricity price (18:00–22:00), showing the characteristics of peak clipping and valley filling. However, the virtual heat load shows a trend of overall reduction. The reason for this phenomenon lies in the obvious price change trend of urban electricity price. When ESP perceives the price stimulus signal, it will dispatch the electric-thermal units to cooperate with users for game optimization, so

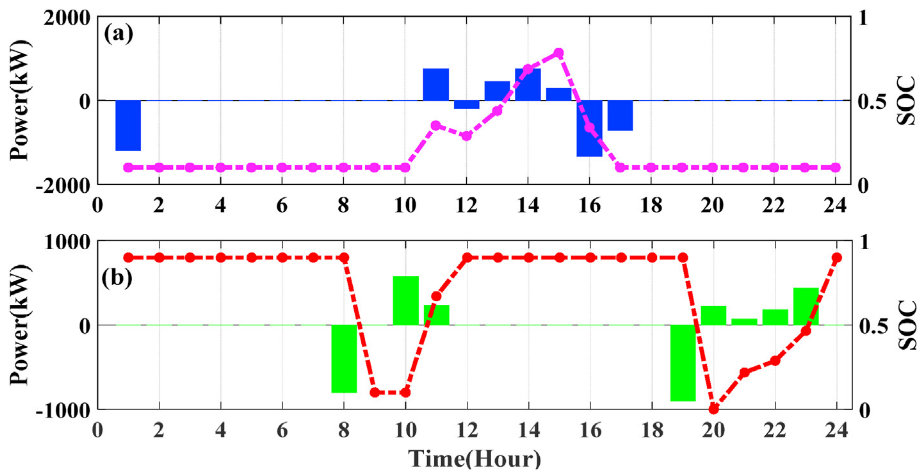

Fig. 11. Optimization results of ES unit.

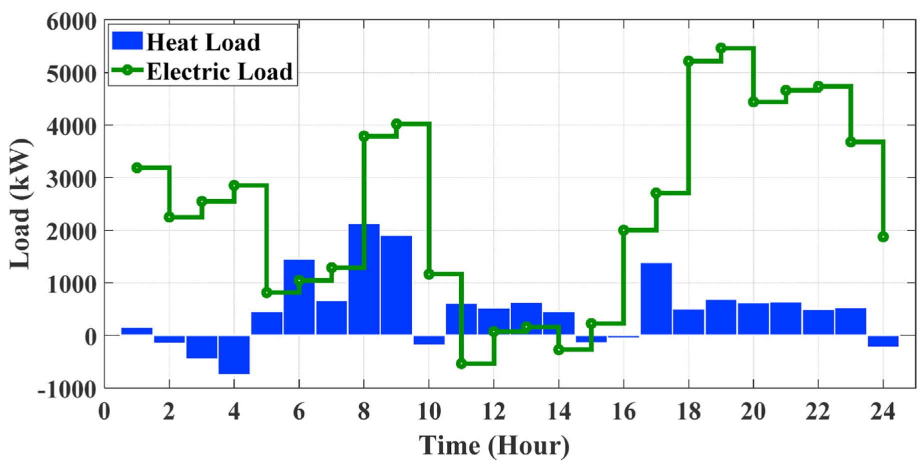

Fig. 12. Optimization results of campus virtual load curve.

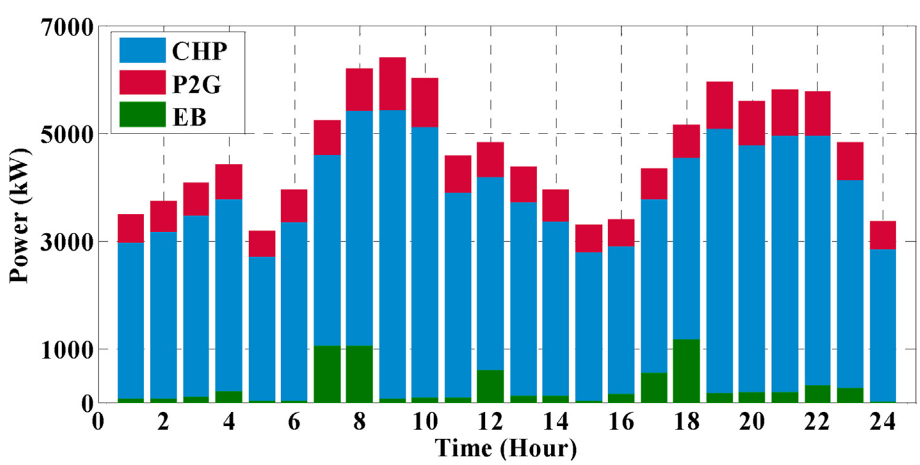

Fig. 13. Optimization results of electric-heat unit.

as to maximize the price dividend and DR subsidy income. As far as heat load is concerned, the urban heat price is constant, and the only factor that promotes the adjustment of virtual heat load is the internal heating price signal given by ESP to users. That is to say, the adjustment of virtual heat load mainly depends on the reduction of user heat load.

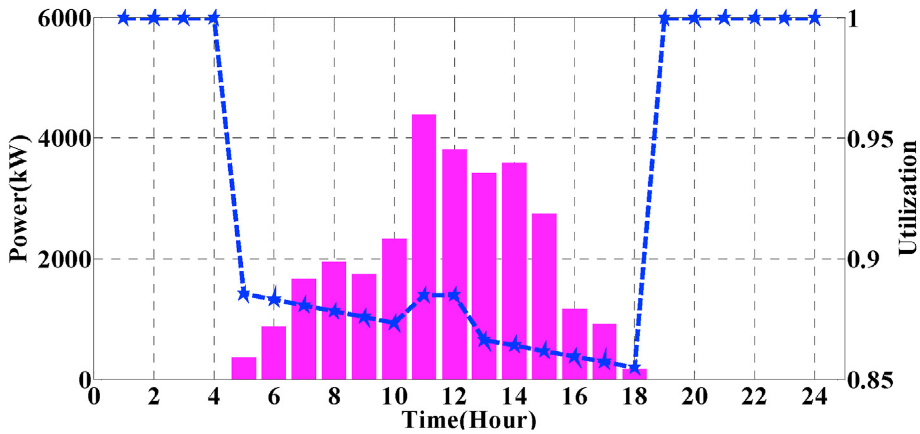

Fig. 14. Output and utilization efficiency of photovoltaic unit.

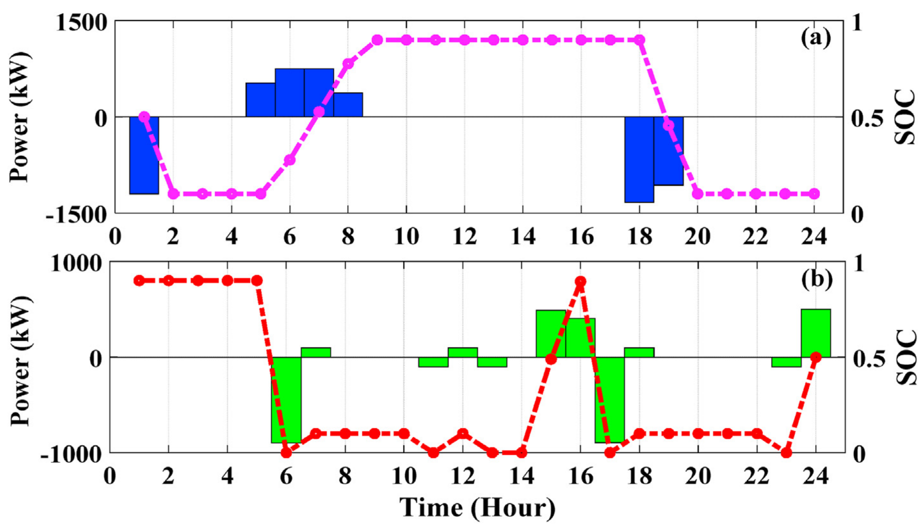

Fig. 15. Optimization results of ES unit.

4.4. Game utility analysis of users and the ESP

1) Economic benefit analysis

After iterative calculation, the final results of the game between users and ESP are shown in Figs. 19–21. Fig. 19 shows the utility function curve of ESP and users, and the energy prices and IDR subsidy income distribution results are shown in Fig. 20 and Fig. 21, respectively.

According to the iterative process of ESP benefit and user benefit optimization shown in Fig. 19 (a) and Fig. 19 (b), with the increase of iteration times, ESP benefit gradually increases and converges after about 50 iterations. On the contrary, the benefit of users decreases with the increase of iteration times, and converges after the same iteration times. It can be seen that ESP plays a dominant role in the Stackelberg game, which ensures that ESP can get the maximum profit. However, as followers in the game, user can only make their own optimal decisions according to ESP decisions, which leads to the benefits gradually decreasing with the iteration.

Table 5 shows the composition of comprehensive benefits of ESP. It can be seen from the table that the cost of ESP mainly comes from the cost of interaction between IES and urban energy network, which accounts for 40.19% of the total cost. In addition, due to the operation of P2G system, the carbon emission of the system is always within the limit, and the carbon emission right worth 9370.60 CNY has been sold. This is also the main reason why the fuel cost of the system is relatively low.

Combined with the benefit data analysis in Fig. 19 the energy cost paid by users is the main revenue source of ESP. And the daily energy supply income of ESP is as high as 139682.20yuan, accounting for 79.7% of the total income. In addition, ESP has gained DR subsidy income of 9370.60 CNY in the real-time energy market by guiding users to adjust load and optimize unit output, and the distribution of this income is one of the focuses of the game between ESP and users.

According to the analysis of the above simulation results, in the optimization of real-time stage, the energy sales price and DR subsidy price in IES are the focus of inducing game optimization. Figs. 20 and 21 show the dynamic pricing results of Stackelberg game between ESP and users.

It can be seen from the Fig. 20 that the internal electricity price of the system is always lower than the electricity price of the power

Table 4
Electricity-heat load adjustment result of Users.

Time/h	Electrical load/kW			Heat load/kW		
	Before DR	After DR	Reduction ratio	Before DR	After DR	Reduction ratio
1	3854	3620	6.07%	3126	2900	7.21%
2	3749	4199	−12.00%	3021	2786	7.79%
3	3749	4397	−17.28%	3021	2775	8.14%
4	3749	4493	−19.85%	3021	2764	8.50%
5	3893	4649	−19.42%	3165	2898	8.43%
6	5368	6010	−11.96%	3912	3641	6.92%
7	7409	7943	−7.21%	5370	5102	4.99%
8	10,462	11,002	−5.16%	7550	7310	3.17%
9	10,107	9725	3.78%	7340	7138	2.75%
10	7548	7170	5.01%	4927	4759	3.41%
11	6887	6467	6.10%	4412	4212	4.53%
12	7133	6767	5.13%	4804	4621	3.80%
13	6439	6201	3.70%	4255	4074	4.25%
14	5857	5575	4.81%	3819	3650	4.43%
15	5031	4729	6.00%	3139	2979	5.10%
16	5290	4918	7.03%	3251	3082	5.20%
17	6445	6137	4.78%	4261	4069	4.51%
18	7483	6745	9.86%	5153	4973	3.49%
19	8240	7462	9.44%	5765	5574	3.31%
20	8017	6963	13.15%	5396	5198	3.68%
21	8362	7330	12.34%	5595	5382	3.80%
22	8218	7270	11.54%	5452	5242	3.86%
23	6606	6216	5.90%	4568	4347	4.83%
24	3854	3590	6.85%	3126	2901	7.21%

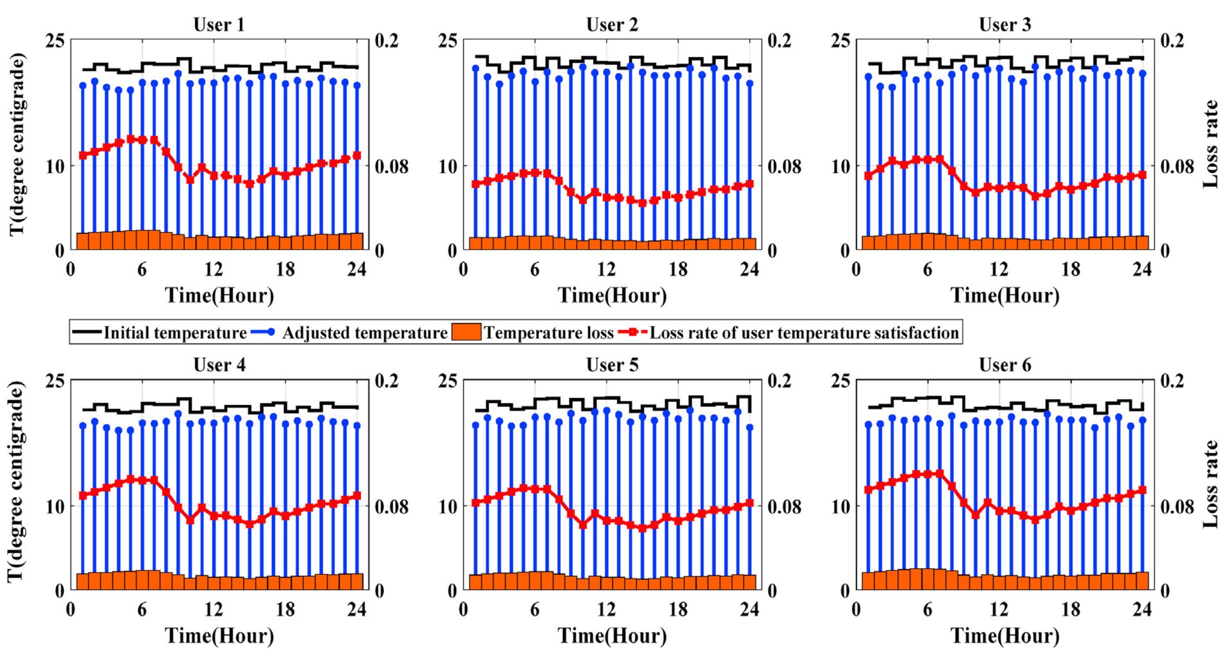

Fig. 16. Indoor temperature and satisfaction curves of 6 Users.

grid, so as to ensure that users are willing to respond to ESP scheduling. The IES heating price remained stable at night and was at the lowest level in the afternoon, and reached the maximum at 11:00 and 23:00. In the process of real-time coordination scheduling, the user load and ESP units respond to DR plan of urban energy system through continuous interaction. The DR subsidy income obtained from urban energy system is the second focus of the game between users and ESP. As shown in Fig. 21, the DR subsidy price given by ESP to users is at a similar level to the DR subsidy price of urban energy system, which is to further guide users to make load adjustment. Users and ESP allocate the DR subsidies obtained by the game, and the allocation is based on their respective contributions to the virtual load adjustment capacity. From 1: 00 to 7: 00, the decoupling operation of CHP unit and coordination of ES system makes ESP adjustment more flexible, and the sharing ratio between users and ESP is 50%. In other periods, the electric load and heat load are active, and the users have great adjustability, which leads to the users having a great advantage in DR subsidy income distribution.

In addition to operating economy, energy efficiency is also a key indicator for efficient operation of IES. Through collaborative optimization of user load and system electric-thermal units, the

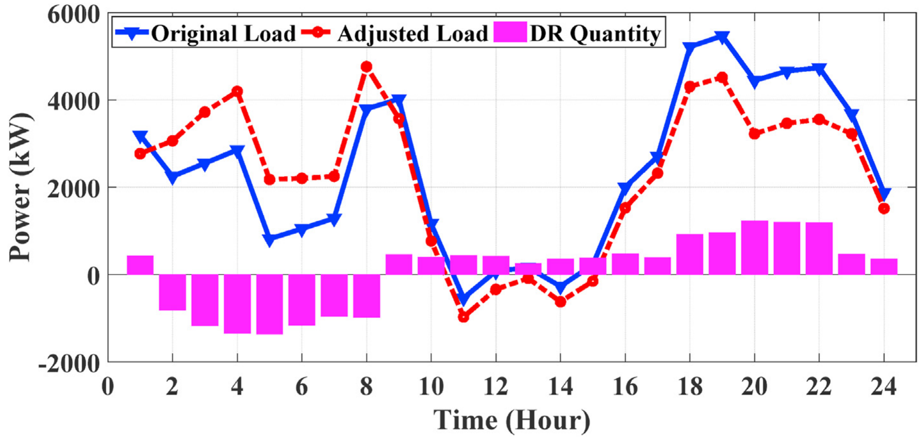

Fig. 17. Response results of virtual electric load demand.

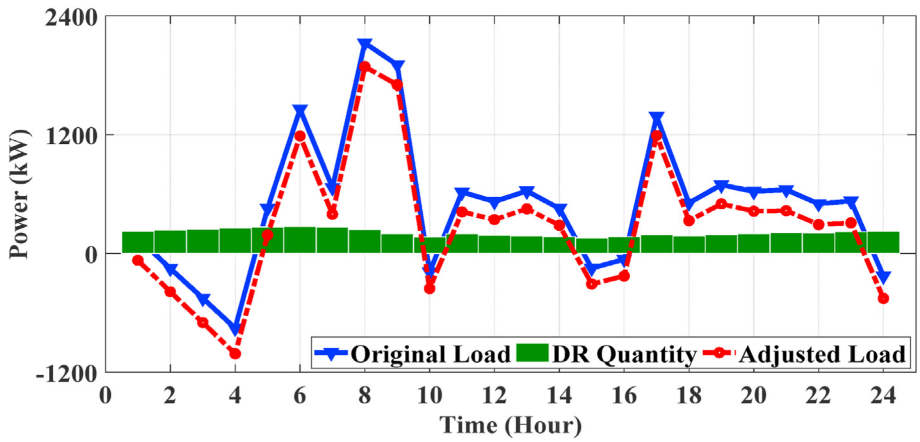

Fig. 18. Response results of virtual heat load demand.

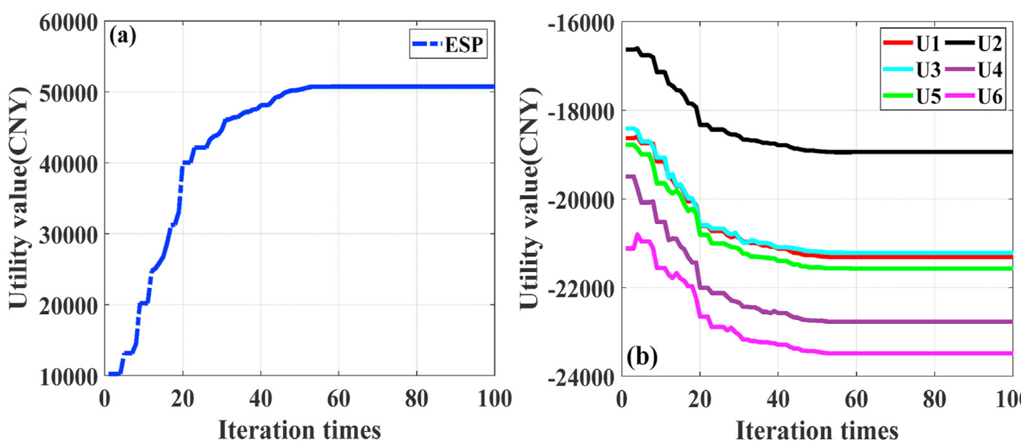

Fig. 19. Utility function curve of ESP and users.

pollutant utilization level and comprehensive energy efficiency of the system have been significantly improved. The calculation results of system energy efficiency index are shown in Fig. 22, Fig. 23 and Fig. 24.

According to the operating efficiency of CHP unit in Fig. 22, the operation mode of CHP system has changed according to the system scheduling requirements. The CHP system is decoupled in the stage of low heat load demand (1:00–5:00), and the system load rate is increased from 0.5 to 0.6. Under this load-generator joint optimization scheduling mode, the Exergy efficiency of the system is kept at an ideal level, and the average energy efficiency of the system is over 0.52.

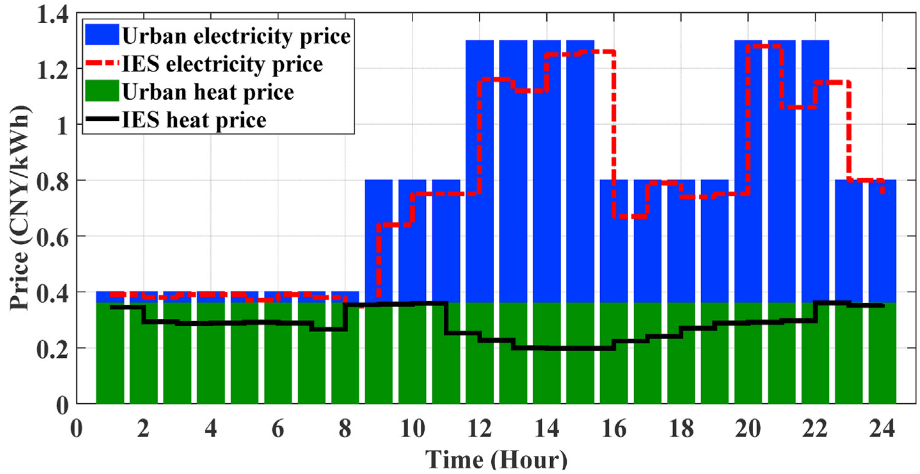

Fig. 20. Dynamic energy transaction pricing results in different periods of time.

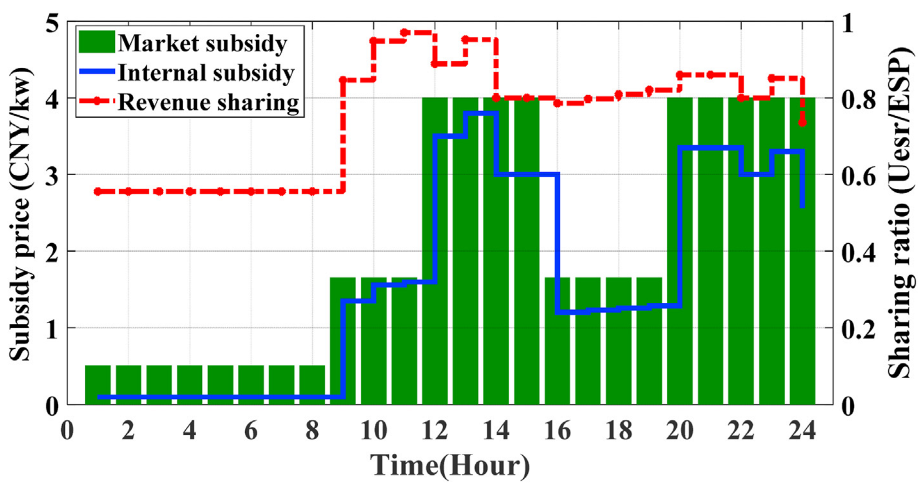

Fig. 21. Dynamic DR subsidy pricing results and DR income distribution ratio.

2) Energy efficiency analysis

Table 5
Composition of ESP cost-benefit.

Cost-benefit composition		Calculated value CNY
ESP Cost	Operation cost	39273.11
	Fuel cost	35270.66
	Carbon trading cost	0
	Virtual load cost	50085.10
ESP Income	Energy supply income	139682.20
	DR income	26197.19
	Carbon trading income	9370.60
ESP Benefit		50621.12

The system energy efficiency level is shown in Fig. 23, and the Fig. 24 shows the change of carbon emission and carbon consumption level of the system.

Through the absorption and conversion of P2G system, most of the carbon emissions of CHP units are absorbed and converted into natural gas for reuse by CHP system. Through this recycling mode, P2G system can use lower electricity price to improve the operation level, increase the consumption of carbon emissions and increase the NG output. According to the simulation results, the carbon emission of the system not only did not exceed the quota, but also 67.99% of the carbon emission quota was sold in the real-time market. In addition, the amount of NG converted by P2G accounts for 71.26% of the total consumption of NG in CHP units. This utilization mode not only improves the system energy efficiency, but also increases the system economic benefits.

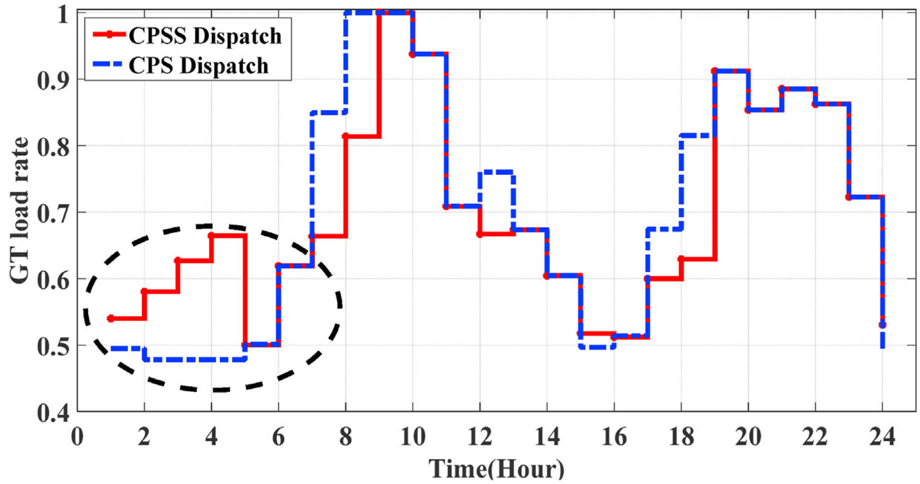

Fig. 22. Operation efficiency of CHP unit.

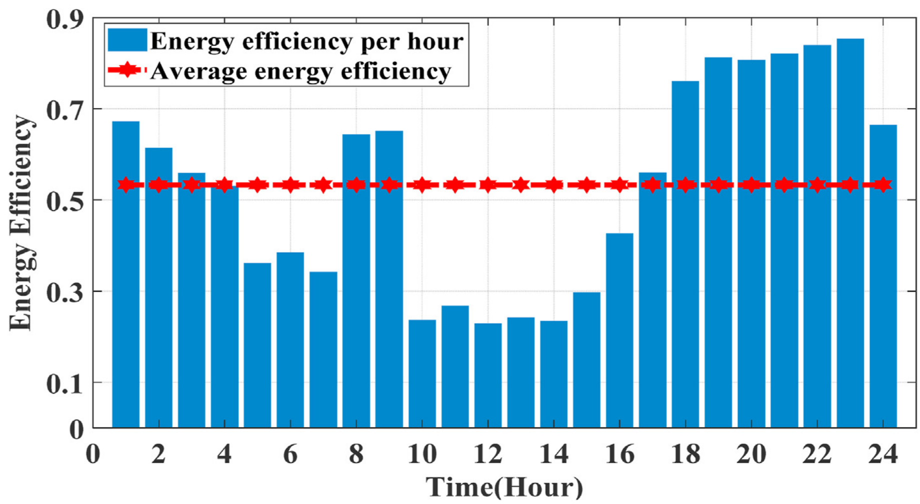

Fig. 23. System energy efficiency level curve.

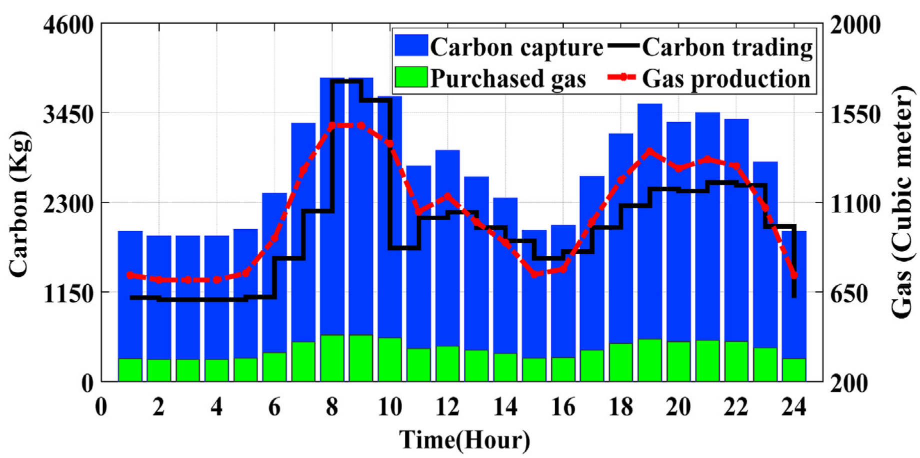

Fig. 24. Transaction of natural gas and carbon emission.

5. Conclusion

In this paper, a new energy management framework of HE-IES considering source-load interactive strategy is developed, which realizes hybrid energy conversion and energy efficiency improvement through two-stage optimization. And the core conclusions are as follows.

(1) The energy management of IES involves collaborative optimization in different fields of cyber, physics and society. On the basis of traditional centralized optimization in energy management modeling, social domain ESP and user game model are introduced to carry out collaborative optimization of power supply and load, and realize the combination of physical equipment collaborative optimization and social domain game optimization, which can enhance the flexibility of system regulation and promote the effect of energy efficiency improvement.

(2) Through simulation calculation, it is found that the efficiency improvement effect of the system is sensitive to the change of carbon trading price, and can coordinate the carbon trading cost and energy cost of the system according to the carbon trading price. To a certain extent, the increase of carbon trading price can increase the system benefit. At the same time, the capacity change of coupling elements affects the low-carbon economic scheduling results. In a certain range, the capacity of P2G increases, which promotes carbon conversion, reduces energy costs and improves the economic benefits of the system.

The model established in this paper is mainly for energy management of IES, making the optimal pricing strategy and realizing the economic operation of IES in response to grid demand response price. In the next stage, based on the energy management framework established in this paper, the existing model will be optimized and improved to realize its application in auxiliary services such as peak shaving and frequency modulation.

Author statement

Yujing Huang: Methodology; Project administration; Roles/Writing - original draft, Yudong Wang: Methodology; Writing – review & editing, Nian Liu: Funding acquisition; Project administration; Supervision.

Declaration of competing interest

All authors declare that there is no conflict of interest.

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