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A two-level game optimal dispatching model for the park integrated energy system considering Stackelberg and cooperative games

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ABSTRACT

Due to the reform and liberalization of the multi-energy market and the increasing complexity of the internal main body coupling of the park integrated energy system, the effective use of the external multi-energy market and the flexible participation of internal multiple subjects to compensate for the shortage of supply in the park integrated energy system has practical research significance. Therefore, in this paper, a two-layer game model was constructed to optimize the park integrated energy system internally and externally. Firstly, an upper-level Stackelberg game model of the superior energy network and park system was constructed to carry out external optimization of the park integrated energy system. Second, a cooperative game model was constructed for the park users, the gas supply system, and the park integrated energy system to undertake internal optimization of the park integrated energy system. In addition, a multi-agent cooperative game benefit distribution model was constructed based on the Shapley value method, the Banzhaf value method, the solidarity value method, and the improved risk factor. Finally, multiple scenarios were established and the solution was optimized using a two-stage solution algorithm. The results show that cooperation between users, the gas supply system, and the park integrated energy system of the lower-level park can improve the internal supply and demand matching of the park integrated energy system, and enhance its competitiveness in the upper Stackelberg game.

1. Introduction

In recent years, due to the development of the social economy, it has been observed that single power system transactions can no longer meet increasingly complicated energy demand. In addition, park integrated energy system (PIES) have increasingly participated in the multi-energy market, in which competition has increased and become more intense [1]. The participation of users in the comprehensive price-based demand response, and the participation of power-to-gas converters (P2Gs) in PIES scheduling, have become important factors affecting the operation optimization results and market competitiveness of the PIES. Therefore, it is of guiding significance for the PIES to be efficiently involved in multi-energy market competition by expanding the transactions of traditional power systems and the systems coupled with multiple energy resources. It is also essential to analyze the transaction scenario of the PIES under the cooperation of multiple entities to participate in the external energy market.

To date, scholars have conducted research relating to power market game trading, the comprehensive price-based demand response, and cooperative games. For example, in terms of participating in competitive transactions in the power market, Li et al. [2] built an optimal dispatching model for a combined system coupled with wind power and cascade hydropower on the basis of a Stackelberg game. Sivanantham et al. [3] established a Stackelberg game between the service provider and the users, which reduces the user's electricity bill by considering the game optimization of the demand response. Ying et al. [4] established a Stackelberg game between the energy control center and the electric vehicle users, and used a genetic algorithm to solve the Nash equilibrium. Yu et al. [5] created a two-layer Stackelberg game model including grid enterprises, multiple service providers, and corresponding users. Yin et al. [6] proposed using a Stackelberg game to solve the problem of

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Nomenclature

PIES park integrated energy system
SEN superior energy network
GSS gas supply system
WPP wind power plant
EHP electric heat pump
CHP combined heat and power equipment
CH heat exchanger
GSD gas storage device
$f(v)$ the wind speed function
v the wind speed
$P_{W,R}$ the rated power of the WPP
$v(t)$ real-time wind speed over time t;
$f_{PV}(t)$ the solar radiation function
r_{max} the maximum irradiance over time t
α,β the shape parameters of beta distribution
η_{PV} the solar radiation efficiency
E_j^{be},E_j^{af} the load of users of load j before and after the implementation of the CPBDR
e_j the demand elasticity coefficient of the class j load
$E_{p,j}^{af},E_{f,j}^{af},E_{v,j}^{af}$ the autoelastic coefficients of load j in peak, flat, and valley periods
$E_{p,j}^{be},E_{f,j}^{be},E_{v,j}^{be}$ the peak, flat, and valley power consumptions before the implementation of CPBDR
$p_{p,j}^{be},p_{f,j}^{be},p_{v,j}^{be}$ the peak, flat, and valley energy prices before the implementation of the class j CPBDR
$R_{SEN,w}(t),C_{SEN,w}(t)$ the revenue and cost of the SEN over time t under scenario w
$Q_{E,w}^{O}(t),Q_{H,w}^{O}(t),Q_{G,w}^{O}(t)$ the electricity, heat, and gas volume that the SEN sold to the park system over time t under scenario w
$\pi_{SEN,w}^{ss}(t)$ the start-up cost of SEN over time t under scenario w
$g_{SEN,w}(t)$ the total quantity of energy purchased
$u_{SEN,w}(t),N_{EBS}$ the rev-stop state and the start-up cost of SEN over time t under scenario w
$g_{SEN,w}(t-1)$ he energy supply of SEN in the $t-1$ period under scenario w
$v(t)$ 0–1 variables of SEN operation state
M_{on},M_{off} the time required to prepare for power supply and the time required to stop the power supply of SEN
$\pi_{PIES,w}(t),\pi_{PIES,w}^{*}(t)$ the net income of the PIES before and after the demand response over time t under scenario w
∂,δ the 0–1 state variables
$p_E(t),p_H(t)$ the internal power price and the internal heat price
$Q_{E,w}^{PIES}(t),Q_{H,w}^{PIES}(t)$ represent the power and heat load of the PIES supplied to the park before the CPBDR implemented over time t under scenario w
$p_E^{*MAX}(t),p_H^{*MAX}(t)$ the highest electric and heating price in the park after the CPBDR
$p_g(t)$ the unit price of gas purchase
$C_{PIES,w}^{OM,i}(t)$ the operation and maintenance cost of unit i in the PIES over time t under scenario w
$c_{i,om}$ the unit operation and maintenance cost of unit i
σ the maximum permissible abandonment rate
$Q_{PIES,w}^{U}(t)$ the total amount of power used over time t under scenario w
$C_{PIES,w}^{PBDR}(t)$ the CPBDR cost of the PIES over time t under scenario w
$P_j^{PBDR}(t)$ the unit compensation price for the load of class j over time t
$Q_{j,1},Q_{j,2}$ the critical points of the first and second step section, respectively, of the class j load
$R_{GS,w}(t),C_{GS,w}(t)$ the revenue and cost of the GSS over time t under scenario w
$\Delta Q_{G,w}^{GS}(t)$ the variation of gas load supplied by the GSS after users participate in cooperation over time t under scenario w;
$C_{GS,w}^{OM,g}(t)$ the operation and maintenance cost of unit g over time t under scenario w
$c_{g,om}$ the unit operation and maintenance cost of unit g
$Q_{E,GS,w}^{PIES}(t)$ the power purchase of the GSS over time t under scenario w
$Q_{E,w}(t),Q_{H,w}(t)$ the electrical and heat load demands of users over time t under scenario w before CPBDR implementation
$Q_{E,w^*}(t),Q_{H,w^*}(t)$ the electrical and heat load demands of users after the implementation of the CPBDR over time t under scenario w.
$\Delta Q_{PIES,w}^{AC}(t)$etc. the changes in variables after CPBDR implementation over time t under scenario w.
$V_{k,shapley}$ the income based on the Shapley value method of the member k
n the number of alliance participants
$v(s/k)$ the income of the alliance $(s-1)$ that excludes k
$v_{k,solidarity}$ the income based on the solidarity value method of the member k
V the total income
V_k the income under the basic distribution model
V the alliance income
p_i^{WPP} the probability of wind power scenario i occurring
$p_j^{\overline{WPP}}$ the probability of the remaining scenario j
P2G power-to-gas
PU park users
PV photovoltaics
ESD electricity storage device
HSD heat storage device
GT gas turbine
WHB waste heat boiler
CPBDR comprehensive price-based demand response
c the scale parameter of the Weibull distribution
k the state parameter
v_{in},v_R,v_{out} the cut-in, rated, and cut-out wind speeds of the WPP
$P_{WPP}(t)$ WPP's power supply over time t
r the solar irradiance
$\Gamma(\cdot)$ the gamma function
$P_{PV}(t)$ the amount of energy that PV supplies over time t
S_{PV} the radiating area
p_j^{be},p_j^{af} the energy prices before and after the implementation of the CPBDR for the load of class j
e_j^{tt},e_j^{st} the autoelastic coefficient, the cross-elasticity coefficient
$E_{p,j}^{af},E_{f,j}^{af},E_{v,j}^{af}$ the peak, flat, valley power consumptions of the class j load
$p_{p,j}^{af},p_{f,j}^{af},p_{v,j}^{af}$ the energy prices of the peak, flat, and valley periods after the implementation of class j CPBDR
F_{SEN} the net income of the SEN
$p_{E,w}^{O}(t),p_{H,w}^{O}(t),p_{G,w}^{O}(t)$ the prices of electricity, heat, and gas sold to the park system by the SEN over time t under scenario w
$\pi_{SEN,w}^{pg}(t)$ the generating cost of SEN over time t under scenario w
a_{SEN},b_{SEN},c_{SEN} the cost coefficients of SEN
ρ_{coal} the coal price
$Q_{E,w}^{PS}(t),Q_{H,w}^{PS}(t),Q_{G,w}^{PS}(t)$ the amount of electricity, heat, and gas that the GSS needs to purchase externally over time t under scenario w
$\Delta g_{SEN,w}^{+},\Delta g_{SEN,w}^{-}$ the limit of increase in energy supply and the limit of the reduction in SEN under scenario w

$T_{\text{on}}(t-1).T_{\text{off}}(t-1)$ the accumulative energy supply time and the cumulative stop time of SEN
F_{PS} net income of the park system
$\pi_{\text{GS},w}(t)$,$\pi_{\text{PU},w}(t)$ the net income of the GSS and PU over time t under scenario w
$R^*_{\text{PIES},w}(t)$,$C^*_{\text{PIES},w}(t)$ the benefits and costs of the PIES after CPBDR implementation over time t under scenario w
$p^*_{\text{E}}(t)$,$p^*_{\text{H}}(t)$ the internal power price and internal heat price after implementing the CPBDR
$Q^{\text{LACK}}_{\text{E},w}(t)$,$Q^{\text{LACK}}_{\text{H},w}(t)$ the power and heat load that the PIES cannot supply to the park over time t under scenario w
$C^{\text{G}}_{\text{PIES},w}(t)$,$P_{g,w}(t)$ the gas purchase cost and gas purchase quantity of the PIES over time t under scenario w
$\Delta Q^{\text{PIES}}_{\text{E},w}(t)$,$\Delta Q^{\text{PIES}}_{\text{H},w}(t)$ the electricity and heat load transfer volumes of users after CPBDR implementation
$P_{i,w}(t)$ the output force of unit i over time t under scenario w
$C^{\text{AC}}_{\text{PIES},w}(t)$ the discard penalty cost of PIES over time t under scenario w
$Q^{\text{AC}}_{\text{PIES},w}(t)$ the total discard power of the PIES over time t under scenario w
p_{ac} the unit energy disengagement penalty cost
$\Delta Q^{\text{PIES}}_{j,w}(t)$ the transfer of the user's electricity and the heat load of the PIES over time t under scenario w
$P^{\text{PBDR}}_{j,n}(t)$ the unit compensation price for load of class j in the paragraph n over time
$Q_{j,min}$,$Q_{j,max}$ the minimum and maximum piecewise critical points, respectively, of class j load
$Q^{\text{GS}}_{\text{G},w}(t)$ the gas load of the park supplied by the GSD over time t under scenario w
$p_{\text{G}}(t)$ the internal gas selling price of the GSS over time t;
$P_{g,w}(t)$ the output force of unit g over time t under scenario w
$C^{\text{E}}_{\text{GS},w}(t)$ the power purchase cost of the GSS over time t under scenario w
$\Delta Q^{\text{PIES}}_{\text{E,GS},w}(t)$ the change of the GSS purchasing power after the user participates in the cooperation
$p^*_{\text{H}}(t)$,$p^*_{\text{E}}(t)$ the heat and electricity price of PIES after implementing the CPBDR
$Q^{\text{PIES,in}}_{\text{WPP},w}(t)$, etc WPP, PV, GT, ESD, EHP, CH, HSD, P2G, and GSD to meet the needs of electricity and heat load over time t under scenario w
E^{min}_{peak},E^{max}_{valley} the minimum load among the peaks and the maximum load among valleys
s the number of participants in the alliance S
$v(s)$ the income of alliance S
$v_{k,\text{banzhaf}}$ the income based on the Banzhaf value method of the member k
R_k the actual operational risk of the member k and $\sum_{k=1}^{n} R_k = 1$
V''_k the income obtained from the distribution model based on the operational risk improvement of the member k
X_k the income of the member k while acting alone
$P^i_{WPP}(t)$,$P^j_{WPP}(t)$ wind power scene i and scene j
M the collection of reduced scenes
M_j a collection of scenes in a reduced set that are replaced by the scene j

virtual power plant aggregators participating in the day-ahead power market and real-time power market transactions. Feng et al. [7] designed a Stackelberg game model of demand response strategy makers and demand response strategy followers from the perspective of demand response. Reza Sharifi et al [8] proposed a Stackelberg game model of an electricity retailer and consumers, in which the upper level consists of a price-maker retailer modeled as the leader who seeks to maximize their profit by adopting optimal pricing strategies for a pool-based electricity market. Kuang et al. [9] designed an energy-sharing operation mechanism and established a non-cooperative game model with a virtual power plant operator as the leader and producer, and a consumer as the follower. The aforementioned papers have closely studied implementations of the Stackelberg game between different power supply and consumption subjects, and thus laid the research foundation for the construction of a Stackelberg game model in the current paper. In addition, although Waqas Amin et al. [10] proposed an optimization model integrating non-cooperative and cooperative games, the above research literature only involves the trading of power systems, and does not include a multi-energy dimension.

Regarding integrated demand response applications, Wang et al. [11] extended the traditional electricity demand response to the "thermoelectricity" demand response, and established a price-type demand response model based on the price elasticity matrix. Gao et al. [12] incorporated interruptible and transferrable heat loads into the scope of the traditional electrical demand response, and constructed an excitable heat demand response model. Tan et al. [13] further developed a "cooling, heat and electricity" comprehensive demand model, which effectively transferred various load demands of users and improved the benefits of the system economically and environmentally. The above literature verifies the positive role of the comprehensive demand response in enhancing user engagement and the degree of supply–demand matching, laying the research foundation for the construction of a comprehensive demand response in the current paper.

Regarding cooperative game research, Yang et al. [14] constructed a PIES stochastic optimization model of cooperative alliance and used the Shapley value method to determine the income distribution of the partners. Kazi et al. [15] applied the Shapley value method to derive the benefit-based allocation of the network usage cost. Tan et al. [16] constructed a framework of a wind–thermal cooperative game and determined income distribution based on the Shapley value method. Pusillo et al. [17] focused on the Banzhaf value for cooperative games. Ma et al. [18] constructed a cooperative game model based on the solidarity value and distributed benefits to participants. Ge Erli et al. [19] constructed a cost allocation model for power storage expansion based on a cooperative game. Omrani et al. [20] constructed a performance evaluation model for Iranian power distribution companies based on cooperative games. Hasan et al. [21] constructed a benefit distribution model of cooperative entities based on the Shapley value, Aumann–Shapley value, and nucleolus value approaches. In addition, because the basic cooperative game model has a single consideration factor, studies have aimed to improve it. Zhong W et al. [22] constructed a cooperative game allocation model with consideration of ecological investment, risk factors, and technological enhancement. Cao W et al. [23] constructed an improved cooperative game allocation model based on fairness and efficiency, return, and risk. The above literature has examined the cooperative game, including incorporation of the income distribution model, thus laying a research foundation for the establishment of the cooperative game model in the current paper.

To summarize, the above studies have laid a good theoretical research foundation for the current study. Due to the continuous development of comprehensive park energy systems, the coupling of various energies has increased. The multi-energy market has experienced constant improved and fierce competition. Studying competitive transactions in the traditional electricity market alone cannot meet the diversified development trend of energy use. However, existing research has failed to either extend the Stackelberg game of the traditional power system to multiple energy fields, or to study the interaction of the Stackelberg game in a market involving multiple energy fields. Furthermore, users change from being recipients of system scheduling results to participants via the demand response. P2G satisfies gas load by absorbing clean energy that has been discarded, thus improving clean energy utilization efficiency. However, existing studies have not studied the incremental benefits of the PIES and the importance of improving competitiveness in an upper Stackelberg game that incorporates users' participation in a multi-type demand response and P2G electrical conversion from the perspective of a cooperative game.

Therefore, combined with the above analysis, this paper took the PIES as the basic research object and constructed a two-layer game model, including a Stackelberg game and a cooperative game. This study extended the traditional power system game to the heating system game, and a model of a PIES participating in the external multi-energy market was constructed. In addition, an internal benefit distribution model under the cooperation of users and GSSs to participate in the PIES was constructed for both internal and external optimization to maximize the overall benefits of the PIES. The main innovations of this study are as follows:

(1) Construction of an external optimization model of the PIES based on the Stackelberg game. Extension of the traditional power system game to the heating system game and comprehensive study of the game interaction between the superior energy network (SEN) and the park system in the multi-energy market, with the goal of maximizing the net income of both parties in the Stackelberg game, and compensating for the imbalance of supply and demand in the park system.
(2) Construction of an internal optimization model of the PIES based on a cooperative game. Design of park users (PU), using an approach in which the gas supply system (GSS) participates in the PIES cooperation alliance, and construction of a lower-level cooperative game benefit distribution model based on the Shapely value, Banzhaf value, and solidarity value methods. Improve the risk factors, effectively distribute the lower-level cooperative subjects, reflect the main body's contribution to the cooperative alliance, and enhance the stability of the lower-level cooperative alliance.
(3) Construction of a two-stage solution algorithm based on the Latin hypercube and synchronous back-generation reduction to address the uncertainty of the distributed unit output of the PIES, and based on the particle swarm algorithm to determine the upper Stackelberg–Nash equilibrium solution.

The remainder of this paper is organized as follows. Section 2 presents construction of a two-layer game interaction framework, including the upper Stackelberg game and the lower cooperative game. Section 3 presents construction of a two-layer optimization model, including the upper Stackelberg game optimization scheduling model and the lower cooperative game benefit distribution model. Section 4 presents construction of a two-stage solution algorithm, including PIES uncertainty processing and the upper-level game Stackelberg–Nash equilibrium solution method. Section 5 selects an industrial park in northern China as an example object to verify the validity and applicability of the proposed model. Section 6 summarizes the contributions and conclusions of this paper.

2. The interaction framework of the two-layer game

2.1. The Stackelberg game framework

In the Stackelberg game constructed in this paper, the SEN is the game subject, which is composed of a superior power grid, and heat and gas networks, and the park system is the game follower, which is composed of the PIES, the GSS, and PU. In the park system, the park operator has the right to operate the PIES. Only when thePU and GSS reach a cooperative alliance with the PIES can they participate in the game with the SEN [24].

The SEN, to achieve a goal of own profit maximization, can develop a variety of energy sales prices (in this paper, natural gas is not considered to participate in the game from the perspective of power and heating supply), thus affecting the purchasing of the park operator. The superior energy grid can constantly adjust the energy sale price and the park operator constantly adjusts the purchasing power during the process of the game between the two sides until they are unable to adjust the decision variables to improve their income separately. The game interaction framework constructed in this paper between the SEN and park operators is shown in Fig. 1. This paper assumes that when the park system cannot meet the load demand within the park, it will be purchased from the SEN, without considering the margin.

2.2. The cooperative game framework and model

2.2.1. The cooperative game framework

This paper builds a lower-level cooperation framework based on the PIES as the basic participant, and the GSS and PU as the flexible participants. Any combination of the three parties constitutes the park system, and forms the slave in the upper-level game. The basic assumptions and specific ways of cooperation within the park system are as follows:

(1) All three parties have the intention to reach a cooperative alliance;
(2) When the three parties operate independently, no demand response strategy is implemented for the PIES, and the GSS does not participate in the dispatching of the PIES;
(3) In the GSS, P2G takes part in the cooperative alliance by consuming the remaining power of the PIES for power–gas conversion to satisfy the gas load demand of the park;
(4) PU participates in the alliance by participating in the demand response program implemented by the PIES.

The interaction framework within the park system based on the cooperative game at the lower level is shown in Fig. 2.

In the industrial park, the park operator conducts energy management of the PIES, and the PIES employs the wind power plant (WPP), photovoltaics (PV), the electricity storage device (ESD), the electric heat pump (EHP), the heat storage device (HSD), and combined heat and power equipment (CHP) to satisfy the power and heat load demands of users. In addition, the CHP is composed of the gas turbine (GT), the waste heat boiler (WHB), and the heat exchanger (CH). The GSS is composed of P2G and the gas storage device (GSD) to satisfy the gas load demand of users, of which the gas load demand of the park is the daily operation demand of the CHP. The park system structure is represented in Fig. 3.

2.2.2. The unit model and the game interaction model

2.2.2.1. The unit model of park system.

(1) Considering the uncertainty of the WPP

The uncertainty of the wind speed is fitted with a Weibull distribution [14]:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}} \tag{1}$$

The power supply model of the WPP in which the risk is considered is as follows:

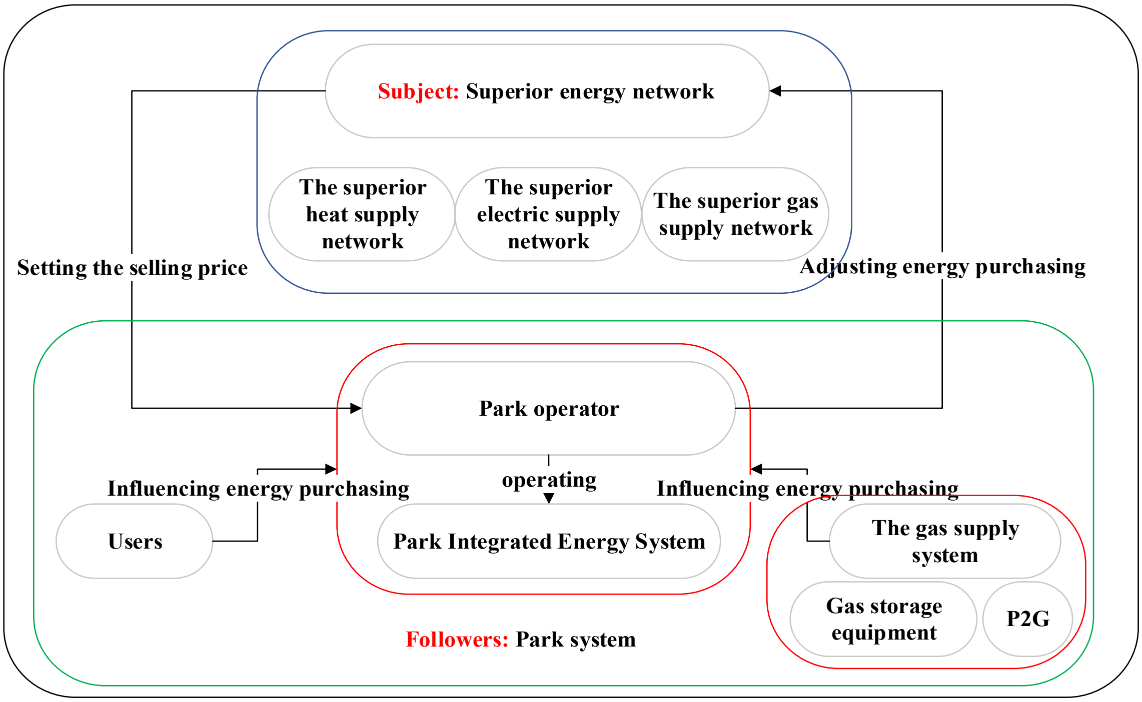


Fig. 1. The upper layer of the Stackelberg game framework.

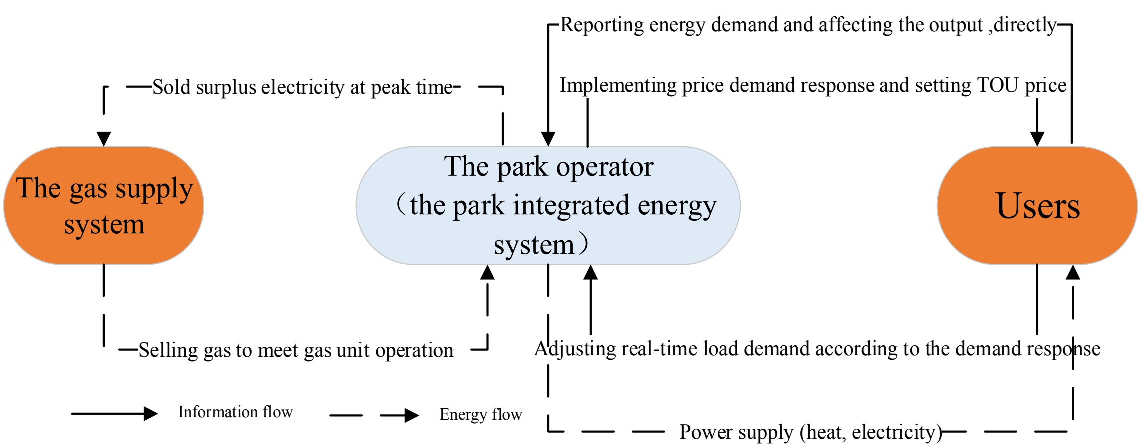


Fig. 2. The lower layer of the cooperative game framework.

$$P_{WPP}(t) = \begin{cases} 0 & v(t) \leqslant v_{in} \\ \dfrac{v - v_{in}}{v_R - v_{in}} P_{W,R} & v_{in} \leqslant v(t) \leqslant v_R \\ P_{W,R} & v_R \leqslant v(t) \leqslant v_{out} \\ 0, & v(t) \geqslant v_{out} \end{cases} \tag{2}$$

(2) Considering the uncertainty of PV

A beta distribution is used to fit the uncertainty of solar radiation [14]:

$$f_{PV}(t) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)} \left(\frac{r}{r_{max}}\right)^{\alpha-1} \left(1 - \frac{r}{r_{max}}\right)^{\beta-1} \tag{3}$$

The PV energy supply model that considers the uncertainty is as follows:

$$P_{PV}(t) = \eta_{PV} S_{PV} f_{PV}(t) \tag{4}$$

(3) Other unit model construction

The CHP, ESD, EHP, HSD, P2G, and GSD models can be referred to in previous research [25].

2.2.2.2. Comprehensive price-based demand response model. In this section, the cooperative alliance of users in the park is built as a comprehensive price-based demand response (CPBDR) [26]:

$$e_j = \frac{(E_j^{af} - E_j^{be})/E_j^{be}}{(p_j^{af} - p_j^{be})/p_j^{be}} \tag{5}$$

According to the three peak, flat, and valley periods, the demand–-price elasticity matrix can be given by:

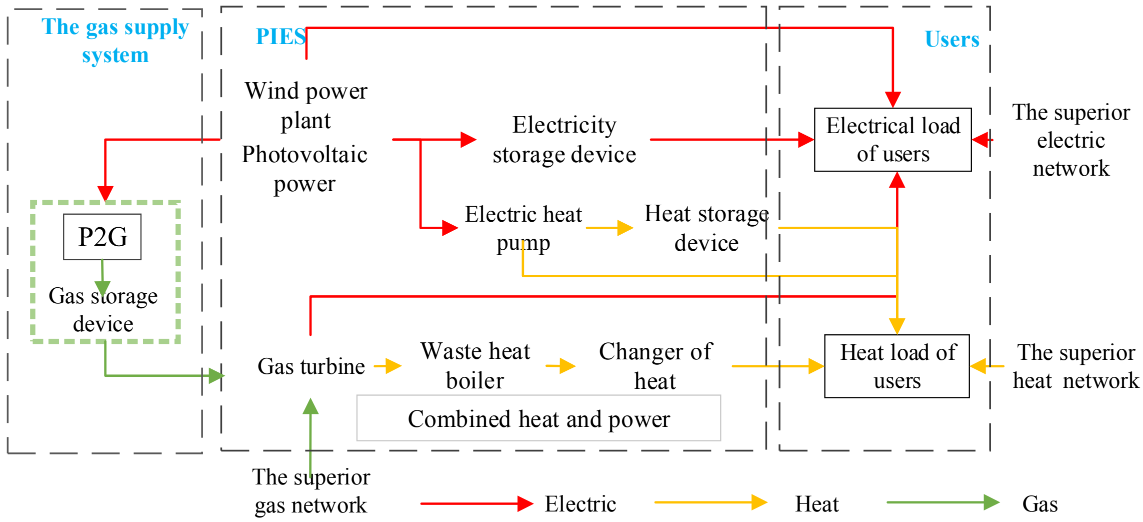


Fig. 3. The park system.

$$E_j = \begin{bmatrix} e_j^{pp} & e_j^{pf} & e_j^{pv} \\ e_j^{fp} & e_j^{ff} & e_j^{fv} \\ e_j^{vp} & e_j^{vf} & e_j^{vv} \end{bmatrix} \tag{6}$$

Based on the demand elasticity matrix, the user energy after the implementation of the class j CPBDR can be obtained, namely:

$$\begin{bmatrix} E_{p,j}^{af} \\ E_{f,j}^{af} \\ E_{v,j}^{af} \end{bmatrix} = E_j \times \begin{bmatrix} E_{p,j}^{be} & 0 & 0 \\ 0 & E_{f,j}^{be} & 0 \\ 0 & 0 & E_{v,j}^{be} \end{bmatrix} \times \begin{bmatrix} (p_{p,j}^{af} - p_{p,j}^{be})/p_{p,j}^{be} \\ (p_{f,j}^{af} - p_{f,j}^{be})/p_{f,j}^{be} \\ (p_{v,j}^{af} - p_{v,j}^{be})/p_{v,j}^{be} \end{bmatrix} + \begin{bmatrix} E_{p,j}^{be} \\ E_{f,j}^{be} \\ E_{v,j}^{be} \end{bmatrix} \tag{7}$$

3. Two-layer decision optimization model

3.1. An upper Stackelberg game optimal scheduling model

Based on the upper Stackelberg game interaction framework, the game strategy of the SEN is to set the real-time energy purchase price, and the game goal is to obtain the maximum benefit. The park system is based on the real-time energy purchase price set by the SEN, taking the optimization of energy purchase as the game strategy, and the game goal is to maximize the income of the internal system. The game optimization model of the subject and subordinate subject is shown below.

3.1.1. Game model of the superior energy network

3.1.1.1. Utility function of the superior energy network

$$maxF_{\mathrm{SEN}} = \sum_{t=1}^{T} (R_{\mathrm{SEN},w}(t) - C_{\mathrm{SEN},w}(t)) \tag{8}$$

$$\begin{cases} R_{\mathrm{SEN},w}(t) = p_{\mathrm{E},w}^{\mathrm{O}}(t) \times Q_{\mathrm{E},w}^{\mathrm{O}}(t) + p_{\mathrm{H},w}^{\mathrm{O}}(t) \times Q_{\mathrm{H},w}^{\mathrm{O}}(t) + p_{\mathrm{G},w}^{\mathrm{O}}(t) \times Q_{\mathrm{G},w}^{\mathrm{O}}(t) \\ C_{\mathrm{SEN},w}(t) = \rho_{\mathrm{coal}}(\pi_{\mathrm{SEN},w}^{\mathrm{pg}}(t) + \pi_{\mathrm{SEN},w}^{\mathrm{ss}}(t)) \\ \pi_{\mathrm{SEN},w}^{\mathrm{pg}}(t) = a_{\mathrm{SEN}} + b_{\mathrm{SEN}} g_{\mathrm{SEN},w}(t) + c_{\mathrm{SEN}} (g_{\mathrm{SEN},w}(t))^2 \\ g_{\mathrm{SEN},w}(t) = Q_{\mathrm{E},w}^{\mathrm{O}}(t) + Q_{\mathrm{H},w}^{\mathrm{O}}(t) + Q_{\mathrm{G},w}^{\mathrm{O}}(t) \end{cases} \tag{9}$$

$$\pi_{\mathrm{SEN},w}^{\mathrm{ss}}(t) = [u_{\mathrm{SEN},w}(t)(1 - u_{\mathrm{SEN},w}(t))] \cdot N_{\mathrm{SEN}} \tag{10}$$

3.1.1.2. Constraints of SEN.

(1) Constraint of the energy sale balance

$$\begin{cases} Q_{\mathrm{E},w}^{\mathrm{O}}(t) = Q_{\mathrm{E},w}^{\mathrm{PS}}(t) \\ Q_{\mathrm{H},w}^{\mathrm{O}}(t) = Q_{\mathrm{H},w}^{\mathrm{PS}}(t) \\ Q_{\mathrm{G},w}^{\mathrm{O}}(t) = Q_{\mathrm{G},w}^{\mathrm{PS}}(t) \end{cases} \tag{11}$$

(2) Start and stop constraints

$$\begin{cases} v(t) \cdot \Delta g_{\mathrm{SEN},w}^{-} \leqslant g_{\mathrm{SEN},w}(t) - g_{\mathrm{SEN},w}(t-1) \leqslant v(t) \cdot \Delta g_{\mathrm{SEN},w}^{+} \\ (T_{\mathrm{on}}(t-1) - M_{\mathrm{on}})(v(t-1) - v(t)) \geqslant 0 \\ (T_{\mathrm{off}}(t-1) - M_{\mathrm{off}})(v(t) - v(t-1)) \geqslant 0 \end{cases} \tag{12}$$

3.1.2. Game model of park system

3.1.2.1. Utility function of park system

$$maxF_{\mathrm{PS}} = \sum_{t=1}^{T} \left\{ \left(\delta - 1 \right) \times \pi_{\mathrm{PIES},w}(t) + \delta \times \pi_{\mathrm{PIES},w}^{*}(t) + \partial \times \pi_{\mathrm{GS},w}(t) + \delta \times \pi_{\mathrm{PU},w}(t) \right\} \tag{13}$$

(1) The net benefit of the PIES

This section implements the CPBDR as an example; the model is:

$$\pi_{\mathrm{PIES},w}^{*}(t) = R_{\mathrm{PIES},w}^{*}(t) - C_{\mathrm{PIES},w}^{*}(t) \tag{14}$$

$$\begin{cases} R^{*}_{\mathrm{PIES},w}(t) = p^{*}_{\mathrm{E}}(t)\times(Q^{\mathrm{PIES}}_{\mathrm{E},w}(t)+\delta\times\Delta Q^{\mathrm{PIES}}_{\mathrm{E},w}(t)) + p^{*}_{\mathrm{H}}(t)\times(Q^{\mathrm{PIES}}_{\mathrm{H},w}(t)+\delta\times\Delta Q^{\mathrm{PIES}}_{\mathrm{H},w}(t)) \\ C^{*}_{\mathrm{PIES},w}(t) = \sum_{i=1}^{I} C^{\mathrm{OM},i}_{\mathrm{PIES},w}(t)+C^{\mathrm{G}}_{\mathrm{PIES},w}(t) + C^{\mathrm{AC}}_{\mathrm{PIES},w}(t)+C^{\mathrm{LACK}}_{\mathrm{PIES},w}(t) + R_{\mathrm{SEN},w}(t)+\delta\times C^{\mathrm{PBDR}}_{\mathrm{PIES},w}(t) \\ C^{\mathrm{OM},i}_{\mathrm{PIES},w}(t)=P_{i,w}(t)\times c_{i,\mathrm{om}},\quad i=\mathrm{PV},WPP,ESD,GT,WHB,CH,EHP,HSD \\ C^{\mathrm{G}}_{\mathrm{PIES},w}(t)=P_{g,w}(t)\times p_{\mathrm{g}}(t) \\ C^{\mathrm{AC}}_{\mathrm{PIES},w}(t)=\begin{cases} 0, & Q^{\mathrm{AC}}_{\mathrm{PIES},w}(t)-Q^{\mathrm{U}}_{\mathrm{PIES},w}(t)\times\sigma\leqslant 0 \\ (Q^{\mathrm{AC}}_{\mathrm{PIES},w}(t)-Q^{\mathrm{U}}_{\mathrm{PIES},w}(t)\times\sigma)\times p_{\mathrm{ac}}, & Q^{\mathrm{AC}}_{\mathrm{PIES},w}(t)-Q^{\mathrm{U}}_{\mathrm{PIES},w}(t)\times\sigma>0 \end{cases} \\ C^{\mathrm{LACK}}_{\mathrm{PIES},w}(t)=p^{*\mathrm{MAX}}_{\mathrm{E}}(t)\times Q^{\mathrm{LACK}}_{\mathrm{E},w}(t)+p^{*\mathrm{MAX}}_{\mathrm{H}}(t)\times Q^{\mathrm{LACK}}_{\mathrm{H},w}(t) \\ C^{\mathrm{PBDR}}_{\mathrm{PIES},w}(t)=P^{\mathrm{PBDR}}_{j}(t)\times\Delta Q^{\mathrm{PIES}}_{j,w}(t), j=\mathrm{H},E \\ P^{\mathrm{PBDR}}_{j}(t)=\begin{cases} P^{\mathrm{PBDR}}_{j,1}(t), Q_{j,min}\leqslant\Delta Q^{\mathrm{PIES}}_{j,w}(t)\leqslant Q_{j,1} \\ P^{\mathrm{PBDR}}_{j,2}(t), Q_{j,1}<\Delta Q^{\mathrm{PIES}}_{j,w}(t)\leqslant Q_{j,2} \\ \vdots \\ P^{\mathrm{PBDR}}_{j,n}(t), Q_{j,max}<\Delta Q^{\mathrm{PIES}}_{j,w}(t) \end{cases}, j=\mathrm{H},E \end{cases} \tag{15}$$

(2) Net income of GSS

$$\pi_{\mathrm{GS},w}(t)=(R_{\mathrm{GS},w}(t)-C_{\mathrm{GS},w}(t)) \tag{16}$$

$$\begin{cases} R_{\mathrm{GS},w}(t) = p_{\mathrm{G}}(t)\times(Q^{\mathrm{GS}}_{\mathrm{G},w}(t)+\partial\times\Delta Q^{\mathrm{GS}}_{\mathrm{G},w}(t)) \\ C_{\mathrm{GS},w}(t) = \sum_{g=1}^{G} C^{\mathrm{OM},g}_{\mathrm{GS},w}(t)+C^{\mathrm{E}}_{\mathrm{GS},w}(t) \\ C^{\mathrm{OM},g}_{\mathrm{GS},w}(t)=P_{g,w}(t)\times c_{g,\mathrm{om}}\quad g=\mathrm{P2}G,GSD \\ C^{\mathrm{E}}_{\mathrm{GS},w}(t)=p_{E}(t)\times(Q^{\mathrm{PIES}}_{\mathrm{E,GS},w}(t)+\partial\times\Delta Q^{\mathrm{PIES}}_{\mathrm{E,GS},w}(t)) \end{cases} \tag{17}$$

(3) The net income function of user is as follows:

$$\pi_{\mathrm{PU},w}(t)=\sum_{t=1}^{T}\left\{\begin{array}{c} ((p_{\mathrm{E}}(t)\times Q_{\mathrm{E},w}(t) + p_{\mathrm{H}}(t)\times Q_{\mathrm{H},w}(t)) \\ -(p^{*}_{\mathrm{E},w}(t)\times Q_{E,w^{*}}(t)-p^{*}_{\mathrm{H},w}(t)\times Q_{H,w^{*}}(t)) \\ +C^{\mathrm{PBDR}}_{\mathrm{PIES},w}(t) \end{array}\right\} \tag{18}$$

3.1.2.2. Constraints of the park system.

(1) The supply–demand balance of electric heat before the CPBDR:

$$\begin{cases} Q_{\mathrm{E},w}(t) = Q^{\mathrm{PIES}}_{\mathrm{E},w}(t) + Q^{\mathrm{LACK}}_{\mathrm{E},w}(t) \\ Q^{\mathrm{PIES}}_{\mathrm{E},w}(t) = Q^{\mathrm{PIES,in}}_{\mathrm{WPP},w}(t)+Q^{\mathrm{PIES,in}}_{\mathrm{PV},w}(t)+Q^{\mathrm{PIES,in}}_{\mathrm{GT},w}(t)+Q^{\mathrm{PIES,in}}_{\mathrm{ESD},w}(t) + Q^{\mathrm{O}}_{\mathrm{E},w}(t) \\ Q_{\mathrm{H},w}(t) = Q^{\mathrm{PIES}}_{\mathrm{H},w}(t) + Q^{\mathrm{LACK}}_{\mathrm{H},w}(t) \\ Q^{\mathrm{PIES}}_{\mathrm{H},w}(t)=Q^{\mathrm{PIES,in}}_{\mathrm{EHP},w}(t)+Q^{\mathrm{PIES,in}}_{\mathrm{CH},w}(t)+Q^{\mathrm{PIES,in}}_{\mathrm{HSD},w}(t) + Q^{\mathrm{O}}_{\mathrm{H},w}(t) \\ Q_{\mathrm{G},w}(t)=Q^{\mathrm{O}}_{\mathrm{G},w}(t)+Q^{\mathrm{GS}}_{\mathrm{G},w}(t) \\ Q^{\mathrm{GS}}_{\mathrm{G},w}(t) = Q^{\mathrm{GS}}_{\mathrm{P2G},w}(t)+Q^{\mathrm{GS}}_{\mathrm{GSD},w}(t) \end{cases} \tag{19}$$

(2) The supply–demand balance of electric heat after the CPBDR:

$$\begin{cases} Q_{E,w^{*}}(t)=Q^{\mathrm{PIES}}_{\mathrm{E},w}(t)+\Delta Q^{\mathrm{PIES}}_{\mathrm{E},w}(t) \\ Q_{\mathrm{H},w^{*}}(t) = Q^{\mathrm{PIES}}_{\mathrm{H},w}(t)+\Delta Q^{\mathrm{PIES}}_{\mathrm{H},w}(t) \\ Q_{\mathrm{G},w^{*}}(t)=Q^{\mathrm{O}}_{\mathrm{G},w}(t)+Q^{\mathrm{GS}}_{\mathrm{G},w}(t)+\Delta Q^{\mathrm{GS}}_{\mathrm{G},w}(t) \\ \sum_{t=1}^{T}(Q_{\mathrm{E},w}(t))=\sum_{t=1}^{T}(Q_{E,w^{*}}(t)),\sum_{t=1}^{T}(Q_{\mathrm{H},w}(t)) = \sum_{t=1}^{T}(Q_{\mathrm{H},w^{*}}(t)) \end{cases} \tag{20}$$

(3) The constraints of the wind–solar power generation power balance:

$$\begin{aligned} Q^{\mathrm{U}}_{\mathrm{PIES},w}(t) &= P_{\mathrm{WPP},w}(t)+P_{\mathrm{PV},w}(t)-Q^{\mathrm{AC}}_{\mathrm{PIES},w}(t) + \delta\cdot\Delta Q^{\mathrm{AC}}_{\mathrm{PIES},w}(t) \\ &= Q^{\mathrm{PIES,in}}_{\mathrm{WPP},w}(t)+\delta\cdot\Delta Q^{\mathrm{PIES,in}}_{\mathrm{WPP},w}(t)+Q^{\mathrm{PIES,in}}_{\mathrm{PV},w}(t)+\delta\cdot\Delta Q^{\mathrm{PIES,in}}_{\mathrm{PV},w}(t) \\ &\quad +Q^{\mathrm{PIES,in}}_{\mathrm{ESD},w}(t)+\delta\cdot\Delta Q^{\mathrm{PIES,in}}_{\mathrm{ESD},w}(t)+Q_{EB,w}(t)+\delta\cdot\Delta Q_{EB,w}(t) \\ &\quad +Q_{P2G,w}(t)+\delta\cdot\Delta Q_{P2G,w}(t) \end{aligned} \tag{21}$$

(4) Constraint of unit operation

For the PIES unit constraints consult ref. [26].

(5) Constraint of CPBDR

1) The income constraints of the PIES:

$$\pi_{\mathrm{PIES},w}(t)-\pi^{*}_{\mathrm{PIES},w}(t)\leqslant 0 \tag{22}$$

2) The cost of PU:

$$((p_{\mathrm{E}}(t)\times Q_{\mathrm{E},w}(t)\ +\ p_{\mathrm{H}}(t)\times Q_{\mathrm{H},w}(t)) - (p^{*}_{\mathrm{E},w}(t)\times Q_{E,w^{*}}(t) - p^{*}_{\mathrm{H},w}(t) \times Q_{H,w^{*}}(t))\geqslant 0 \tag{23}$$

3) The threshold of the peak–valley ratio:

$$\frac{E^{min}_{\mathrm{peak}}}{E^{max}_{\mathrm{valley}}}\geqslant 1 \tag{24}$$

3.2. The income allocation model of the lower cooperative game

Based on the interaction framework of the game at the lower level, it can be seen that the cooperation game at the lower level involves the PIES, users, and the GSS, so the reasonable distribution of the benefits of the alliance and guaranteeing the alliance's stability are the key points of the game interaction at the lower level.

3.2.1. Allocation model based on the Shapley value method

The Shapley value method equitably distributes the benefits of participating parties by considering the level of participants' importance in the alliance [16]:

$$V_{k,shapley} = \sum_{s\subseteq S/k}\frac{(s-1)!(n-s)!}{n!}\times(v(s)-v(s/k)) \tag{25}$$

3.2.2. Allocation model based on the Banzhaf value method

The Banzhaf value means that the profit shared to alliance participants is the same, in number, as the mean value of their margin contribution to all alliances [17]:

$$v_{k,\mathrm{banzhaf}} = \sum_{s\subseteq S/k}\frac{1}{2^{|n|-1}}(v(s)-v(s/k)) \tag{26}$$

3.2.3. Allocation model based on the solidarity value method

The solidarity value method means that the profit shared to alliance participants is the same, in number, as the expected number of their average marginal contribution to all alliances [18]:

$$v_{k,\mathrm{solidarity}} = \sum_{s\subseteq S/k}\frac{(s-1)!(|\mathrm{n}|-\mathrm{s})!}{|n|!|\mathrm{S}|}\sum_{j\in S}(v(S)-v(s/j)) \tag{27}$$

3.2.4. Improved allocation model based on risk factors

Each allocation model assumes that the risks assumed by the partners are the same, which is contrary to the actual situation. Therefore, risk conditions are introduced to improve the basic allocation model:

$$V''_{k} = (R_i - \frac{1}{n})\cdot V + V_k \tag{28}$$

3.2.5. Constraints of the allocation model

The following conditions shall be met when the Shapley value method, the Banzhaf value method, the solidarity value method, and improved allocation model based on risk factors are used for benefit allocation:

$$V_k \geqslant X_k \tag{29}$$

$$\sum_{k\subset I} V_k = V \tag{30}$$

4. The two-stage solution algorithm

4.1. Uncertainty processing

This paper samples the probability distribution of wind power and PV to generate wind power and PV scenarios using the Latin hypercube method. The steps refer to [27].

This paper these reduces the scenarios by adopting the synchronous rollback reduction method. Wind power scenarios are used as an example to show the calculation steps, as follows [28]:

Step 1: Calculating the distance between scenarios:

$$d_t(i,j) = \left\|P^{i}_{wpp}(t) - P^{j}_{wpp}(t)\right\|_2 \quad t = 1,2\dots,T \tag{31}$$

Step 2: Defining the scenario deletion target:

$$\sum_{i\in M} p_i^{wpp}\cdot \min_{j\notin M} d_t(i,j) \tag{32}$$

where p_i^{WPP} is the probability of wind power scenario i occurring; M is the collection of reduced scenes.

Step 3: Calculating the scenario l_k to delete for the k iteration:

$$\sum_{i\in M^{(k-1)}\cup\{l\}} p_i^{wpp}\cdot \min_{j\notin M^{(k-1)}\cup\{l\}} d_t(i,j) \tag{33}$$

Step 4: Deleting the scenario l_k, then obtaining $M^{(k)} = M^{(k-1)}\cup\{l_k\}, k = k+1$.

Step 5: Determining whether $k < M$. If so, go back to step 3; if not, move on to step 6.

Step 6: $M = M^{(k)}$, the deleted scene i is replaced by the scene j that is closest to it in the set of the scenes that remain. Supposing the probabilities of scenario j occurrence are p_j^{WPP}, then the probability of remaining scenes j is:

$$\overline{p}_j^{wpp} = p_j^{wpp} + \sum_{i\in \mathrm{M(j)}} p_i^{wpp} \tag{34}$$

4.2. Solution of the upper layer game Stackelberg–Nash equilibrium value

In the upper Stackelberg game stage, the SEN sets the price of electricity ($p^{\mathrm{O}}_{\mathrm{E},w}(t)$) and heat sales energy ($p^{\mathrm{O}}_{\mathrm{H},w}(t)$) as a strategy, the park system adopts power purchase ($Q^{\mathrm{PS}}_{\mathrm{E},w}(t)$) and heat purchase ($Q^{\mathrm{PS}}_{\mathrm{H},w}(t)$) as strategies, and both sides are constantly adjusting their utility F. When the park system makes the optimal strategy response according to the strategy of the SEN, and the SEN can also get the optimal response according to the response of the park system, the Stackelberg–Nash equilibrium solution in the superior game can be obtained.

If the model equilibrium solution is $\left\{p^{\mathrm{O}*}_{\mathrm{E},w}(t), p^{\mathrm{O}*}_{\mathrm{H},w}(t), Q^{\mathrm{PS}*}_{\mathrm{E},w}(t), Q^{\mathrm{PS}*}_{\mathrm{H},w}(t)\right\}$, the following conditions must be met:

$$\begin{cases} F_{\mathrm{SEN}}\left\{p^{\mathrm{O}*}_{\mathrm{E},w}(t), p^{\mathrm{O}*}_{\mathrm{H},w}(t), Q^{\mathrm{PS}*}_{\mathrm{E},w}(t), Q^{\mathrm{PS}*}_{\mathrm{H},w}(t)\right\}\geqslant F_{\mathrm{SEN}}\left\{p^{\mathrm{O}*}_{\mathrm{E},w}(t), p^{\mathrm{O}*}_{\mathrm{H},w}(t), Q^{\mathrm{PS}}_{\mathrm{E},w}(t), Q^{\mathrm{PS}}_{\mathrm{H},w}(t)\right\} \\ F_{\mathrm{PS}}\left\{p^{\mathrm{O}*}_{\mathrm{E},w}(t), p^{\mathrm{O}*}_{\mathrm{H},w}(t), Q^{\mathrm{PS}*}_{\mathrm{E},w}(t), Q^{\mathrm{PS}*}_{\mathrm{H},w}(t)\right\}\geqslant F_{\mathrm{PS}}\left\{p^{\mathrm{O}}_{\mathrm{E},w}(t), p^{\mathrm{O}}_{\mathrm{H},w}(t), Q^{\mathrm{PS}*}_{\mathrm{E},w}(t), Q^{\mathrm{PS}*}_{\mathrm{H},w}(t)\right\} \end{cases} \tag{35}$$

In the upper Stackelberg game stage, the core of the optimal solution lies in determining the clearing price of electricity and the heat sold in the SEN, in addition to determining the purchase energy of the park system. In this paper, particle swarm optimization is adopted for optimal solution [29].

Table 1
Multiple scenario settings.

Scenes	SEN	PIES	PU	GSS
Scenario 1	√	√	–	–
Scenario 2	√	√	–	√
Scenario 3	√	√	√	–
Scenario 4	√	√	√	√

In the table, "√" means to participate in the upper layer game; "–" means not to participate in the upper layer game.

5. Analysis of example

5.1. The scenario setting

Whether the PU and the GSS form a cooperative alliance with the PIES to participate in the upper-level game is an important factor that affects the main body's own income. It is also an important factor that directly affects the result of the upper-level game. The influence on the main body's own income and the competitiveness of the PIES in higher-level competition is the key to deriving the benefits of the lower-level multi-agent cooperative game. Therefore, this paper sets up four scenarios for optimization analysis. The details are shown in Table 1 below.

Table 2
Time-of-use (TOU) energy price.

Types	Time division	Time quantum	price($/ kW·h)
Electricity price of PIES	Valley period	(23:00–7:00)	0.046
	Ordinary period	(11:00–14:00) (18:00–23:00)	0.098
	Peak period	(7:00–11:00) (14:00–18:00)	0.178
Heat price of PIES	Valley period	(21:00–6:00)	0.042
	Ordinary period	(6:00–9:00) (12:00–18:00)	0.074
	Peak period	(9:00–12:00) (18:00–21:00)	0.107
Gas price of SNE	All the time	(0:00–24:00)	0.087
Gas price of GSS	All the time	(0:00–24:00)	0.082

5.2. Basic data

In this study, an industrial park in Northern China was selected as the research object. The PIES is equipped with 50 MW WPP and PV, the CHP unit is equipped with 10 MW GT and 10 MW WHB, CH, and EHP, and the electrical and heat energy storage devices are each 10 MW. The GSS is equipped with 5 MW P2G and 15 MW gas storage devices. The Latin hypercube sampling method generates 100 initial scenes of WPP and PV output, and then 10 groups of typical scenes of WPP and PV output are obtained after reduction, and the average value is calculated as the basic

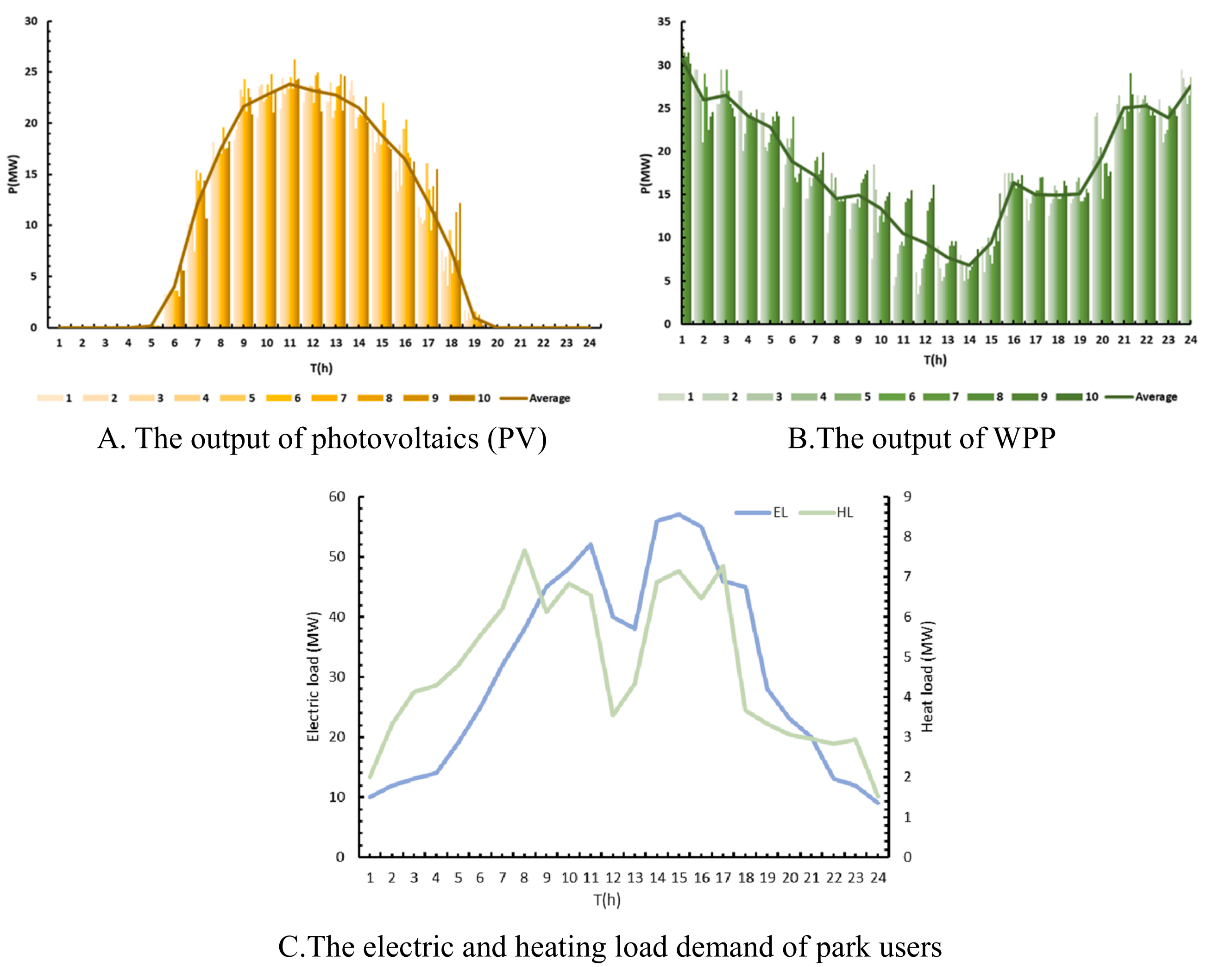
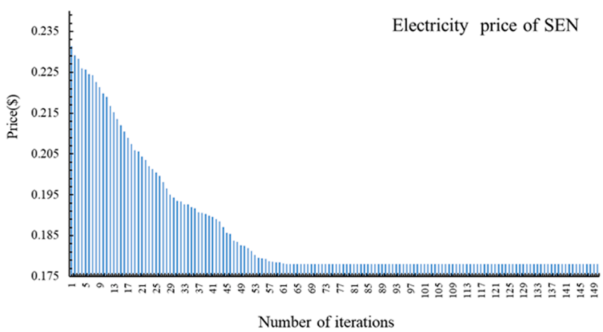


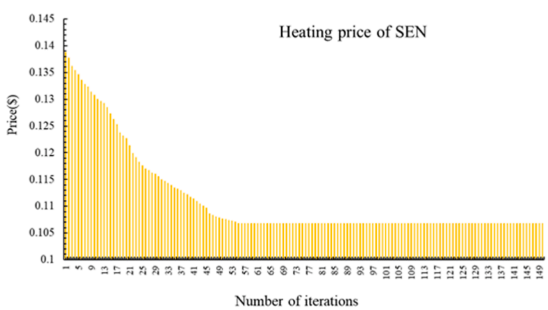
Fig. 4. The output of WPP and PV and load demand.

Table 3
The step cost of the CPBDR.

Load types	Increase or decrease of the load/MW	Compensation price of reducing load/ ($/ kW·h)
Electricity	(1.6,3.2]	0.014
	(0.8, 1.6]	0.009
	(0, 0.8]	0.005
Heat	(3.4]	0.012
	(2, 3]	0.009
	(1, 2]	0.006
	(0, 1]	0.003



A. Convergence of the ninth hour of electricity price



B. Convergence of the ninth hour of heating price

Fig. 5. Convergence of the ninth hour in the upper layer game in scenario 1.

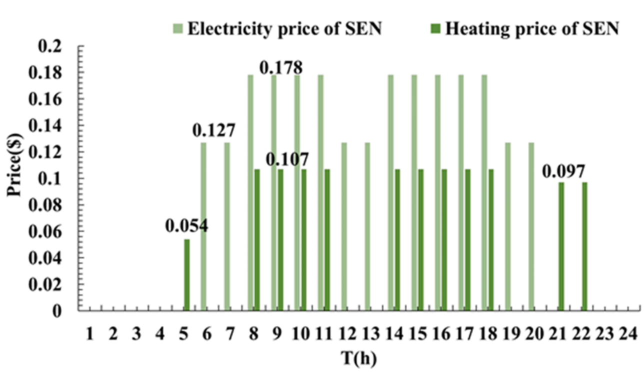


Fig. 6. The price in the upper layer game in scenario 1.

scenes of WPP and PV output. The typical daily heat power load demand of users in the park was obtained, as shown in Fig. 4. It is assumed that the maximum allowable energy abandoned within the park is 5% of the total power generation, and the unit energy abandoning cost is the highest electricity price in the park. Related output parameters and cost parameters of other equipment can be referred to in [30] and [31]. In addition, the initial population is 100 and the maximum number of iterations is 300. In this paper, the upper limit of the market clearing price of heat price and electricity price is no more than 30% of the park selling energy price, and the lower limit is the park selling energy price. The selling energy prices of the park are shown in Table 2. The cost of the step-type CPBDR is shown in Table 3.

5.3. Multi-scenario result analysis

5.3.1. Optimization results analysis of scenario 1

5.3.1.1. Iterative convergence analysis of upper layer game interaction. This section takes 9 h of electric and heat game interaction as an example to analyze the iterative convergence of the energy price of superior energy in scenario 1, as shown in Fig. 5.

Based on Fig. 5, the SEN constantly adjusts the game strategy, that is, the selling energy price is quoted in the market from the quotation ceiling. When the number of iterations reaches about 50, the equilibrium point is gradually reached. Based on the full-time game interaction deduction, the electricity price and the heat price of the SEN within a 24 h period are shown in Fig. 6.

Based on Fig. 6, from the perspective of electricity sales, the variation range of the electricity price of electricity sales is [0.127, 0.178], which sells electricity to the PIES from 6:00 to 20:00. From the perspective of selling heat, the range of selling heat price was [0.054, 0.107], and the PIES were sold at 5:00–6:00, 8:00–11:00, 14:00–18:00, and 21:00–22:00.

5.3.1.2. Analysis of upper layer game optimization results. The optimal strategic response made by the PIES according to the superior energy net strategy is shown in Fig. 7. In addition, the optimization results of the superior net and the PIES in the superior Stackelberg–Nash game were obtained, as shown in Table 4.

Based on Fig. 7, from the perspective of the internal unit of the PIES, WPP and PV separately met the electricity demand in the trough period and reduced the abandonment of clean energy. The flexible charging and discharging function of the power storage unit satisfies part of the electricity demand; furthermore, the EHP conversion satisfies the heat demand of about 34.668 MW. However, based on Table 4, the energy abandonment rate is still higher than the maximum energy abandonment rate of 3.72%, resulting in a penalty cost of about USD 4380.84. In the CHP, the GT met the power demand of about 140 MW during the peak period of electricity consumption, and the CH met the heat demand of 154.2 MW. The heat storage unit absorbed the residual heat energy of the CH and released it during the peak period of heat consumption, which met part of the heat demand and improved energy utilization efficiency. However, the PIES could not meet the electricity and heat load demands of users in the park alone. After the superior energy net first applied the strategy (to determine the electric and heat price), the responders bought 185.976 MW electric and 52.433 MW heat from the superior energy net, otherwise the punishment cost would be about USD 38,707.74.

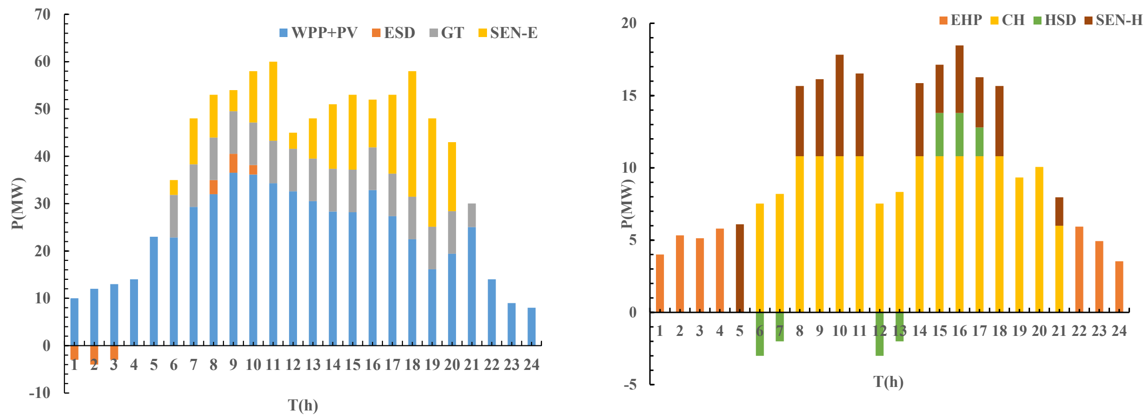


Fig. 7. Optimal results of the upper layer game in scenario 1.

Table 4
The upper layer game optimization results in scenario 1.

Types	Value
The income of SEN	33950.736$
The income of PIES	68466.492 $
The penalty cost of abandoning energy	4380.84$
The rate of abandoning energy	8.72%

Table 5
The upper layer game optimization results in scenario 2.

Types	Value
The income of SEN	33328.44$
The penalty cost of abandoning energy	2600.64$
The rate of abandoning energy	7.21%
The income of GSS	261.612$
The income of PIES	72556.308$
The income of park system	72817.92$

5.3.2. Optimization results analysis of scenario 2

In scenario 2, the GSS and the PIES form a cooperative alliance to participate in a Stackelberg game with the SEN. Because the gas system game is not involved in the Stackelberg game with the SEN, the results of power, heat price, and PIES dispatching are the same as those in Scenario 1. However, the GSS forms a partnership with the PIES, in which electric–gas conversion is used to reduce the cost of buying gas for the PIES while reducing the use of clean energy. Therefore, scenario 2 focuses on analyzing the optimization results of the cooperative game at the lower level of the park system.

Based on Fig. 8 and Table 5, P2G absorbs clean energy that was discarded at 1:00–4:00, and the gas load requirement of about 6 MW from electricity to gas is met at 6:00–9:00. Compared with scenario 1, the net income of the PIES increased by USD 4089.816. To reflect the contribution of the GSS to the park system alliance, it is necessary to conduct income distribution for the lower-level cooperative game; the results are shown in Table 6.

Based on Table 6, the Shapley value method and Banzhaf value method met the constraints of the cooperative game and belong to the core of cooperative game, and the allocation strategy was established. However, the sum of the two profits under the solidarity value method exceeded the total profits of the alliance, which failed to satisfy the overall rational conditions and did not belong to the core of the cooperative game; therefore, the distribution strategy was invalid.

The Shapley value method and Banzhaf value method had the same distribution results. Compared with the original income, P2G income increased by about USD 1914.876, which reflects the important role of the GSS in absorbing clean energy in the lower-level cooperation alliance and improving the overall efficiency of the park system.

However, combined with Table 5, the energy abandonment rate of clean energy within the park is still high. To further reduce the clean

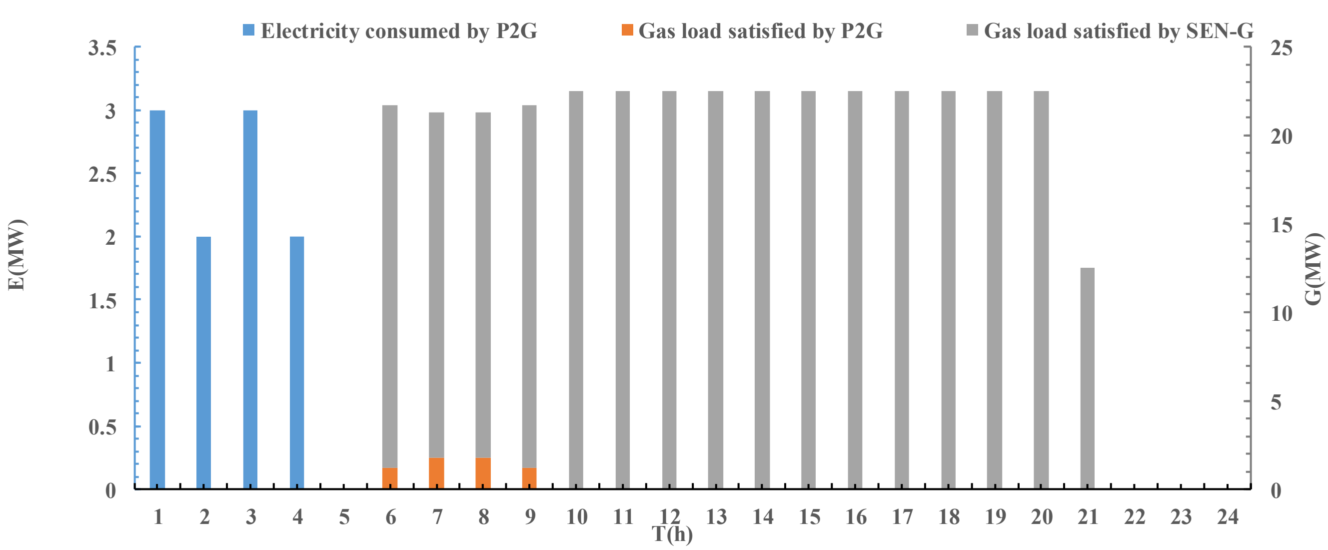


Fig. 8. The GSS absorbs the electric and gas supply in scenario 2.

Table 6
The lower layer game optimization results in scenario 2.

	Result of income distribution form Shapley/$	Result of income distribution form Banzhaf/$	Result of income distribution from Solidarity/$
PIES	70641.432	70641.432	53525.196
GSS	2176.488	2176.488	36408.96

energy abandonment and improve the utilization efficiency of internal clean energy, it is necessary to implement the CPBDR to transfer the user load and increase the internal supply–demand matching degree.

5.3.3. Optimization results analysis of scenario 3

Under scenario 3, users in the park form a cooperative alliance with the PIES by implementing the CPBDR strategy that is implemented by the PIES, and participate in a Stackelberg game with the SEN. Therefore, scenario 3 includes two levels of game.

5.3.3.1. Analysis of the CPBDR implementation results. The PIES electricity and heat prices, in addition to the power and heat loads of users in the park after the implementation of the CPBDR, are respectively shown in Table 7 and Fig. 9.

The combined results of Table 7 and Fig. 9 shows that users adjust the demand of electric and heating energy when affected by the change of electricity price and heating price, which smooths the electricity consumption curve.

5.3.3.2. Iterative convergence analysis of upper layer game interaction. This section takes 9 h of electric and heat game interaction as an example to analyze the iterative convergence of the energy price of the superior energy in scenario 3, as shown in Fig. 10.

When the number of iterations reaches 60, the electricity price of the equilibrium point is gradually reached. When the number of iterations reaches about 45, the heat price of the equilibrium point is gradually reached. Based on the full-time game interaction deduction, the electricity price and the heat price of the SEN within a 24 h period are shown in Fig. 11.

Based on Fig. 11, from the perspective of electricity sales, the variation range of the electricity price is [0.054, 0.18], and electricity is sold to the PIES at 6:00–20:00. From the perspective of selling heat, the range of the heat price is [0.045, 0.116], and the PIES are sold in the range of 2:00–5:00, 8:00–11:00, and 14:00–21:00.

5.3.3.3. Analysis of the optimization results of two-layer game. The optimal strategy response of the PIES was made according to the strategy of the superior net, as shown in Fig. 12. Meanwhile, the optimal results of the superior energy net and the PIES in the superior Stackelberg–Nash game were obtained, as shown in Table 8.

Table 7
The peak–valley time-share energy price after the CPBDR.

Types	Time division	Time quantum	The peak-valley time-share energy price after CPBDR ($/kW·h)
Electricity price of PIES	Valley period	(23:00–7:00)	0.042
	Ordinary period	(11:00–14:00) (18:00–23:00)	0.095
	Peak period	(7:00–11:00) (14:00–18:00)	0.180
Heat price of PIES	Valley period	(21:00–6:00)	0.035
	Ordinary period	(6:00–9:00) (12:00–18:00)	0.07
	Peak period	(9:00–12:00) (18:00–21:00)	0.116

Based on Fig. 12 and Fig. 7, it can be seen that, compared with scenario 1, due to their participation and cooperation, users in the park transfer their load under the guidance of price. The WPP and PV increased their electric load by about 14.849 MW and increased their heat use in the valley period. The clean energy abandonment consumed by EHP increased from 36.493 to 53.362 MW, and the satisfied heat load increased from 34.668 to 50.694 MW, effectively absorbing the clean energy that was abandoned.

Although the PIES cannot meet the electricity and heat load demands of users in the park alone, the responders should purchase the electricity and heat load from the SEN after first implementing the strategy (to determine the electricity and heat price). However, compared with scenarios 1 and 2, electric and heat loads were reduced by 17.67 and 19.666 MW, respectively, by purchasing the park system from the SEN. Therefore, by comparing Figs. 6 and 11, to obtain higher income, the unit price of electricity and the heat sold on the superior power network also increased in the same period. However, compared with scenarios 1 and 2, although the implementation of the CPBDR results in a CPBDR cost of about USD 1201.248 to the PIES, the net income of the PIES still increased by USD 5543.388 and USD 1453.572 respectively, resulting in USD 4670.316 of net income to the users of the park.

To reflect the contribution of users in the park to the park system alliance, it is necessary to determine the income distribution for the lower-level cooperative game; the results are shown in Table 9.

Based on Table 9, similar to scenario 2, the Shapley value method and Banzhaf value method have the same distribution results. Compared with the original income, the income of users in the park increased by about USD 436.536, which reflects the important role of users in the park in absorbing clean energy, and the improvement in the overall efficiency of the park system by transferring load demand in the lower-level cooperation alliance.

5.3.4. Optimization results analysis of scenario 4

In scenario 4, the GSS, users in the park, and the PIES form a cooperative alliance to participate in a Stackelberg game with the SEN, which is similar to scenario 2. However, because the gas system game is not involved in the Stackelberg game with the SEN, the results of power and heat price and the PIES dispatching are the same as those in scenario 3. In addition, because the users, GSS, and the PIES form a cooperation alliance in the park, scenario 4 focuses on analyzing the optimization results of the cooperative game in the lower-level of the park system.

Based on Fig. 13 and Table 10, the GSS participated in the cooperation and 5 MW of clean energy that was abandoned was absorbed by P2G at 1:00–2:00. Gas load demand of about 3 MW was satisfied from 6:00 to 7:00, and net income of about USD 920 was obtained. Compared with scenario 3, the gas purchase cost of the PIES was reduced by about USD 1510, and the energy abandonment rate of clean energy was also reduced to 3.24%. The cooperation of users in the park was similar to that of scenario 3. Using energy transfer, the matching degree of internal supply and demand can be improved, directly increasing the energy supply income of the PIES. To reflect the users of the park and their contributions to the park system alliance, it is necessary to allocate benefits for the cooperation game at the lower level. The results are shown in Table 11.

Based on Table 11, from the perspective of the effectiveness of the distribution strategy, the Shapley value method and the solidarity value method met the constraints of the cooperative game, and the distribution strategy was established, whereas the sum of the benefits of the two under the Banzhaf value method exceeded the total benefits of the alliance, and the distribution strategy failed. In terms of distribution results, the income of users and the GSS in the park decreased, whereas the income of the PIES increased under the Shapley value method. This method ignored the important role of users and gas supply in the park in promoting clean energy consumption and the comprehensive benefits of the park, and thus failed to reflect the contribution of users and the GSS in the park to the park system, so that the distribution strategy was not

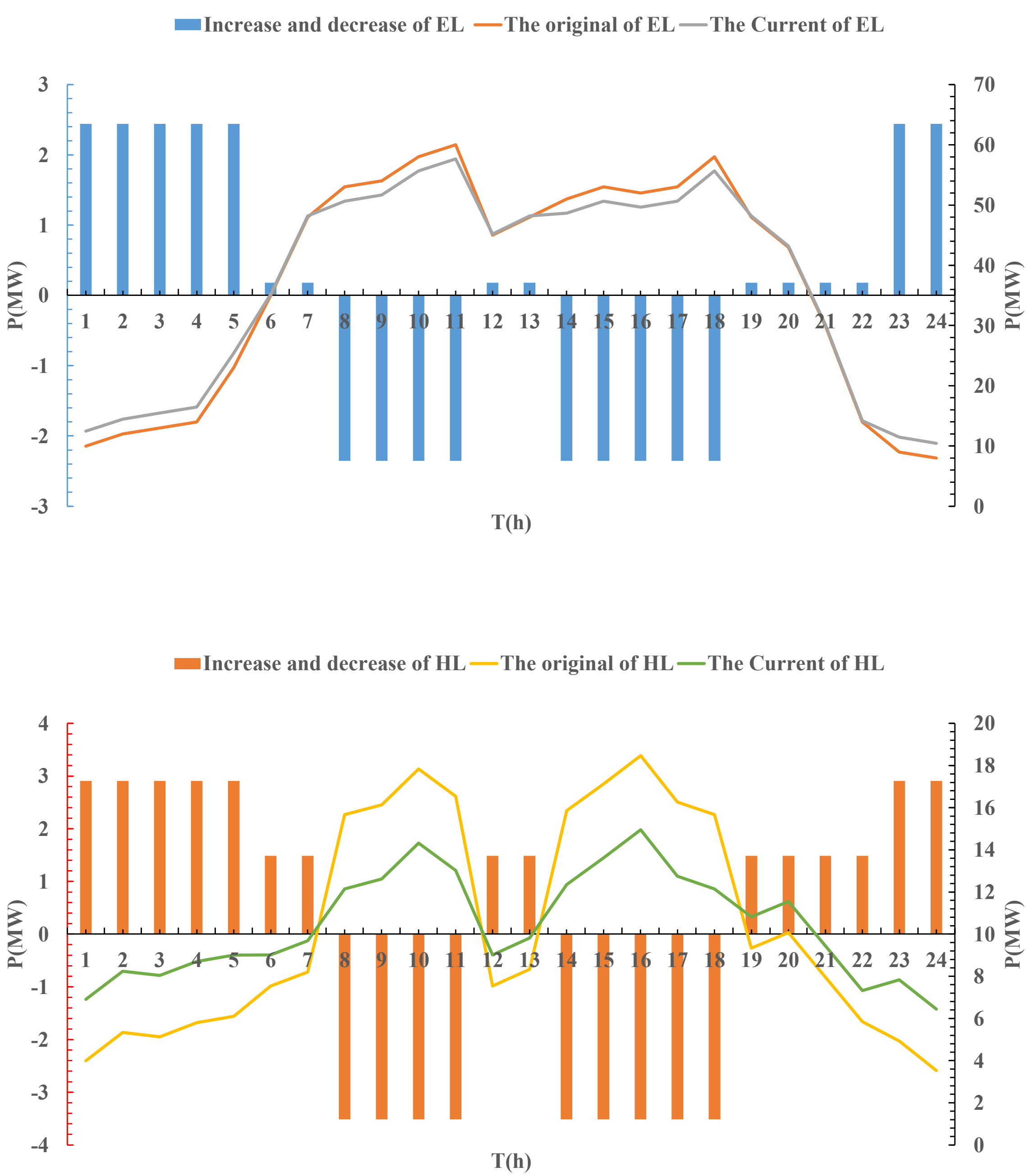
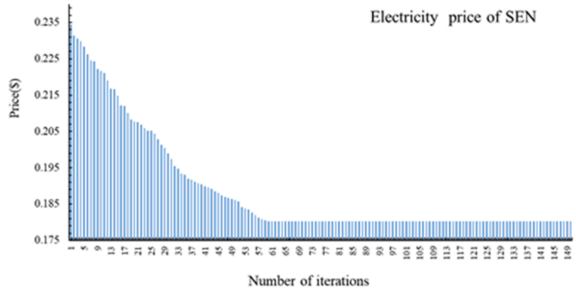
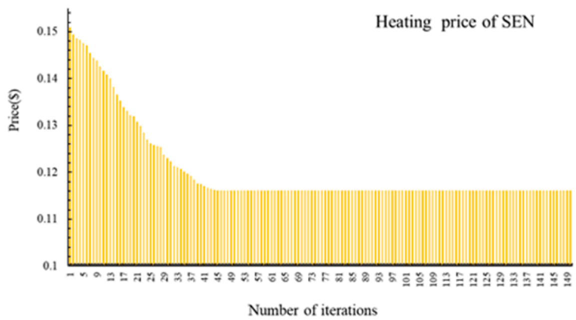


Fig. 9. Electric and heating load transfer after the CPBDR.



A. Convergence of the ninth hour of the electricity price



B. Convergence of the ninth hour of the heating price

Fig. 10. Convergence of the ninth hour in the upper layer game in scenario 3.

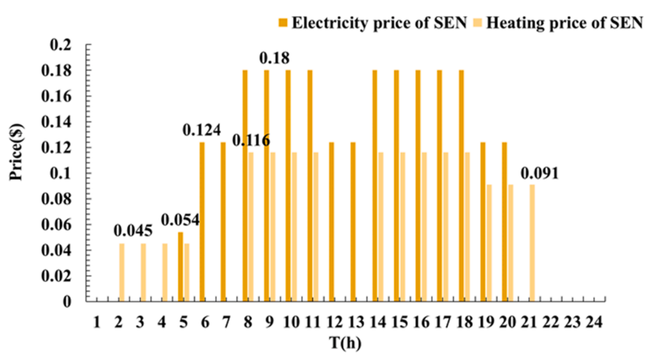


Fig. 11. The price in the upper layer game in scenario 3.

Table 8
The upper layer game optimization results in scenario 3.

Types	Value
The income of SEN	28549.764 $
The penalty cost of abandoning energy	0
The rate of abandoning energy	3.93%
The income of GSS	4670.316 $
The income of PIES	74009.88 $
The income of park system	78680.196 $

Table 9
The lower layer game optimization results in scenario 3.

	Result of income distribution form Shapley/$	Result of income distribution form Banzhaf/$	Result of income distribution from Solidarity/$
PIES	73573.344	73573.344	56457.108
PU	5106.852	5106.852	39340.872

established. Although the solidarity value method reflected the contribution of thePU and the GSS, it over-exaggerated the contribution and ignored the risk of the PIES in meeting the energy use and energy supply of thePU, so the distribution strategy was not advisable. Therefore, it was necessary to further improve the solidarity value method with an improved allocation model based on risk factors; the improved results are shown in Table 12.

Based on Table 12, because distributed clean energy is the main source of the power supply of the PIES, the operation is the riskiest. Secondly, the energy used by users in the park mainly comes from the PIES, and its risk is ranked second, and that of the GSS is the smallest. Further benefits of the allocation result can be obtained based on risk weighting. Under the distribution of the improved solidarity value method, the PIES and solidarity with the original value assignment of earnings increased by USD 175,200, compared with the original results which decreased by USD 848.304. Compared with the original results, the users in the park and the GSS increased by USD 660.996 and USD 187.308, respectively, which not only reflects the risk of the PIES in satisfying the energy use, and of users and the park operation, but also reflects the importance of the GSS and the users in the park to further enhance clean energy consumption and the comprehensive benefits of the park.

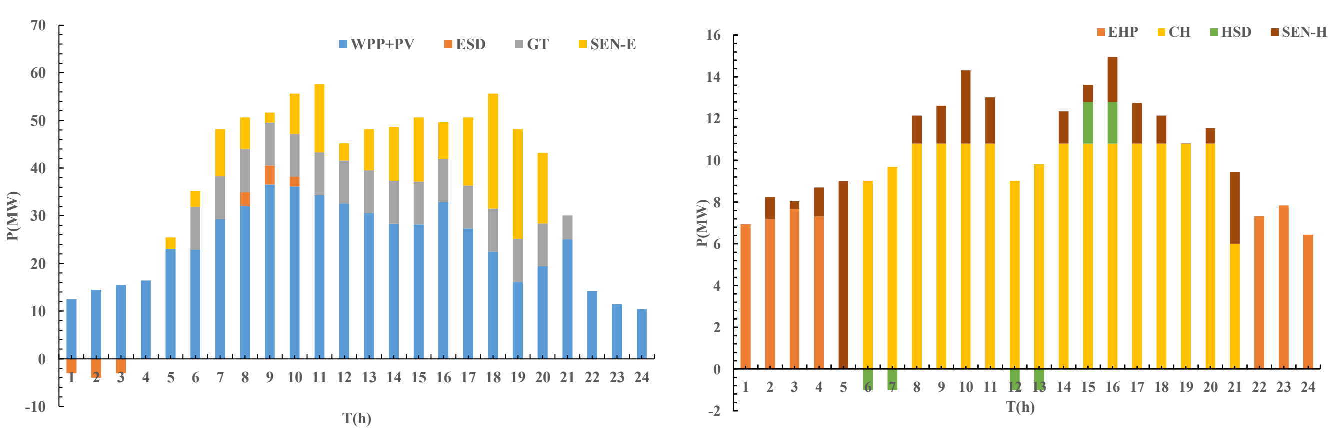


Fig. 12. Optimal results of the upper layer game in scenario 3.

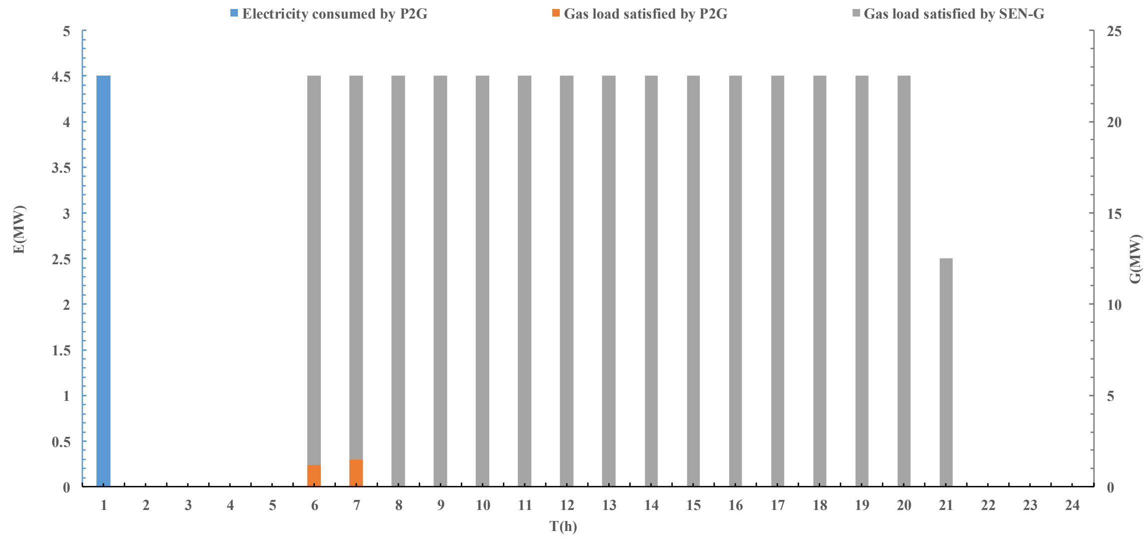


Fig. 13. The GSS absorbs electric and gas supply in scenario 4.

Table 10
The upper layer game optimization results in scenario 4.

Types	Value
The income of SEN	28316.016$
The income of PIES	74102.76$
The penalty cost of abandoning energy	0$
The rate of abandoning energy	3.24%
The income of GSS	142.416$
The income of PU	4670.316 $

Table 12
The optimization results of the lower layer game based on the improved solidarity value method.

	The operating risk weight	Result of income distribution/$	Compared with the original Solidarity result/$	Compared with the original result/$
PIES	0.677	73252.908	27120.96	−848.304
PU	0.187	5331.312	−11548.08	660.996
GSS	0.136	329.724	−15572.88	187.308

Table 11
The lower layer game optimization results in scenario 4.

	Result of income distribution form Shapley/$	Result of income distribution form Banzhaf/$	Result of income distribution from Solidarity/$
PIES	74376.756	74720.412	46131.948
PU	3735.324	4077.432	16879.392
GSS	803.412	1147.068	15902.604

6. Conclusions

This paper constructs a two-layer optimization model that takes into account the Stackelberg game and the cooperative game. Taking the participation of the internal flexibility of the park system in the superior game as the variable factor, multi-scenario optimization solution analysis was carried out using the proposed two-stage solution algorithm. The main conclusions are as follows:

(1) From the perspective of the upper-level game, this paper establishes that the upper-level Stackelberg game has a Nash equilibrium solution, and the equilibrium solution can be obtained when the number of iterations reaches about 50.
(2) From the perspective of the lower-level cooperation game, the GSS, thePU, and the PIES reached a cooperative alliance to form a park system to participate in the Stackelberg game, and maximize the linkage within the park, thus improving the competition between the PIES and the SEN in the Stackelberg game. The PIES income increased by USD 92.88, reflecting the contribution of the GSS and PU in the lower-level cooperative game. Then, using the improved solidarity value method based on risk factors to redistribute the benefit results, the PU and GSS increased by USD 660.996 and USD 187.308, respectively, compared with the original results, which satisfies the role of positioning and quantifies the contribution of the PU and the GSS.
(3) On the basis of the above research, the paper only studies the Stackelberg game with the PIES under the competition in the electricity and heat markets, and does not include the natural gas market in the scope of competition. However, as the energy market continues to improve and the degree of coupling deepens, the competition results of different energy markets will affect each other. In addition, the paper only studies the internal cooperation game and the corresponding benefit distribution from the perspective of a single PIES. With the development of PIESs, the cooperation of different PIESs to form a complementary relationship will also have an impact on superior competition and its income. Therefore, incorporating the gas market into the upper-level Stackelberg game category and studying cooperative games between different PIESs will be important research directions in the future.

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Declaration of Competing Interest

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

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