Bi-level Programming of Park Energy Internet Considering Economy and Security

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Abstract. Park energy Internet is an important research and development direction catering to the requirements of energy sustainability. In this paper, a typical structure of park energy Internet and models of several energy equipment are built. Multiple evaluation indexes including overall energy utilization rate, overall energy self-sufficiency rate and energy shortage expectation are proposed. Based on this, a bilevel programming model of park energy Internet considering economy and security is proposed. Further, a hybrid solving strategy of cataclysmic genetic algorithm and CPLEX solver is used to reduce the time of solution and improve the convergence. Finally, it is proved that the proposed method can meet the requirements of the economy and security of the system as well as the energy sustainability.

1. Introduction

Faced with the growing problem of energy shortage and worsening ecological environment, energy Internet provides a new direction for sustainable energy development [1-3]. The scale of energy Internet can cover the globe, a certain district or a park, among which, the Park Energy Internet, also called PEI [4], is a miniature multi-energy system built on user terminals. The PEI has diverse structure, flexible operation mode and strong controllability, so it is also the current research hotspots. The PEI involves multiple energy sources, such as electricity, heat, cold and natural gas, and involves a variety of energy equipment, such as cogeneration, gas boilers, and so on. Therefore, there are multiple energy supply methods and operational strategies of PEI.

There have been a series of research on the planning of multi-energy systems. In [5], the capacity design of the rooftop photovoltaic (PV) system and the compressed air energy storage system of the community micro-energy network is carried out. Further, the capacity of the compressed air energy storage system is determined according to the ratio of the capacity of PV and the power of energy storage system. In [6], a comprehensive design of Combined Cooling Heating and Power System with PV is carried out, taking into account the power supply of PV and external grid, determining the PV capacity with roof area and the equipment capacity with the demand of average heat load, average cooling load, 50% electrical load. In [7], a Bilevel optimization model of comprehensive energy system is established, which is aiming at the optimal total cost and pollutant emission in each level, the type and quantity of equipment is optimized in the upper layer and the output of them during operation is optimized in the lower layer, and the model is solved with particle swarm optimization. In summary, the current research mainly focuses on the planning of single energy systems, and does not comprehensively consider the type selection, quantity configuration, operation strategy of energy equipment, and does not achieve the overall design and optimization of multi-energy systems [8-9].
Therefore, a bilevel programming model of the PEI is built in this paper, based on the proposed multiple evaluation indexes including overall energy self-sufficiency rate, overall energy utilization rate and energy shortage expectation. In the model, the upper layer aims at minimizing the annual comprehensive cost and optimizes the types and quantity of energy equipment, the lower layer aims at minimizing the operating cost and optimizes the output of energy equipment, considering the above evaluation indexes. The bilevel model is solved with a hybrid algorithm combined with catastrophe genetic algorithm and CPLEX solver. The proposed model is determined to be effective and reasonable with an example.

2. Modelling of park energy internet

2.1. The structure of Park Energy Internet

The PEI includes the production, conversion and storage of energy. The energy hub (EH) model is used in this paper to describe the energy flow coupling relationship of PEI, and the typical structure of PEI is as shown in figure 1, whose energy equipment including: 1) Renewable energy equipment: photovoltaic (PV); 2) Energy conversion equipment: combined heat and power (CHP), gas boiler (GB), electric boiler (EB); 3) Energy storage equipment: electrical energy storage (ES) and heat energy storage (HS).

![Figure 1. Typical structure of PEI.](image)

2.2. The model of energy equipment

2.2.1. The model of energy conversion equipment.

\[
\begin{align*}
P_{\text{CHP}}^e &= \eta_{\text{CHP}} P_{\text{CHP}}^g, \\
P_{\text{CHP}}^h &= \eta_{\text{CHP}}^h P_{\text{CHP}}^g, \\
P_{\text{GB}}^h &= \eta_{\text{GB}} P_{\text{GB}}^g, \\
P_{\text{EB}}^h &= \eta_{\text{EB}} P_{\text{EB}}^e.
\end{align*}
\]

Equation (1) is a CHP model. Where, \(P_{\text{CHP}}^e\), \(P_{\text{CHP}}^h\) and \(P_{\text{CHP}}^g\) are respectively the power of electricity, heat and natural gas of CHP model. \(\eta_{\text{CHP}}\) and \(\eta_{\text{CHP}}^h\) are respectively the power generation efficiency and heat production efficiency of CHP model. Equation (2) is a GB model. Where, \(P_{\text{GB}}^h\) and \(P_{\text{GB}}^g\) are respectively the heat and natural gas of GB model. \(\eta_{\text{GB}}\) is the efficiency of GB. Equation (3) is an EB model. Where, \(P_{\text{EB}}^h\) and \(P_{\text{EB}}^e\) are respectively the power of electricity and heat of EB. \(\eta_{\text{EB}}\) is the efficiency of EB.

2.2.2. The model of energy storage equipment.
\[ S_{ES,t} = S_{ES,t-1} + P_{ES, \text{ch}}^{\text{ES}} \eta_{\text{ES}}^{\text{ch}} \Delta t - P_{ES, \text{dis}}^{\text{ES}} / \eta_{\text{ES}}^{\text{dis}} \Delta t \]
\[ S_{HS,t} = S_{HS,t-1} + P_{HS, \text{ch}}^{\text{HS}} \eta_{\text{HS}}^{\text{ch}} \Delta t - P_{HS, \text{dis}}^{\text{HS}} / \eta_{\text{HS}}^{\text{dis}} \Delta t \]

\( \Delta t \) is the optimized time interval; \( S_{ES,t} \) and \( S_{HS,t} \) are respectively the energy stored in ES and HS equipment during the period \( t \); \( P_{ES, \text{ch}}^{\text{ES}}, P_{ES, \text{dis}}^{\text{ES}}, P_{HS, \text{ch}}^{\text{HS}} \) and \( P_{HS, \text{dis}}^{\text{HS}} \) are respectively the electric power of charging and discharging of ES and the efficiency of charging and discharging working of HS; \( \eta_{\text{ES}}^{\text{ch}}, \eta_{\text{ES}}^{\text{dis}}, \eta_{\text{HS}}^{\text{ch}} \) and \( \eta_{\text{HS}}^{\text{dis}} \) are respectively the efficiency of charging and discharging electricity of ES and the efficiency of charging and discharging heat of HS.

2.2.3. The model of renewable energy equipment.

\[ P_{PV} = \begin{cases} P_{PV}^{\text{rated}} \frac{\alpha}{\alpha^{\text{rated}}} & 0 \leq \alpha \leq \alpha^{\text{rated}} \\ P_{PV}^{\text{rated}} \frac{\alpha}{\alpha^{\text{rated}}} & \alpha \geq \alpha^{\text{rated}} \end{cases} \]

where, \( P_{PV} \) and \( P_{PV}^{\text{rated}} \) are respectively the actual power PV outputs and the rated power of PV; \( \alpha \) and \( \alpha^{\text{rated}} \) are respectively the actual light intensity and rated light intensity.

3. Evaluation indexes of park energy internet

Under the background of adhering to the path of sustainable energy development, the programming and construction of PEI can not only be based on economic interests, but also comprehensively consider the demand of green, security and high efficiency. To this end, multiple evaluation indexes including overall energy self-sufficiency rate, overall energy utilization rate and energy shortage expectation are proposed in this paper, to evaluate the energy sustainability, efficiency and reliability of PEI.

3.1. Overall energy self-sufficiency rate

The overall energy self-sufficiency rate refers to the ratio of the total energy produced by renewable energy equipment to the total energy demanded by users in the PEI. The index is an important indicator to evaluate the energy sustainability of PEI, whose value is larger means that the ratio of renewable energy consumed is greater and the energy sustainability is higher.

\[ w_{\text{CESR}} = \frac{E_{\text{res}}}{E_e + E_h + v_LHV E_g} \]

where, \( w_{\text{CESR}} \) is the overall energy self-sufficiency rate; \( E_e, E_h \) and \( E_g \) are respectively the electricity, heat and natural gas the PEI outputs; \( v_LHV \) is the low calorific value of natural gas combustion, it is taken as 9.73 kWh/m\(^3\) in the paper; \( v_K \) is the unit conversion factor of electrical energy and heat energy, which is 3.6 MJ/kWh; \( E_{\text{res}} \) is the electrical energy produced by renewable energy equipment.

3.2. Overall energy utilization rate

The overall energy utilization rate refers to the ratio of the total energy output to the total energy input of PEI. The index is an important indicator to evaluate the operating efficiency of PEI. The larger value of it means that the fewer power loss and the more efficient operation.

\[ w_{\text{CEUR}} = \frac{E_e + E_h + v_LHV E_g + E_{\text{sell}}}{E_{\text{res}} + E_{\text{buy}} + v_LHV E_{\text{buy}}} \]

where, \( w_{\text{CEUR}} \) is the overall energy utilization rate; \( E_{\text{buy}}, E_{\text{sell}} \) and \( E_{\text{buy}} \) are respectively the amount of electricity PEI purchases and purchased by PEI.

3.3. Energy shortage expectation

The energy shortage expectation of \( \beta \)-type energy refers to the expected shortage of the PEI while the N-1 fault occurs in the energy equipment, considering the failure probability of component. The index
is an important indicator to evaluate the reliability of PEI to supply $\beta$-type energy. The smaller value of it means the fewer $\beta$-type energy should be removed while the N-1 fault occurs and the reliability of PEI to supply $\beta$-type energy is higher. The calculation method will be described in detail below.

4. Bilevel program model of park energy internet

As the energy market is gradually liberalized, the integrated energy companies generally construct and operates the PEI driven by economic interests. On the other hand, the government can regulate and guide them by formulating relevant policies and regulations required by the evaluation indexes, which can be described as constraints in the planning of PEI. Therefore, from the perspective of integrated energy companies, the planning and programming of PEI should aim at the optimal economy and consider the constraints of evaluation indexes. Based on this, a bilevel programming model of PEI considering the above evaluation indexes is proposed in this paper. The upper layer model aims to minimize the annual comprehensive cost and takes the installed type and quantity of energy equipment as decision variable. The configuration scheme will be passed to the lower layer. The lower layer model aims to minimize the operating cost with the above specific scheme and takes the dispatch situation of the energy equipment as decision variable. The operating cost will be returned to the upper layer, for it to calculate the comprehensive cost and further optimize the installed type and quantity of energy equipment.

4.1. The programming model of the upper layer

The objective function of the upper layer model is to minimize the annual comprehensive cost, which is the sum of equivalent annual investment cost and annual operating cost, and the decision variable is the type and quantity of the energy equipment installed.

$$\min C = C_{\text{Dep inv}} + 365 \sum_{s=1}^{S} p_s C_{\text{Op}}$$

where, $C$ is the annual comprehensive cost; $C_{\text{Dep inv}}$ is the equivalent annual investment cost of all the equipment; $p_s$ is the probability the typical day, $s$, occurs; $S$ is the total number of typical days selected; $C_{\text{Op}}$ is the operating cost during the typical day $s$.

$$C_{\text{Dep inv}} = \sum_{\gamma} \sum_{k} I_{\gamma k} C_{\text{Inv} \gamma} \eta_{\gamma}^{\text{Crf}}$$

where, $I_{\gamma k}$ is a 0-1 logic variable to mark the installation state of the NO. $k$ $\gamma$-type energy equipment, including $i$-type energy conversion equipment, $j$-type energy storage equipment and $l$-type renewable energy equipment. If the equipment is installed, $I_{\gamma k} = 1$, otherwise $I_{\gamma k} = 0$; $C_{\text{Inv} \gamma}$ is the investment cost for $\gamma$-type energy equipment; $\eta_{\gamma}^{\text{Crf}}$ is the equivalent annual fund recovery rate of $\gamma$-type energy equipment, which can be calculated as follows:

$$\eta_{\gamma}^{\text{Crf}} = \frac{r(1+r)^{y_{\gamma}}}{(1+r)^{y_{\gamma}} - 1}$$

where, $r$ is the discount rate; $y_{\gamma}$ is the service life of $\gamma$-type energy equipment.

$C_{\text{Op}}$ is composed of operation and maintenance cost $C_{\text{OM}}$, fuel cost $C_{\text{Fuel}}$, energy transaction cost $C_{\text{Trade}}$, carbon tax $C_{\text{CO2}}$, and energy deficiency penalty cost $C_{\text{P}}$, which are described in detail below:

$$C_{\text{Op}} = C_{\text{OM}} + C_{\text{Trade}} + C_{\text{Fuel}} + C_{\text{CO2}} + C_{\text{P}}$$

$$C_{\text{OM}} = \sum_{i} \sum_{k} \sum_{t} o_{t}^{\text{EC} \min_{i,k,t}} + \sum_{j} \sum_{k} \sum_{t} o_{t}^{\text{ES} \min_{j,k,t}} (p_{\text{dis}_{j,k,t}} + p_{\text{ch}_{j,k,t}}) + \sum_{l} \sum_{k} o_{t}^{\text{RES} \min_{l,k,t}} p_{\text{dis}_{l,k,t}}$$

$$C_{\text{Trade}} = \sum_{t} (c_{t}^{\text{buy,e}} p_{t}^{\text{buy,e}} - c_{t}^{\text{sell,e}} p_{t}^{\text{sell,e}}) \Delta t$$
\[
C_{\text{Fuel}} = \sum_t c_{\text{Fuel}} \frac{P_{buy,g}^t \Delta t}{V_{\text{LHV}}} 
\]
\[
C_{\text{CO2}} = \sum_t c_t (a_e P_{buy,e}^t + a_g P_{buy,g}^t) \Delta t 
\]
\[
C_p = \lambda_e g^{e}_{\text{EES}} + \lambda_h g^{h}_{\text{EES}} 
\]

where, \(P_{\text{in}}^i\) is the input power of the NO. \(i\)-type energy conversion equipment during the period \(t\); \(P_{\text{dis}}^{e,j}\) and \(P_{\text{ch}}^{e,j}\) are respectively the charge and discharge power of the NO. \(j\)-type energy storage equipment during the period \(t\); \(P_{\text{out}}^{e,l}\) is the output power of the NO. \(l\)-type renewable energy equipment during the period \(t\); \(a_e^i\) and \(a_g^i\) are respectively the carbon emission factors of electricity and natural gas; \(c_{\text{Fuel}}\) is the price of natural gas; \(a_e^e\) and \(a_g^g\) are respectively the carbon emission factors of electricity and natural gas; \(c_c\) is the price of carbon tax; \(\lambda_e^i\) and \(\lambda_h^i\) are respectively the penalty cost for interruptions of electrical and heat load; \(E^{e}_{\text{EES}}^i\) and \(E^{h}_{\text{EES}}^i\) are respectively the shortage expectation of electrical energy and heat energy.

4.2. The programming model of the lower layer

The lower layer model aims to optimize the coordinated operation of the energy equipment inside the PEI during typical days, with the goal of minimizing the operating costs, as is shown in (17):

\[
\min C_{Op}
\]

And the details of all constraints are as follows:

4.2.1. Constraints of energy balance.
\[
P_{buy,e}^t - P_{sell,e}^t + \sum_i \sum_k P_{in,k}^i + \sum_i \sum_k P_{out,k}^i = \sum_i \sum_k P_{in,k}^e + \sum_j \sum_k (P_{ch,k}^j - P_{dis,k}^j) + P_{L,e}^t 
\]
\[
\sum_i \sum_k P_{out,h}^i = \sum_j \sum_k (P_{ch,k}^h - P_{dis,k}^h) + P_{L,h}^t 
\]
\[
P_{buy,g}^t = P_{L,g}^t + \sum_i \sum_k P_{in,k}^g 
\]

where, \(P_{\text{in}}^{e,i}\), \(P_{\text{dis}}^{e,j}\), \(P_{\text{ch}}^{e,j}\) and \(P_{\text{dis}}^{h,j}\) are respectively the input electric power and natural gas power, the output electric power and output thermal power of the NO. \(i\)-type energy conversion equipment during the period \(t\); \(P_{\text{ch}}^{h,j}\) and \(P_{\text{dis}}^{h,j}\) are respectively the charging and discharging electric power and heat power of the NO. \(j\)-type energy storage equipment during the period \(t\); \(P_{\text{in}}^{e,i}\), \(P_{\text{ch}}^{h,j}\) and \(P_{\text{dis}}^{h,j}\) are respectively the electricity, heat and natural gas loads during the period \(t\).

4.2.2. Operating constraints of energy storage equipment.
\[
0 \leq P_{\text{ch}}^{h,j} \leq u_{\text{ch},j} P_{\text{max}}^{h,j} 
\]
\[
0 \leq P_{\text{dis}}^{h,j} \leq (1 - u_{\text{ch},j}) P_{\text{max}}^{h,j} 
\]
\[
S_{j,0} = S_{j,t} 
\]
\[
S_{\text{min}}^{j} \leq S_{j,t} \leq S_{\text{max}}^{j} 
\]
where, \( P_{\text{max}} \) is the maximal charge and discharge power of \( j \)-type energy storage equipment; \( S_{j,k,0} \) and \( S_{j,k,T} \) are respectively the energy stored in the NO. \( k \)-type energy storage equipment during the initial and end periods; \( S_{\text{max}}^{j,k} \) and \( S_{\text{min}}^{j,k} \) are respectively the upper and lower limits of the energy stored in the NO. \( k \)-type energy storage equipment; \( u_{j,k,t} \) is a binary variable indicating the state of NO. \( k \)-type energy storage equipment during the period \( t \), if it is charging, \( u_{j,k,t} = 1 \), otherwise \( u_{j,k,t} = 0 \).

4.2.3. Operating constraints of energy conversion equipment.

\[
0 \leq P_{\text{in},i,k,t} \leq I_{i} P_{\text{rated},i} \tag{25}
\]

\[
-r_{i} \Delta t \leq P_{\text{in},i,k,t}^{\text{in}} - P_{\text{in},i,k,t-1}^{\text{in}} \leq r_{i} \Delta t \tag{26}
\]

where, \( P_{\text{rated},i} \) is the rated capacity of \( i \)-type energy conversion equipment; \( r_{i} \) is the maximal climbing rate of \( i \)-type energy conversion equipment.

4.2.4 Constraints of energy interaction power.

\[
0 \leq P_{b_{\text{buy},e},t} \leq u_{b_{\text{buy},e},t} P_{\text{buy},e,\text{max}} \tag{27}
\]

\[
0 \leq P_{s_{\text{sell},e},t} \leq (1-u_{b_{\text{buy},e},t}) P_{\text{sell},e,\text{max}} \tag{28}
\]

\[
0 \leq P_{b_{\text{buy},g},t} \leq P_{\text{buy},g,\text{max}} \tag{29}
\]

where, \( P_{b_{\text{buy},e},\text{max}} \), \( P_{b_{\text{sell},e},\text{max}} \) and \( P_{b_{\text{buy},g},\text{max}} \) are respectively the largest amount of gas power the PEI purchases, the largest amount of electricity the PEI purchases from and sales to the upper grid; \( u_{b_{\text{buy},e},t} \) is the state variable of electricity purchase of the PEI, if the PEI purchases, \( u_{b_{\text{buy},e},t} = 1 \), the remaining state \( u_{b_{\text{buy},e},t} = 0 \).

4.2.5 Constraints of energy reserve.

\[
\begin{align*}
R_{\beta,ik,t}^\beta & \leq I_{i} P_{\text{rated},i}^{\beta} - P_{\text{in},i,k,t}^{\beta} \\
0 \leq R_{\beta,ik,t}^0 & \leq I_{i} r_{i}^\beta \\
R_{j,k,t}^\beta & \leq I_{i} P_{\text{in},i,k,t}^{\text{dis}} - (P_{\text{in},i,k,t}^{\text{dis}} - P_{\text{dis},i}^{\text{ch}}) \\
0 \leq R_{j,k,t} & \leq (S_{j,k,t}^{\text{dis}} - S_{j,k,t}^{\text{min}}) / \eta_{\text{dis}}^{j,k} \tag{31}
\end{align*}
\]

where, \( P_{\text{in},i,k,t}^{\beta} \) and \( R_{\beta,ik,t}^\beta \) are respectively the output power and reserve power of the \( \beta \)-type energy source of the NO. \( k \)-type energy conversion equipment during the period \( t \); \( P_{\text{rated},i}^{\beta} \) is the rated power the \( i \)-type energy conversion equipment providing \( \beta \)-type energy source; \( r_{i}^{\beta} \) is the maximal climbing rate the \( i \)-type energy conversion equipment providing \( \beta \)-type energy source; Where, \( \eta_{\text{dis}}^{j,k} \) is the energy release efficiency of \( j \)-type energy storage equipment; \( R_{j,k,t} \) is the reserve power of the NO. \( k \)-type energy storage equipment during the period \( t \).

4.2.6 Constraints of overall energy self-sufficiency rate.

\[
w_{\text{CESR}} \geq w_{\text{CESR}} \tag{32}
\]

where, \( w_{\text{CESR}} \) is the lower limit of overall energy self-sufficiency rate.

4.2.7 Constraints of overall energy utilization rate.

\[
w_{\text{CEUR}} \geq w_{\text{CEUR}} \tag{33}
\]

where, \( w_{\text{CEUR}} \) is the lower limit of overall energy utilization rate.

4.2.8 Constraints of energy shortage expectation.

\[
P_{\text{EES},e}^{\beta} \leq \sum_{\gamma} I_{\gamma} P_{\gamma}^{\beta} \Psi_{\gamma,\beta}^{\gamma} (P_{\gamma,\beta,\text{in}}^{\beta} + R_{\gamma,\beta,\text{in}}^{\beta} - R_{\gamma,\beta,\text{in}}^{\beta}) \leq P_{\text{EES}}^{\beta} \tag{34}
\]

where, \( w_{\text{CEUR}} \) is the upper limit of energy shortage expectation.
4.3. Solution
The bilevel programming model belongs to the mixed integer nonlinear bilevel programming problem. It is difficult and time-consuming to solve with non-numeric optimization algorithm and guarantee convergence. To improve the convergence and reduce the time of solution, the hybrid strategy of Cataclysmic Genetic Algorithm (CGA) and CPLEX solver in GAMS software is used in this paper. Based on the genetic algorithm, CGA introduces the catastrophe operator to avoid the population falling into local optimum. It has wide applicability, strong searching ability and good convergence. The CGA is used to solve the configuration problem of energy equipment of the upper layer planning. If there is no new optimal solution in four consecutive generations, then the catastrophic operation is carried out, the optimal individual is retained, and other individuals are randomly generated. CPLEX is suitable for solving MILP problem. It has the advantages of fast solution speed and strong robustness. So, it is used to solve the operation optimization problem of PEI in the lower layer.

5. Simulation

5.1. Introduction to the example

A typical residential quarter is taken as the research object in this paper, and its equivalent structure is shown in figure 1. The typical daily load curve and PV output curve are respectively shown in figure 2–figure 5. Among them, the probability a typical spring and autumn day occurs is 0.5, and the probability of a typical summer and winter day occurs is 0.25. The peak-flat-valley time-of-use price is also used. The peak (7:00~12:00, 17:00~22:00), flat (12:00~17:00, 22:00~24:00) and valley (1:00~7:00) price are respectively 1.2 yuan/kWh, 0.8 yuan/kWh and 0.4 yuan/kWh. The price of natural gas is 3.15 yuan / m$^3$. The CO2 emission factors of natural gas and conventional power plants are respectively 1.85 kg/m3 and 0.80 kg/kWh. The price of carbon tax is 0.3 yuan/kg.
Table 1. The comparison of 4 optimization configuration situations.

| Situation | Overall energy self-sufficiency rate | Overall energy utilization rate | Energy shortage expectation |
|-----------|-------------------------------------|--------------------------------|-----------------------------|
| 1st       | No                                  | No                             | No                          |
| 2nd       | Yes                                 | No                             | No                          |
| 3rd       | Yes                                 | Yes                            | No                          |
| 4th       | Yes                                 | Yes                            | Yes                         |

To verify the validity and correctness of the proposed method, there were four optimization situations be set in this paper, as shown in table 1. The 1st situation does not consider any evaluation indexes. The 2nd situation adds the index of overall energy self-sufficiency rate based on the 1st situation. The 3rd situation adds the index of overall energy utilization rate based on the 2nd situation. The 4th situation adds the index of energy shortage expectation based on the 3rd situation. The lower limits of the above indexes are respectively 15%, 87.5% and 10%, the penalty cost for electric and heat load interruption are respectively 20 yuan/kWh and 36 yuan/MJ.

5.2. Analysis of the programming and configuration results

The configuration number of energy equipment and in different situations is shown in table 2. The optimization results in different situations is shown in table 3.

The 1st situation does not consider constraints of any evaluation metrics. The heat load is jointly supplied by CHP, GB and EB; the electric load is mainly supplied by CHP and PV. The capacity of EB is less than CHP and GB, because the cost of configurating EB and using electric energy for heating is higher than the cost of configurating CHP and GB or using natural gas for heating.

The compare between the 1st and 2nd situation. The 2nd situation has 4 more PVs than the 1st situation to meet the requirements of overall energy self-sufficiency rate, and has one more EB2 to absorb the surplus power generated by PV. Meanwhile, the capacity of GB is reduced and the capacity of HS is increased, to meet the balance of heat load. The equivalent annual investment cost of the 2nd situation is greater than that of 1st situation, but its installation capacity of PV is larger. There is less input energy from the upper energy network to PEI in 2nd situation, so the annual operating cost of it is less. Generally, the annual comprehensive cost of 2nd situation is greater.

The compare between the 2nd and 3rd situation. To meet the requirements of overall energy utilization rate, in the 3rd situation, the configuration of ES and HS is reduced, thereby the energy loss of charge and discharge is reduced. Meanwhile, the capacity of EB is increased to directly absorb the power generated by PV, thereby the loss of ES energy storage is reduced. Due to the increase constraint of the index, the annual comprehensive cost of the 3rd situation is greater.

The compare between the 3rd and 4th situation. The electric and heat energy shortage expectation of the 3rd situation are respectively 30386 kWh and 88367 MJ, while in the 4th situation they are all zero. In 4th situation, one more ES, two more HS and one more GB is added to provide sufficient reserve, it can reduce the penalty cost of removing load after the N-1 fault occurs in the energy equipment. Meanwhile, an EB1 is reduced to meet the balance of heat load. It can be seen that after considering the index of reliability, the equivalent annual investment cost of the system increases, but the annual operating cost and the annual penalty cost are reduced, and the comprehensive cost is reduced.

In summary, after considering the overall energy self-sufficiency rate and overall energy utilization rate, the energy sustainability and efficiency of the system can be qualified, but the economy is reduced; after considering the energy shortage expectation, the reliability of the system can be qualified as well as the economy is also improved.

Table 2. The configuration number of energy equipment under different scenes.

| Situation | CHP1 | CHP2 | GB1 | GB2 | EB1 | EB2 | ES | HS | PV |
|-----------|------|------|-----|-----|-----|-----|----|----|----|
| 1st       | 0    | 3    | 5   | 1   | 1   | 0   | 10 | 6  | 13 |
| 2nd       | 0    | 3    | 0   | 2   | 0   | 2   | 10 | 10 | 17 |
| 3rd       | 0    | 3    | 0   | 2   | 1   | 2   | 9  | 5  | 17 |
| 4th       | 0    | 3    | 1   | 2   | 0   | 2   | 10 | 7  | 17 |
Table 3. The optimization results under different scenes.

| Situation | Equivalent annual investment cost /1,000yuan | Annual operating cost /1,000yuan | Annual penalty cost /1,000yuan | Annual comprehensive cost /1,000yuan | Electric energy shortage expectation /kWh | Heat energy shortage expectation /MJ |
|-----------|---------------------------------------------|---------------------------------|-------------------------------|--------------------------------------|------------------------------------------|-------------------------------------|
| 1st       | 1684.6                                      | 4150.9                          | 56.0                          | 5891.5                               | 26554                                    | 86396                               |
| 2nd       | 1933.0                                      | 3961.5                          | 28.6                          | 5923.2                               | 34493                                    | 80811                               |
| 3rd       | 1933.8                                      | 3958.5                          | 65.0                          | 5957.3                               | 30386                                    | 88367                               |
| 4th       | 1950.9                                      | 3929.1                          | 0.0                           | 5880.0                               | 0                                        | 0                                   |

6. Conclusion
The evaluation index system of PEI is constructed in this paper. Taking into account the constraints of the proposed evaluation indexes, a bilevel optimal programming model of PEI is established. Through the simulation and analysis, it is proved that the proposed model of PEI can fully consider the impact of the operating cost on the type and quantity selected of energy equipment, therefore the configuration scheme is more reasonable and practical; at the same time, the configuration scheme can meet the requirements of economy, security, efficiency and energy sustainability. Under the background of energy marketization, the construction and operation of PEI aims at economic interests, but the government can constrain and guide them through setting different evaluation indexes.

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