Multi-scene upgrade and renovation method of existing park-level integrated energy system based on comprehensive analysis

Yan Cao¹ | Yunfei Mu¹ | Hongjie Jia¹ | Yan Qi² | Congshan Wang¹

¹ Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin, China
² Electric Power Research Institute, State Grid Tianjin Electric Power Company, Tianjin, China

Correspondence
Yunfei Mu, Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin, China. Email: yunfeimu@tju.edu.cn

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Abstract
Some of the existing park-level integrated energy systems (PIESs) experience problems such as mismatch between energy supply and demand, high operation costs, and low renewable energy consumption capacity. To improve the energy supply level of the existing PIES, the multi-scene upgrade and renovation method of the existing PIES based on comprehensive analysis is proposed. First, the physical model of the existing PIES for renovation is constructed, including expansion of existing equipment and newly added candidate equipment. Second, to determine the deficiencies, the current situation of the existing PIES is analysed based on the planning and operation data as well as indexes including economy, photovoltaic consumption capacity, and so on. On this basis, multiple renovation scenes are set up, and the upgrade and renovation model is constructed, assuming minimal investment, operation, and maintenance costs to be the objective function. Thereafter, the equipment allocation scheme of each scene is solved, for which comprehensive evaluation is performed. Finally, considering an existing PIES as an example, the weak energy storage and heating links are upgraded and renovated, effectively improving the performance of the existing PIES in reducing costs and carbon emissions, and improving energy utilisation efficiency.

1 | INTRODUCTION

Integrated energy system (IES) is a system coupling energy production, supply, and consumption, and is coordinated and optimised organically during planning, design, construction, and operation [1,2]. Park-level integrated energy system (PIES) can realise the coupling and joint supply of electricity, gas, heat, and other energy resources through the technologies of combined cooling (CCHP), and power, distributed generation, and so on [3], which can effectively enhance the consumption capacity of renewable energy generation [4], energy-supply reliability [5], and comprehensive energy utilisation efficiency [6]. PIES includes new PIES and existing PIES. For the new PIES, the design of the planning scheme should fully consider the future demand for electricity, heating, and cooling in the park and realise complementary optimisation of the system in different seasons in the long term and different periods in the short term via collaboration among different energy-production, -conversion, and -storage units to reduce the system's energy cost [7,8]. For the existing PIES, the operation data is sufficient, further improvement of the economy of the energy supply, environmental protection performance, and renewable energy consumption capacity should be considered through the optimisation and renovation of energy-conversion equipment based on the existing system.

To date, there have been many studies on PIES's planning. Optimising the capacity allocation of equipment and reducing the cost of PIES is the first consideration. The authors of [9] established a two-stage model including capacity planning and operation optimisation. Through the optimal selection of planning schemes, the installed capacity of renewable energy can be maximised to reduce the system's energy consumption and environmental cost. A model combining equipment investment constraints and capacity planning was established in [10] to realise the minimum annual total cost and carbon dioxide emissions under the constraint of limited funds. A planning model for the PIES in the data centre was proposed in [11], and the Markov-based reliability estimation method was adopted to carry out redundant design of equipment capacity to improve PIES's reliability. The authors of [12] proposed a
coordinated optimal allocation method integrating the comprehensive demand response of PIES, which fully considered the characteristics and uncertainties of flexible loads and further reduced the system's allocation cost. However, there are also many uncertainties to consider, which make the planning of PIES more difficult. The authors of [13] considered future gas price fluctuations and introduced the concept of regret aversion in the PIES planning model, which can effectively reduce the risk of decision making. The uncertainty set was constructed and analysed through machine learning, and a robust planning model was established in [14], which could reduce the operating cost of PIES and improve its robustness. The authors of [15] aimed at the selection and capacity allocation of distributed power generation and energy storage during the initial planning of PIES, and the worst-case scenario was considered in the robust economic optimisation model to reduce the cost variation due to uncertainty. Further, evaluating and choosing the best planning scheme among the various candidate plans and determining the order in which the equipment should be installed are also issues to be considered in PIES's planning. A hybrid fuzzy multi-criteria decision-making approach was adopted in [16], through performance analysis and evaluation, the wind–gas complementary system had the best comprehensive performance among the five schemes considered. Considering the reliability, economy, and electrothermal coupling characteristics, an evaluation index system of PIES was built in [17], according to which the priority loading order of each energy supply unit was determined.

The above references describe in-depth studies on the planning of new PIES from the perspectives of equipment selection and capacity allocation, which play an important role in guiding the construction of new PIES to reduce the investment costs and risks, as well as to improve the environmental protection performance and renewable energy consumption capacity. However, through investigation, it is found that among the numerous existing PIES, the deviations between the initial planning scheme and the later actual operation, load prediction, and other aspects have led to problems, such as energy supply and demand mismatch, high operation costs, and low renewable energy consumption capacity [18–20]. On the one hand, during the initial planning of some existing PIESs, the equipment capacity allocation was redundant, which led to low utilisation rate of some equipment, photovoltaic energy abandonment, and so on [21,22], resulting in the waste of resources [20]. On the other hand, as the load increases year by year, the capacity of some equipment will be insufficient and the output efficiency will decrease, as a result, the energy supply cannot meet the load demand [23].

To tackle the above problems of existing PIES, research has been performed from the perspectives of improving load forecasting accuracy, matching energy supply and demand, and optimising scheduling, demand response, and energy cascade utilisation. A combined forecasting model for electricity, heat, cooling, and gas loads based on the multi-task learning and the least-square support vector machine was constructed in [18], which helps improve the comprehensive efficiency and gain more economic benefits of various types of energy. The authors of [21] established a novel energy supply and demand matching model, which provided operators with more reasonable strategies of operational control to enhance the supply–demand match. Furthermore, operation optimisation models for PIES considering the integrated demand response were proposed in [24,25], where the overall peak power value was reduced and the net profits and energy utilisation efficiency were improved. Moreover, considering reasonable correspondence between the energy supply and demand, the authors of [22] proposed an energy-management strategy based on stepped energy utilisation to further minimise the daily cost and make full use of the energy.

Through these methods, the above problems can be alleviated, but they cannot be fundamentally solved. Therefore, it is necessary to start with PIES's planning and improve the economy, energy utilisation efficiency, energy savings, and emission reduction of existing PIES by renovating and optimising the equipment type and capacity, about which there are a few studies. In view of the above problems, the main contributions of this paper are as follows:

(i) A detailed model of PIES for upgrade and renovation is developed, including the existing equipment and newly added candidate equipment.

(ii) The current situation of the existing PIES is analysed based on the data of planning and operation, index evaluation system, and other information, and the weak links of energy storage and heat supply are found.

(iii) Multiple renovation scenes are designed considering various renovation schemes, where the capacity of existing equipment will be expanded and new equipment will be added. To optimise the economy, the upgrade and renovation model of existing PIES is established, where equipment operation, power balance, and renovation constraints under the existing PIES's architecture are set.

(iv) The effect of each renovation scheme in terms of economy, CO₂ emissions, photovoltaic consumption capacity, and other aspects is evaluated comprehensively, and the best renovation scheme is selected.

The rest of this paper is organised as follows: The existing PIES is modelled in Section 2. A multi-scene upgrade and renovation method of existing PIES based on comprehensive analysis is established in Section 3. The effectiveness in improving the performance of the existing PIES via the proposed method is validated by the case study in Section 4. Section 5 draws the conclusions.

## 2 MODELLING FOR EXISTING PARK-LEVEL INTEGRATED ENERGY SYSTEM

### 2.1 Structure of a typical park-level integrated energy system

A typical existing PIES is used as the research object, and its unified bus-based structure [26] is shown in Figure 1, including energy-production, -conversion, and -storage equipment. Energy-production and -conversion equipment converts
one form of energy into another through a coupling link, and the existing equipment includes combined heat and power system (CHP), ground source heat pump (HP), and photovoltaic system (PV). Energy-storage equipment stores energy in the form of heat and electricity, and releases it for use at a certain moment. Existing energy-storage equipment includes electricity storage (ES) and heat storage (HS). Besides, PIES can also satisfy insufficient electricity load demand by purchasing power from the external grid.

To upgrade the existing PIES, in addition to capacity expansion of existing equipment, new types of candidate equipment can also be added. As shown in Figure 1, candidate equipment will be connected into the existing PIES to form a new energy-conversion relationship during the upgrade and renovation, according to its energy-input and -output relationship.

### 2.2 Model of existing equipment

#### 2.2.1 Combined heat and power system

CHP generates heat and electricity by consuming natural gas. Its model and operating constraints are

\[
H_{\text{CHP}}(t) = G_{\text{CHP}}(t) \eta^\text{H,CHP}, \\
P_{\text{CHP}}(t) = G_{\text{CHP}}(t) \eta^\text{P,CHP}, \\
H_{\text{CHP}} \leq H_{\text{CHP}}(t) \leq \overline{H}_{\text{CHP}},
\]

where \(H_{\text{CHP}}(t)\) and \(P_{\text{CHP}}(t)\) are the heat power and electric power supply of CHP at time \(t\); \(G_{\text{CHP}}(t)\) is the natural gas power consumed by CHP at time \(t\); \(\eta^\text{H,CHP}\) and \(\eta^\text{P,CHP}\) are the heat power supply efficiency and electric power supply efficiency of CHP; \(\overline{H}_{\text{CHP}}\) and \(\underline{H}_{\text{CHP}}\) are the upper and lower limits of heat power of CHP.

#### 2.2.2 Ground source heat pump

HP consumes electrical energy and transfers thermal energy from the low-temperature heat source to the high-temperature heat source to provide heat energy. Its operating constraints are

\[
H_{\text{HP}}(t) = P_{\text{HP}}(t) \text{COP}_{\text{HP}}^\text{H,HP}, \\
0 \leq H_{\text{HP}}(t) \leq H_{\text{HP},u},
\]

where \(H_{\text{HP}}(t)\) is the heat power of HP at time \(t\); \(P_{\text{HP}}(t)\) is the electric power consumed by HP at time \(t\); \(\text{COP}_{\text{HP}}^\text{H,HP}\) is the coefficient of performance, and \(H_{\text{HP},u}\) is the upper output limit of HP.

#### 2.2.3 Photovoltaic system

The actual consumption power of PV at time \(t\) cannot exceed the predicted maximum output power under the maximum power point tracking (MPPT) mode [27] at that moment, namely,

\[
0 \leq P_{\text{PV},c}(t) \leq P_{\text{PV}}(t),
\]

where \(P_{\text{PV},c}(t)\) is the consumption power at time \(t\); \(P_{\text{PV}}(t)\) is the predicted maximum output power of PV under MPPT mode at time \(t\).

#### 2.2.4 Energy-storage equipment

A universal energy-storage model [13] is used to describe the energy-storage mechanism of ES and HS, as shown in (4):

Energy-storage equipment cannot store more energy than its capacity, whose charging and discharging power should be within the upper and lower limits. Its charging and discharging...
processes cannot be performed simultaneously, and its state of charge at the beginning and the end of the dispatch period is equal.

\[
0 \leq P_c(t) \leq P_{c\text{max}}
\]

\[
0 \leq P_d(t) \leq P_{d\text{max}}
\]

\[
SOC(t + \Delta t) = SOC(t) + \frac{(\eta_i P_i(t) \Delta t - P_d(t) \Delta t / \eta_d)}{S_{\text{ESS}}},
\]

\[
SOC_{\text{min}} \leq SOC(t) \leq SOC_{\text{max}}
\]

\[
P_i(t)P_d(t) = 0
\]

\[
SOC(0) = SOC(T)
\]

where \(P_c(t)\) and \(P_d(t)\) are the charging and discharging power in period \(\Delta t\); \(\Delta t\) is the dispatch period; \(P_{c\text{max}}\) and \(P_{d\text{max}}\) are the maximum charging and discharging power; \(SOC(t)\) is the state of charge; \(SOC_{\text{max}}\) and \(SOC_{\text{min}}\) are the upper and lower limits of the state of charge; \(\eta_i\) and \(\eta_d\) are the energy charge and discharge efficiency; \(S_{\text{ESS}}\) is the capacity of energy-storage equipment; \(SOC(0)\) and \(SOC(T)\) are the state of charge at the beginning and end of the dispatch period, respectively.

### 2.2.5 Capacity-expansion model

The capacity \(S_{\text{ESS}}\) of the energy-storage equipment in (4) should be increased in new constraints after capacity expansion.

The operation margin of energy-production and -conversion equipment becomes larger after capacity expansion, so the upper limit of the operation constraint needs to increase the expansion capacity. Taking the \(i\)th existing equipment as an example, its operation constraint after upgrade is as follows:

\[
\begin{cases}
0 \leq P'(t) \leq \frac{W'}{P_U} + (P_{O} + Q_{\text{ex}}), \\
\end{cases}
\]

where \(P_{O}\) and \(P_U\) are the upper limits of output power of the \(i\)th existing equipment before and after upgrade, respectively; \(P'(t)\) is the power of the \(i\)th existing equipment at time \(t\); \(Q_{\text{ex}}\) is the expansion capacity of the \(i\)th existing equipment.

### 2.3 Model of new candidate equipment

Newly added energy-storage equipment is modelled according to the universal energy-storage equipment model in (4). Newly added energy production and conversion equipment needs to meet the energy-conversion relationship and upper and lower limits of the output. For example, the \(j\)th newly added equipment is modelled as:

\[
P_{\text{out}}^j(t) = P_{\text{in}}^j(t) \eta_j \\
0 \leq P_{\text{out}}^j(t) \leq Q_{\text{new}},
\]

where \(P_{\text{out}}^j(t), P_{\text{in}}^j(t), \eta_j, Q_{\text{new}}\) are respectively the output energy power, input energy power, energy-conversion efficiency, and allocation capacity of the \(j\)th newly added equipment.

### 2.4 Power-balance model

As shown in Figure 1, the power balance constraint of electricity bus of the existing PIES is described as

\[
P_{\text{grid}}(t) + P_{\text{CHP}}(t) + P_{\text{PV},c}(t) + P_{\text{ES}}^d(t) + \sum_{j=1}^{m} P_{j}^\text{gen} = P_{\text{grid}}(t) + P_{\text{HP}}(t) + P_{\text{ES}}^c(t) + \sum_{j=1}^{m} P_{j}^\text{con},
\]

where \(P_{\text{grid}}(t)\) represents the electrical power purchased from the external grid at time \(t\); \(P_{\text{PV},c}(t)\) and \(P_{\text{ES}}^d(t)\) represent the charging and discharging power of the ES at time \(t\), respectively; \(P_{\text{grid}}(t)\) denotes the power of electrical load at time \(t\); \(P_{\text{HP}}(t)\) and \(P_{\text{ES}}^c(t)\) represent the generation power and consumption power of the \(j\)th newly added equipment at time \(t\), respectively; and \(m\) is the number of types of newly added equipment.

The power balance constraint of the heat bus is described as:

\[
H_{\text{CHP}}(t) + H_{\text{HP}}(t) + H_{\text{ES}}^d(t) + \sum_{j=1}^{m} H_{j}^\text{gen} = H_{\text{CHP}}(t) + H_{\text{ES}}^c(t) + \sum_{j=1}^{m} H_{j}^\text{con},
\]

where \(H_{\text{CHP}}(t)\) and \(H_{\text{ES}}^d(t)\) represent the charging and discharging power of the HS at time \(t\); \(H_{\text{CHP}}(t)\) denotes the power of heat load at time \(t\); \(H_{\text{ES}}^c(t)\) and \(H_{j}^\text{con}\) represent the heat generation and heat consumption power of the \(j\)th newly added equipment at time \(t\), respectively.

### 3 MULTI-SCENE UPGRADE AND RENOVATION METHOD OF EXISTING PIES BASED ON COMPREHENSIVE ANALYSIS

#### 3.1 Analysis of existing PIES’s present situation

The weak links in energy supply, conversion, and storage in the operation of existing PIES are the source driving force for its upgrade and renovation, so it is necessary to analyse the current situation of existing PIES.

First, obtain initial planning data, actual operation data of existing PIES, users’ feedback information etc. Second, process the original data, calculate indexes of the evaluation index system, such as economy, PV consumption capacity, carbon
dioxide emissions, primary energy utilisation efficiency etc. (as shown in Section 3.1.1). Finally, analyse the operating curves and output situation of each equipment by combining qualitative and quantitative analysis. Then, evaluate the overall efficiency of existing PIES, to find out the weak links in energy supply, conversion, and storage, and thus guide the upgrade and renovation of the existing PIES.

### 3.1.1 Evaluation index system

To comprehensively analyse the status of PIES in terms of economy, PV consumption capacity, CO₂ emissions, and primary energy utilisation efficiency, an evaluation index system containing the above indexes is established.

#### Economic index

The economy of the actual operation of PIES is reflected by the total cost C, which includes the operation cost of purchasing electricity and gas from the external network and the equipment maintenance cost.

#### PV consumption index

The PV energy consumption rate is defined to describe the efficiency of PV. The higher the PV energy consumption rate, the stronger the PV consumption capacity. The calculation formulas are expressed as:

\[
\lambda_{PV,c} = \frac{W_{PV,c}}{W_{PV}} \times 100\%,
\]

\[
W_{PV} = \sum_{i=1}^{n} P_{PV}(t) \Delta t,
\]

\[
W_{PV,c} = \sum_{i=1}^{n} P_{PV,c}(t) \Delta t,
\]

where \(\lambda_{PV,c}\) is the PV energy consumption rate, whose measurement period can be selected as 1 h, 1 day, or 1 year; \(W_{PV}\) is the theoretical maximum output energy of PV; \(W_{PV,c}\) is the actual consumption energy of PV; \(n\) is the number of periods included in the measurement interval.

#### CO₂ emission index

Carbon dioxide emissions include two parts, one is the CO₂ emissions from the purchase of gas for power generation and heat production, and the other is the CO₂ emissions from the consumption of electricity purchased from the grid [28]. Their expressions are as follows:

\[
f_e = O_{CO_2,\text{gas}} + O_{CO_2,\text{grid}},
\]

\[
O_{CO_2,\text{gas}} = \beta_{CO_2,\text{gas}} G_{\text{gas}},
\]

\[
O_{CO_2,\text{grid}} = \beta_{CO_2,\text{grid}} W_{\text{grid}}
\]

where \(f_e\) is the total annual CO₂ emissions, \(O_{CO_2,\text{gas}}\) and \(O_{CO_2,\text{grid}}\) are the annual CO₂ emissions corresponding to the purchase of gas for power generation and heat production and the purchase and consumption of electricity from the grid; \(G_{\text{gas}}\) is the natural gas energy consumed by the PIES; \(\beta_{CO_2,\text{gas}}\) is the CO₂ emission factor corresponding to the use of natural gas and is 0.198 kg/kWh; \(W_{\text{grid}}\) is the electricity energy purchased by the park; and \(\beta_{CO_2,\text{grid}}\) is the CO₂ emission factor corresponding to electricity consumption and is 0.137 kg/kWh.

#### Primary energy utilisation efficiency index

To reflect the energy utilisation efficiency of PIES, the simplified primary energy utilisation efficiency index of PIES is defined as follows [29]:

\[
F = \frac{\sum_{t=1}^{T} L(t)}{\sum_{t=1}^{T} S(t)},
\]

\[
L(t) = P_{\text{grid}}(t) + H(t),
\]

\[
S(t) = P_{\text{grid}}(t) + P_{PV}(t) + G_{\text{gas}}(t),
\]

where \(F\) is the primary energy utilisation efficiency, \(L(t)\) is the total load power at time \(t\), \(S(t)\) is the sum of the supply power of primary energy at time \(t\), and \(\eta_e\) and \(\eta_{\text{grid}}\) are the average generation and transmission efficiency and are 0.5 and 0.8, respectively.

### 3.2 Multi-scene analysis method

Due to different upgrade ways and different types of newly added candidate equipment, there are various upgrade and renovation schemes for the existing PIES. Therefore, the multi-scene analysis method is adopted to enumerate all renovation schemes to form the renovation scene set Sce, then obtain the results of each scene, and make the comparison to select the best renovation scheme.

Assuming there are \(N\) types of renovation scenes, denote the \(X\)th scene as Sce \(X\), \(X = 1, 2, \ldots, N\), then the renovation scene set Sce is expressed as:

\[
\text{Sce} = \{\text{Sce}1, \text{Sce}2, \ldots, \text{Sce}X, \ldots, \text{Sce}N\}.
\]

It is assumed that the upgrade and renovation scheme of Sce \(X\) is to expand the capacity of \(k\) types of existing equipment and to add \(m\) types of new candidate equipment. Then, the equipment capacity matrix of Sce \(X\) after upgrade and renovation is

\[
Q_{X} = \left[\begin{array}{c}
Q_{X,\text{exi}} \\
Q_{X,\text{new}}
\end{array}\right] = \left[\begin{array}{c}
Q_{\text{exi}}^1, \ldots, Q_{\text{exi}}^k, \ldots, Q_{\text{exi}}^m \\
Q_{\text{new}}^1, \ldots, Q_{\text{new}}^m
\end{array}\right],
\]
where $Q_X$ is the equipment capacity matrix of Sce $X$ after upgrade and renovation; $Q_{X\text{exi}}$ is the expansion capacity vector of the existing equipment; $i = 1, 2, \ldots, k$; $Q_{\text{Xnew}}$ is the capacity configuration vector for newly added equipment; and $j = 1, 2, \ldots, m$. If $m = 0$, the capacity of the existing equipment will only be expanded in Sce $X$; if $k = 0$, new candidate equipment will only be added in Sce $X$.

The operation power matrix of each equipment in Sce $X$ is defined as

$$P_X = [P_{X\text{exi}}; P_{\text{Xnew}}]^T,$$

where $P_{X\text{exi}} = [P^i(t)]_{i\times8760}$ is the operation power matrix of existing equipment, $P_{\text{Xnew}} = [P^j(t)]_{j\times8760}$ is the operation power matrix of newly added equipment, and $P^i(t)$ represents the power of the $i$th newly added equipment at time $t$, $i = 1, 2, \ldots, 8760$.

### 3.3 Upgrade and renovation model and capacity allocation solution of existing PIES

#### 3.3.1 Objective function

It is assumed that the PIES operators have sufficient funds to upgrade the existing PIES. In Sce $X$, the upgrade and renovation of existing PIES takes the minimum annual value of equipment investment cost and annual operation and maintenance cost as the objective function and is expressed as

$$C = \min (C_I + C_O + C_M),$$

where $C$ is the annual value of total cost, $C_I$ is the annual value of equipment investment cost, $C_O$ is the annual operation cost, and $C_M$ is the annual maintenance cost.

**Annual value of investment cost**

The annual value of investment cost $C_I$ consists of two parts: the investment cost for expansion of PIES's existing equipment and the investment cost of newly added equipment. The expressions of $C_I$ are as follows:

$$C_I = (R_{\text{exi}} \cdot \epsilon_{\text{inv,exi}}) Q_{\text{exi}}^T + (R_{\text{new}} \cdot \epsilon_{\text{inv,new}}) Q_{\text{new}}^T,$$

where

$$\begin{bmatrix} \epsilon_{\text{inv,exi}} \\ \epsilon_{\text{inv,new}} \end{bmatrix} = \begin{bmatrix} \epsilon_{\text{inv,exi}}^1 & \epsilon_{\text{inv,exi}}^2 & \cdots & \epsilon_{\text{inv,exi}}^k \\ \epsilon_{\text{inv,new}}^1 & \epsilon_{\text{inv,new}}^2 & \cdots & \epsilon_{\text{inv,new}}^k \end{bmatrix},$$

$$\begin{bmatrix} R_{\text{exi}} \\ R_{\text{new}} \end{bmatrix} = \begin{bmatrix} R_{\text{exi}}^1 & R_{\text{exi}}^2 & \cdots & R_{\text{exi}}^k \\ R_{\text{new}}^1 & R_{\text{new}}^2 & \cdots & R_{\text{new}}^k \end{bmatrix},$$

$$R = \frac{r(1+r)^n}{(1+r)^n - 1},$$

where $\epsilon_{\text{inv,exi}}$ and $\epsilon_{\text{inv,new}}$ are the investment cost vectors per unit capacity of existing equipment and newly added equipment, respectively; $\epsilon_{\text{inv,exi}}^i$ and $\epsilon_{\text{inv,new}}^i$ are the investment cost per unit capacity of the $i$th existing equipment and $i$th newly added equipment, respectively; $R_{\text{exi}}$ and $R_{\text{new}}$ are annual value coefficient vectors of existing equipment and newly added equipment, respectively; and $R_{\text{exi}}^i$ and $R_{\text{new}}^i$ are the annual value coefficients of the $i$th existing equipment and $i$th newly added equipment, respectively. For a certain type of equipment, the annual value coefficient can be calculated by (25), where $r$ is the discount rate, taken as 3% in this paper, and $n$ is the life of the equipment.

**Annual operation cost**

The annual operation cost $C_O$ includes electricity purchase cost and gas purchase cost from the external network, as follows:

$$C_O = C_{\text{grid}} + C_{\text{gas}},$$

$$C_{\text{grid}} = \epsilon_{\text{grid}} P_{\text{grid}}^T,$$

$$C_{\text{gas}} = \sum (\epsilon_{\text{gas}} G_{\text{gas}}),$$

where $C_{\text{grid}}$ and $C_{\text{gas}}$ are the electricity and gas purchase costs, respectively; $\epsilon_{\text{grid}} = [\epsilon_{\text{grid}}(t)]_{1\times8760}$ is the electricity price vector, where $\epsilon_{\text{grid}}(t)$ is the electricity price at time $t$; $P_{\text{grid}} = [P_{\text{grid}}(t)]_{1\times8760}$ is the power vector of electricity purchase $P_{\text{grid}}(t)$; $G_{\text{gas}}$ is the price of natural gas; $C_{\text{gas}} = [G_{\text{gas}}(t)]_{1\times8760}$ is the natural gas consumption power vector, where $G_{\text{gas}}(t)$ is the natural gas consumption power at time $t$; and $\sum ()$ represents the sum function.

**Annual maintenance cost**

The annual maintenance cost $C_M$ is divided into two parts: one part is the maintenance cost of existing equipment; the other part is the maintenance cost of newly added equipment; the expression of $C_M$ is expressed as

$$C_M = \sum(\epsilon_{\text{Mai,exi}} P_{\text{Xexi}}) + \sum(\epsilon_{\text{Mai,new}} P_{\text{Xnew}}),$$

where $\epsilon_{\text{Mai,exi}}$ and $\epsilon_{\text{Mai,new}}$ are the maintenance cost vectors per unit power of the existing and newly added equipment, respectively, and $\epsilon_{\text{Mai,exi}}^i$ and $\epsilon_{\text{Mai,new}}^i$ are the maintenance cost per unit power of the $i$th existing equipment and $i$th newly added equipment, respectively.

#### 3.3.2 Constraints and solution method

In the upgrade and renovation model, the operation constraints of the existing equipment in (1)–(4), the capacity expansion constraints of the existing equipment in (5), the operation constraints of newly added equipment in (6), and the power balance constraints in (7)–(8) should be satisfied.
Finally, a mixed-integer linear programming (MILP) solver is called with the Yalmip toolbox of MATLAB, and the MILP algorithm is adopted \[30\] to obtain the optimal configuration scheme for each renovation scene.

### 3.4 Comprehensive evaluation and optimal selection of renovation scenes

When solving the capacity allocation plans of renovation scenes, the economical optimisation is the objective function, and the purpose is to minimise the cost to maximise the performance of PIES. Furthermore, according to the preferences of PIES operators, the best renovation scene should be selected based on indexes such as economy, PV consumption capacity, CO\(_2\) emissions, and so on.

To evaluate the effect of each renovation scene, the existing PIES before upgrade and renovation is set as the initial scene, and its operation situation and each index value are used as the benchmark.

The index improvement rate is defined to describe the improvement effect of each index in the renovation scene compared with the initial scene. The higher the index improvement rate, the better the improvement effect of the corresponding index. It is calculated as

$$\lambda_R = \left| \frac{I_{U} - I_{O}}{I_{O}} \right| \times 100\%,$$

where \(\lambda_R\) represents the index improvement rate, taking the four indexes in Section 3.1.1 as the calculation object; \(I_U\) represents the index value of the \(i\)th renovation scene; and \(I_O\) represents the index value of the initial scene.

Finally, the improvement effect of the different renovation scenes is compared and visualised using a radar map, so the PIES operators can choose the most suitable renovation scene and its capacity configuration scheme according to the demand of the existing PIES.

In short, the multi-scene upgrade and renovation method of existing PIES based on comprehensive analysis comprises four stages: analysis of the present status of the existing PIES, setting the renovation scenes, solving the capacity allocation plans, and comprehensively evaluating and selecting the optimal configuration scheme for each renovation scene.
renovation scenes. Finally, the optimal upgrade and renovation scheme is obtained. The flow chart of the method is shown in Figure 2.

4 \ CASE STUDY

4.1 \ Case introduction

The structure of the existing PIES adopted by the case is shown in Figure 1. The equipment in the initial planning of the existing PIES (the existing equipment) includes CHP, HP, ES, and HS, and their capacities, and parameters are listed in Table A1 of the Appendix [13,31]. The time-of-use electricity price is adopted in the park [32], as shown in Table A2 of the Appendix, and the natural gas price is 0.24 Yuan/kWh. To truly reflect the actual operation situation of the existing PIES, three typical daily data are selected every month, including two workdays and one non-workday; the corresponding electricity/heat load curves and predicted PV output curve are shown in Figure 3.

4.2 \ Present status analysis of existing PIES before upgrade and renovation

The comprehensive performance and operation situation of each equipment in the existing PIES (initial scene) are analysed, and the weak links are found to be concentrated mainly in the coupling link of PV and ES as well as the heating link. On the one hand, the initial PV allocation capacity of the existing PIES is relatively large, while the allocation capacity of ES is relatively small, which limits the effect of ES on stabilising the volatility of PV’s output. Therefore, the energy of PV is severely abandoned at the period of high output, and PV cannot supply electric energy for the park during the period without output. The overall PV energy consumption rate is low, as indicated in Figure 4 and Table 2. On the other hand, with the increase in electric and heat load in the park, HP is often at full load due to its own small capacity, and the gap between supply and demand of heat energy increases. The existing PIES needs to purchase a large amount of electricity and gas from the outside, resulting in higher operation cost, as shown in Figures 5 and 6 and Table A3 in the Appendix. In addition, the CO2 emissions of the existing PIES are high and the primary energy utilisation efficiency is low, as shown in Table 2.

4.3 \ Renovation scene-setting

According to the current situation and weak links of the existing PIES, on the one hand, the capacity of the existing energy-storage and heating equipment needs to be expanded to provide more abundant output space. On the other hand, electric boiler (EB) and gas boiler (GB) are selected as newly added candidate equipment to strengthen the heating link of the existing PIES.

Four renovation scenes are set as follows:

See I: Expand the capacity of existing equipment and do not add new equipment.
See II: Add EB while expanding the capacity of the existing equipment.
See III: Add GB while expanding the capacity of the existing equipment.
See IV: Add both EB and GB while expanding the capacity of the existing equipment.
### Renovation scenes’ equipment allocation capacity

| Scene | CHP (kW) | HP (kW) | ES (kWh) | HS (kWh) | EB (kW) | GB (kW) |
|-------|----------|---------|----------|----------|---------|---------|
| Sce I | 0        | 19      | 1087     | 162      | 0       | 0       |
| Sce II| 0        | 13      | 1087     | 10       | 18      | 0       |
| Sce III| 0      | 15     | 1087     | 84       | 0       | 15      |
| Sce IV| 0        | 5       | 1087     | 0        | 19      | 19      |

### Results of upgrade and analysis

#### Equipment allocation capacity

The allocation capacity solution of each equipment in different renovation scenes is shown in Table 1. Owing to the high investment cost per unit capacity of CHP, none of the four scenes expand its capacity. All four scenes expanded ES, and the expansion capacities are the same. Sce I, II, and III expand the capacity of HS. Due to the substitution effect of EB and GB in the heating link, the four scenes have expanded the capacity of the HP to varying degrees.

#### Cost analysis and comparison

The costs of each item of the initial and renovation scenes are listed in Table A3 in the Appendix. First, the total costs of the four renovation scenes do not differ greatly, but they are lower than that of the initial scene, and the total cost of Sce IV is the lowest. Second, the investment costs of the four scenes are related to the types of equipment and allocated capacity. In terms of operation costs, the gas purchase costs of the four scenes are all lower than that of the initial scene, and the electricity purchase costs are greatly reduced. The maintenance cost of each equipment is positively correlated with the equipment output. The maintenance costs of ES and HP increased in the four scenes, indicating that the PIES has increased the use of ES and HP after the upgrade and renovation, and the maintenance costs of HS and CHP in the four scenes are reduced, indicating that the PIES has reduced the use of HS and CHP after the upgrade and renovation.

The following section explains the improvement of the operation efficiency of existing PIES and the reason for the cost reduction after the upgrade and renovation based on analysis of the power supply and heat supply links of the system.

#### Analysis of upgrade and renovation results of the power supply link

The power supply link is analysed first. After the upgrade and renovation, the coupling effect between PV and ES is strengthened, and PV consumption energy in each quarter of the four renovation scenes increased, as shown in Figure 4, which is related to the increase in the ES's capacity. The high-capacity ES combined with the high-penetration PV can store the excess power of PV during high-output periods and release it when PV output is low or zero, thereby increasing the overall consumption energy of PV and reducing the power generation of CHP and the electricity purchased from the external grid.

As shown in Figure 5, in the four scenes, the amounts of electricity purchased from external grid in spring, summer, and autumn are all lower than that in the initial scene, but electricity purchased in winter is increased, which is related to the overall low PV output in winter, reduced CHP generation, and large electricity consumption by HP and EB heating.
4.4.4 Analysis of upgrade and renovation results of the heatsupply link

For the heatsupply link, the output of heating equipment in Spring is shown in Figure 6. HP and CHP are the main heating sources. After upgrade and renovation, HP's output of the four scenes is higher than that of the initial scene, and CHP's output is reduced. See II, III, and IV are provided with a small amount of heat by EB or GB.

The reasons for the change of equipment output are analysed in terms of cost. The maintenance cost per unit output of HP and CHP are the same, both are 0.05 Yuan/kW, but CHP supplies heat and power simultaneously. As the PV energy consumption rate increases, CHP's electric power supply decreases, and the corresponding heat supply decreases. The excess heat load is replaced by HP's supply. Although the maintenance cost of EB and GB (0.04 Yuan/kW and 0.03 Yuan/kW, respectively) are lower than that of HP, but EB needs to consume more electricity, GB needs to consume natural gas, and both are also restricted by investment costs. Therefore, in See II, III, and IV, EB and GB only increase by a small capacity, which replaces part of the HP's output. In short, the above changes and adjustments improve the operation economy of the system.

4.5 Comprehensive evaluation and optimal selection of the allocation schemes of renovation scenes

The PV energy consumption rate, CO$_2$ emissions, and primary energy utilisation efficiency index of the four renovation scenes are shown in Table 2. The PV energy consumption rate of the
TABLE 2  Indexes of four renovation scenes and initial scene

| Scene                | Initial scene | Sce I   | Sce II  | Sce III | Sce IV  |
|----------------------|---------------|---------|---------|---------|---------|
| PV energy consumption rate | 56.10%       | 73.66%  | 74.68%  | 73.61%  | 74.66%  |
| CO₂ emissions        |               |         |         |         |         |
| Total                | 220928.67     | 189851.26 | 190402.15 | 191822.54 | 193262.21 |
| Gas                  | 77140.55      | 69940.08 | 69614.47 | 69820.80 | 69387.11 |
| Electricity          | 143788.12     | 119911.18 | 120787.69 | 122001.74 | 123875.1 |
| Primary energy utilisation rate | 68.37%       | 71.91%  | 71.73%  | 71.67%  | 71.40%  |

FIGURE 7  Evaluation radar map

The economy, PV energy consumption capacity, and environmental protection performance of each renovation scene cannot be optimised simultaneously. The improvement rates of each index of different scenes relative to the initial scene are calculated. The results are shown in Table A4 in the Appendix, and the radar map (Figure 7) is adopted to reflect the advantages and disadvantages of each scene directly under different evaluation dimensions to facilitate the selection of PIES operators.

The comprehensive evaluation results can be obtained as follows:

(i) The improvement of the economy, PV energy consumption capacity, and environmental protection performance of each renovation scene are not significantly different from each other. Different indexes cannot achieve optimal performance simultaneously, and different scenes have their own advantages.

(ii) In Sce I, the primary energy utilisation efficiency is improved the most and the carbon dioxide emissions are reduced the most among all scenes, indicating that Sce I has the best environmental protection performance after the upgrade.

(iii) The PV energy consumption rate of Sce II is the highest, and its PV utilisation after the upgrade is the best.

(iv) Sce IV reduces the total cost the most, indicating that its economy is the best.

If the PIES operators prioritise environmental protection performance, energy conservation, and emissions reduction, then Sce I is the best. If the operators prefer to improve the PV consumption capacity, then Sce II is a good choice. Sce IV works best when the focus is solely on improving the economy.

5  | CONCLUSION

A multi-scene upgrade and renovation method for the existing PIES based on comprehensive analysis is proposed, comprising four links: present status analysis of the existing PIES, establishing the renovation scenes, solution of the allocation schemes, and comprehensive evaluation and optimal selection of renovation scenes. The energy storage and heat supply links of the existing PIES in the case study are renovated, which improved the energy supply economy, PV energy consumption rate, and primary energy utilisation efficiency, and reduced CO₂ emissions, verifying the effectiveness of the method. The conclusions are as follows:

(i) PV with a higher initial allocation capacity needs to expand the capacity of ES to store the excess power of PV during the high output period, so it can be transferred and released during the low output period, and the PV energy consumption rate can be improved.

(ii) In the actual operation of the renovation scenes, the equipment with a lower discounted investment cost plus operation and maintenance cost will partially replace the output of the existing equipment and improve the operation economy of the PIES.

(iii) It is difficult to achieve the optimal PIES operation economy, PV energy consumption capacity, CO₂ emissions, primary energy utilisation efficiency, and other indexes simultaneously. Comprehensive evaluation can reflect the advantages and disadvantages of each renovation scene for PIES operators to make the optimal selection based on their priorities.

The proposed method provides a novel and effective way to upgrade and renovate the existing PIES to improve its comprehensive performance, which is beneficial to the design and management of PIES. In future research, by combining the
characteristics of the existing PIES before and after upgrade and renovation, we will more accurately evaluate and select the renovation scheme from various dimensions based on the upgrade and renovation method described.

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## APPENDIX 1

### TABLE A1  Equipment’s parameters

| Equipment type | Parameter                  | Value  | Equipment type | Parameter                  | Value   |
|----------------|----------------------------|--------|----------------|----------------------------|---------|
| HP             | Initial capacity           | 135 kW | EB             | Initial capacity           | 0 kW    |
|                | Investment cost            | 3000 Yuan/kW |               | Investment cost            | 1000 Yuan/kW |
|                | Lifetime                   | 25 years |               | Lifetime                   | 25 years |
|                | Maintenance cost           | 0.05 Yuan/kW |               | Maintenance cost           | 0.04 Yuan/kW |
|                | COP                        | 3.8    |                | Electric–thermal efficiency | 0.95    |
| CHP            | Initial capacity           | 120 kW | GB             | Initial capacity           | 0 kW    |
|                | Investment cost            | 7000 Yuan/kW |               | Investment cost            | 700 Yuan/kW |
|                | Lifetime                   | 25 years |               | Lifetime                   | 25 years |
|                | Maintenance cost           | 0.05 Yuan/kW |               | Maintenance cost           | 0.03 Yuan/kW |
|                | Gas-thermal efficiency     | 0.45   |                | Gas–thermal efficiency     | 0.95    |
|                | Gas-electric efficiency    | 0.3    | PV             | Initial capacity           | 1000 kW |
|                | Heat/power ratio           | 1.5    |                | Maintenance cost           | 0.039 Yuan/kW |
| ES             | Initial capacity           | 450 kWh | HS             | Initial capacity           | 875 kWh |
|                | Investment cost            | 780 Yuan/kWh |            | Investment cost            | 35 Yuan/kWh |
|                | Lifetime                   | 20 years |               | Lifetime                   | 20 years |
|                | Maintenance cost           | 0.026 Yuan/kWh |         | Maintenance cost           | 0.013 Yuan/kWh |
|                | Charge–discharge efficiency| 0.95   |                | Charge–discharge efficiency | 0.9     |
|                | SOC                        | 0.2–0.9 |                | SOC                        | 0.1–0.9 |
|                | Maximum charge and discharge power | 180 kW/h |        | Maximum charge and discharge power | 350 kW/h |

### TABLE A2  Time-of-use price

| Time period | Electric price (Yuan/kWh) |
|-------------|---------------------------|
| Peak periods (11:00–16:00, 19:00–21:00) | 1.35 |
| Average periods (8:00–11:00, 16:00–19:00, 22:00–0:00) | 0.90 |
| Valley periods (0:00–8:00) | 0.47 |
### TABLE A3  Cost of four renovation scenes and initial scene

| Scene                          | Initial scene | Sce I     | Sce II    | Sce III   | Sce IV     |
|--------------------------------|---------------|-----------|-----------|-----------|------------|
| **Total cost (Yuan)**          | 687044.76     | 579839.61 | 579658.13 | 579729.54 | 579567.04  |
| **Investment cost (Yuan)**     |               |           |           |           |            |
| Total                          | 0.00          | 60644.01  | 60286.42  | 60374.37  | 59705.85   |
| CHP                            | 0.00          | 0.00      | 0.00      | 0.00      | 0.00       |
| HP                             | 0.00          | 3273.39   | 2239.69   | 2584.25   | 861.42     |
| ES                             | 0.00          | 56989.51  | 56989.51  | 56989.51  | 56989.51   |
| HS                             | 0.00          | 381.11    | 23.53     | 197.61    | 0.00       |
| EB                             | 0.00          | 0.00      | 1033.70   | 0.00      | 1091.13    |
| GB                             | 0.00          | 0.00      | 0.00      | 602.99    | 763.79     |
| **Operation cost (Yuan)**      |               |           |           |           |            |
| Total                          | 602052.12     | 424159.76 | 424847.29 | 425059.23 | 425832.93  |
| Gas purchase                   | 174288.63     | 145346.88 | 146409.32 | 147880.90 | 150151.64  |
| Power purchase                 | 427763.49     | 278812.88 | 278077.97 | 277178.33 | 275681.29  |
| **Maintenance cost (Yuan)**    |               |           |           |           |            |
| Total                          | 84992.65      | 95035.83  | 94884.42  | 94295.94  | 94028.27   |
| ES                             | 7289.16       | 20258.88  | 20260.31  | 20268.85  | 20260.45   |
| HS                             | 3996.56       | 3200.34   | 3108.04   | 3058.56   | 3011.90    |
| PV                             | 28185.32      | 28185.32  | 28185.32  | 28185.32  | 28185.32   |
| HP                             | 18289.01      | 20680.84  | 20095.59  | 19864.55  | 18989.8    |
| CHP                            | 27232.60      | 22710.45  | 22876.46  | 22324.17  | 22399.56   |
| EB                             | 0.00          | 0.00      | 358.70    | 0.00      | 365.40     |
| GB                             | 0.00          | 0.00      | 0.00      | 594.49    | 806.84     |

### TABLE A4  Index improvement rate of each scene

| Scene | Improvement rate of economy | Improvement rate of PV energy consumption rate | Improvement rate of CO₂ emissions | Improvement rate of primary energy utilisation efficiency |
|-------|------------------------------|-----------------------------------------------|----------------------------------|--------------------------------------------------------|
| Sce I | 15.60%                       | 31.30%                                        | 14.07%                           | 5.18%                                                  |
| Sce II| 15.63%                       | 33.12%                                        | 13.82%                           | 4.92%                                                  |
| Sce III| 15.62%                       | 31.22%                                        | 13.17%                           | 4.83%                                                  |
| Sce IV| 15.64%                       | 33.09%                                        | 12.52%                           | 4.44%                                                  |