

Article

Expansion Planning Method of the Industrial Park Integrated Energy System Considering Regret Aversion

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Received: 3 October 2019; Accepted: 23 October 2019; Published: 27 October 2019



Abstract: Industrial parks have various sources and conversion forms of energy. The many uncertainties in the planning of industrial park integrated energy systems (IPIES) pose a great risk of regret in planning schemes; thus, an expansion planning method for an IPIES, considering regret aversion, is proposed. Based on comprehensive regret value consisting of min–max regret aversion and the min average regret value, the method optimizes the comprehensive cost of the expansion planning scheme in IPIES under different natural gas price fluctuation scenarios, including costs of construction, operation and maintenance, and environmental protection. A multi-stage expansion planning scheme and typical daily operation plans under multiple natural gas price fluctuation scenarios of the IPIES in an economic and technological development zone in southeast China are used to demonstrate the validity of the method. The results show that, compared with a traditional planning method based on expectation, the proposed expansion planning method could reduce the maximum regret value by 14% on average, and greatly reduces the risk of decision-making regret by up to 18%. At the same time, the influence of natural gas price on expansion planning of the IPIES is discussed.

Keywords: industrial park integrated energy system; expansion planning; natural gas price uncertainty; regret aversion; min–max regret value

1. Introduction

The integrated energy system (IES) integrates energy production, conversion, storage, and consumption [1,2]. It is an important development trend of energy technology to achieve coordinated and complementary optimization of multiple energy sources in the future [3–5]. Industrial parks with intensive demand for electricity, steam, cold, and heat energy are typical application scenarios for IES. How to plan industrial park integrated energy systems (IPIES) is an important issue in current research [6,7]. In order to optimize the structure and capacity of the IES, domestic and foreign scholars have proposed various models, algorithms, and planning objectives. Geidl et al. [8] proposed the concept of an energy hub (EH) and established a planning model for an electric power and natural gas system with the objective function of minimum energy loss in the EH. Zhang et al. [9] considered a variety of combined heat and power (CHP) generation units, designing CHP units with the objective of system economics and environmental performance. Zhang et al. [10] decomposed the planning model into two aspects: Investment and operation feasibility of a power system or natural gas system. Zhao et al. [11] proposed a three-level collaborative global optimization method for a combined cooling, heating, and power (CCHP) system. These research and planning methods were mainly designed for a system plan in a specific state.

Based on EH, Zhou et al. [12] proposed a collaborative expansion optimization configuration method for a renewable power system and a natural gas system. Considering the topological constraints of grid and gas networks, a regional integrated energy system expansion planning model based on CCHP was proposed in [13], and the economic scheduling strategy of the system was analyzed by the scenario method. Considering the value chain of natural gas, the long-term, multi-regional, and multi-stage expansion planning of a gas-electric coupling system was studied in reference [14]. The authors of [15,16] proved that flexible expansion planning can better handle uncertainties, compared to traditional lowest-cost planning methods. Adaptation cost is defined as the additional investments required for a proposed plan, if an unexpected load growth happens. Qiu et al. [17] established a joint expansion planning model for natural gas networks and power grids with the objective of maximizing social benefits. The Monte Carlo simulation was applied to create scenarios that simulate random system characteristics in [18]. An extended planning model based on two-stage stochastic optimization was established to realize the construction planning of natural gas and power facilities under uncertainty of demand growth in [19]. To deal with the uncertainty of renewable energy, the scenario method was used to deal with the wind power and energy storage and load, and the capacity of the internal device in the EH was configured in [20]. Robust optimization was used to obtain an optimized solution that is immune to the effects of all possible wind power realizations within the uncertainty interval in [21,22]. Cesena et al. [23] proposed a unified planning and scheduling method to assess the flexibility of system investment and operation under long-term uncertainty. The proposed approach in [24] reflected real-options thinking borrowed from finance, and had been cast as a stochastic mixed-integer linear program. These integrated energy expansion planning studies did not consider the need for policymakers to avoid the risk of regret in planning schemes together with the lowest cost.

Regret is an emotion that affects decision-making behavior. When decision-makers face a variety of schemes, one scheme is selected and compared with other unselected schemes. When the uncertainty causes the actual situation to be different from the expected, resulting in the profit of the selected scheme being smaller than one or more of the unselected schemes, a feeling of regret in the decision-maker is generated [24,25]. Savage et al. [26] proposed a model based on minimum-maximization regret, which shows that decision-makers will choose a decision with a minimal regret value from the decision plan that maximizes regret. In [27], regret is considered as one of the objectives in a multi-objective optimization framework. By applying the min-max regret criterion, model obtained a solution that minimizes the worst-case regret over all possible scenarios while ensuring system robustness [28]. The theory of regret has been applied in the study of consumer behavior in economics, travel path planning, etc. [29,30]. In [31], the min-max regret criterion is considered for the unit commitment problem. Compared with the min-max cost criterion, it is concluded that min-max regret outperforms min-max cost for certain unit commitment problems. Min-max cost and min-max regret have been proposed to address wind power generation uncertainties in [32]. Both criteria provide good upper bounds for the total costs under scenarios contained in an uncertainty set. The min-max cost criterion provides a smaller upper bound while min-max regret has higher variability. Depending on the characteristics of uncertainty sets and the preference of decision-makers, different models outperform each other under different situations. In the IPIES, the prediction error caused by uncertainty will cause decision-makers to pay excessive construction and operation costs for the system, which will also cause the decision-makers regret. In this paper, there are many types of comprehensive energy sources and conversion forms in industrial parks, such as natural gas, electric, heat, cold, and steam. In view of the various sources and conversion forms of energy in industrial parks as well as the large amount of uncertainty posing a great risk of regret in planning schemes, an expansion planning method of the IPIES considering regret aversion is proposed. The method deals with uncertainty using the scenario method, sets the regret value as the main indicator, and the comprehensive regret value, which considers the min-max regret value with its distribution and average regret value together, as the objective function.

2. IPIES Structure and Expansion Planning Method Model

Referring to [8,11,14,23,33,34], the structure and energy flow of the IPIES studied in this paper is shown in Figure 1. The system is connected to a steam network provided by an external large thermal power plant. The IPIES includes four parts: (1) Supply part: Power grid, natural gas network, steam network, photovoltaic (PV); (2) conversion part: Micro turbine (MT), heat recovery device (HR), electric boiler (EB), gas boiler (GB), heat pump (HP), electric chiller (EC), heat exchanger (HC), absorption chiller (AC); (3) storage part: Battery (BAT), steam heat storage (HS), cold energy storage (CS); and (4) load part: Electrical loads, steam loads, heat loads, cold loads, gas loads.

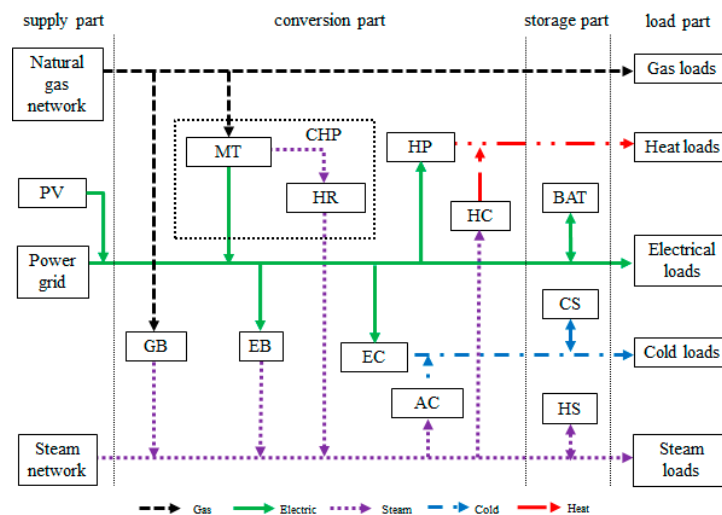


Figure 1. Structure and energy flow of industrial park integrated energy system (IPIES).

Based on the structure and energy flow of the IPIES, the expansion planning method of the IPIES considering regret aversion proposed in this paper is shown in Figure 2. It includes three layers: The stage scenario analysis layer, the expansion planning layer, and the regret aversion layer.

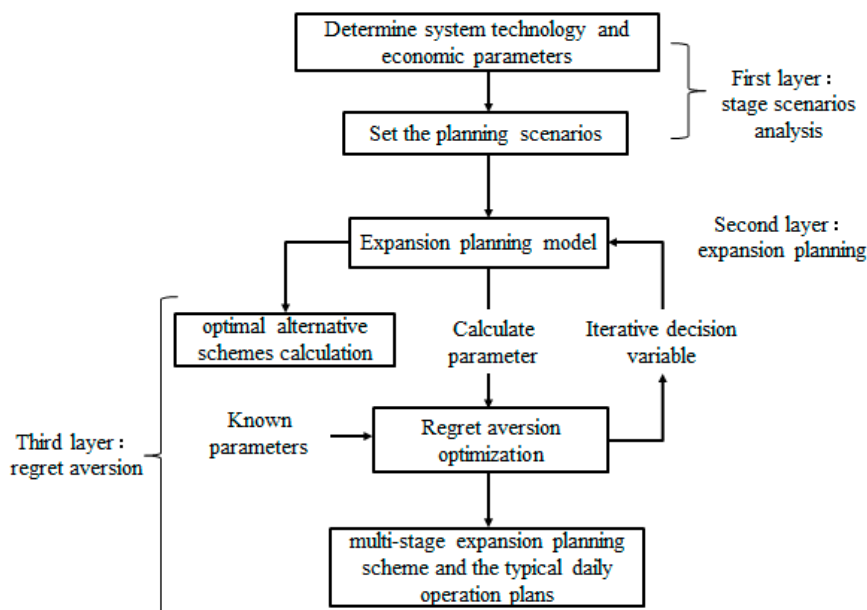


Figure 2. Expansion planning method of IPIES considering regret aversion.

In the stage scenarios analysis layer, the method mainly studies the typical daily load scenarios of the system and the natural gas price fluctuation scenarios.

In the expansion planning layer, the method sets the capacity and the typical daily operating power corresponding to device capacity as the variables. The method establishes an expansion planning model by taking the net present value of the comprehensive cost, including costs of construction, operation and maintenance, and environmental protection, as the objective function.

In the regret aversion layer, the method firstly calculates the optimal alternative schemes under different natural gas price fluctuation scenarios with the lowest comprehensive cost. Then, the method sets a min–max regret value and the lowest average regret value between the final planning scheme and the optimal alternative schemes as the objective function to optimize the device capacity within the final multi-stage expansion planning scheme and the typical daily operation plans under multiple natural gas price fluctuation scenarios.

2.1. Stage Scenarios Analysis Layer

Firstly, the scenario analysis method in [35] is used to deal with the volatility and randomness of each energy load and photovoltaic (PV) unit output power. The number of typical day scenarios after the load scenes and the lighting scenes are reduced is M , and each typical day scenario, m , has D_m days in a whole year. In order to meet the normal operation of the system at all times, an additional daily limit scenario with a constant zero PV output power is added. In view of the growth of energy load during the planning stages, the paper refers to the multi-stage planning method of a power system [36], introduces the continuous load curve to describe the medium and long-term load growth expectations, and divides the load level in the planning period into several horizontal sections, though the simplification will affect the accuracy of the model to some extent. A typical day scenario's load characteristic curves at different load levels can be obtained by equal ratio changes.

In addition, considering the price of the system device will decrease during the planning stages with the development of science and technology, and will stabilize after the technology matures [37], a piecewise exponential function is used to represent the dynamic change in device prices [38]:

$$c^{I,k,y} = \begin{cases} c_0^{I,k}(1+g_k)^y & 1 < y < Y_k^c \\ c_0^{I,k}(1+g_k^c) & Y_k^c < y < Y \end{cases}, \quad (1)$$

where $c^{I,k,y}$ is the construction price of the device k in year y ; g_k is the price correction coefficient of the device k ; g_k^c is the critical price reduction factor; Y_k^c is the time for the device k to reach the critical price; and Y is the operating period of the IPIES.

The electricity market is still not perfect in China, but electricity prices are relatively stable due to policy decisions; natural gas prices, however, will be affected by changes in global trade prices and domestic supply and demand factors, and there will be greater uncertainty in prices over time and space. In the past, natural gas was originally developed as a replacement for traditional fuel, and its pricing was linked to other energy such as oil and the oil-indexed gas imports in China accounted for the majority [39–41]. However, with the changes in the international natural gas supply and demand pattern and the continuous reform of China oil and gas market, natural gas, especially liquefied natural gas (LNG), is gradually becoming an independent energy product. In 2018, China LNG imports accounted for 60% of total natural gas imports [42]. LNG breaks the restrictions on natural gas transmission and trade between regions, greatly enhancing the transmission and impact range of natural gas prices. The 2019 Wholesale Gas Price Survey shows that Henry-Hub priced US LNG exports continued rising and there is more gas price convergence amongst countries since the global gas market and market-related pricing [43]. Figure 3 shows the China LNG ex-factory price index given by the Shanghai Petroleum and Natural Gas Exchange, reflecting the price trend of LNG in the domestic market [42]. The Shanghai Petroleum and Natural Gas Exchange, which was officially launched in 2015, opened the situation that China natural gas prices are determined by competition between supply and demand. It can be seen from Figure 3 that China's LNG spot price also has large fluctuations in different periods.

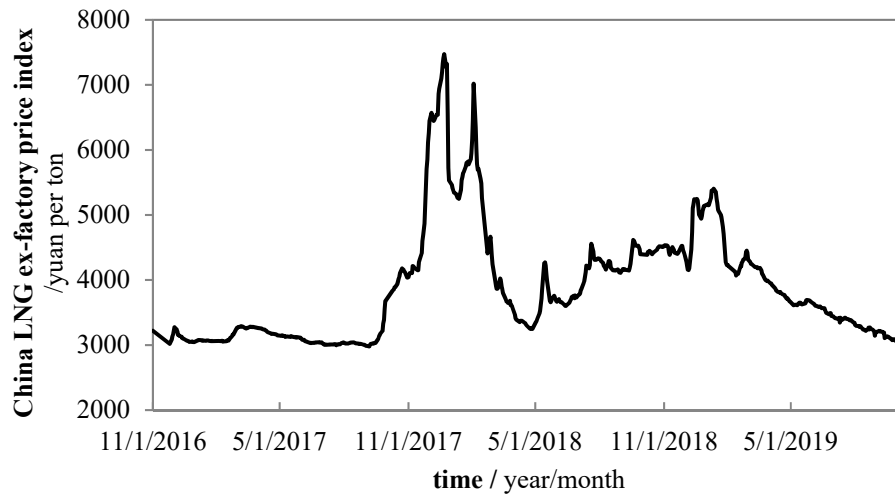


Figure 3. China liquefied natural gas ex-factory price index given by the Shanghai Petroleum and Natural Gas Exchange.

Changes in natural gas prices will directly affect the operating costs of the IPIES, which in turn will affect the economic operation of the system and the expansion of the plan; the greater fluctuation, the higher the impact on the plan. Seasonal or yearly consideration of natural gas price fluctuations during the planning cycle will lead to excessive calculation of the model. The method uses stage scenario analysis techniques to analyze the uncertainty of natural gas prices during expansion planning. The method takes the natural gas price in the initial planning stage as the benchmark price, and considers that there may be fluctuations, η , in the price of the subsequent stage compared to the benchmark price; that is, it may rise, fall, or remain unchanged from the benchmark price. In the resulting natural gas price fluctuation scenario set, S , a planning stages corresponds to 3^{a-1} natural gas price fluctuation scenarios, and the scenario probability corresponding to the natural gas price fluctuation scenario, s , is π^s .

2.2. Expansion Planning Layer

2.2.1. Objective Function

The expansion planning layer takes the net present value of the comprehensive cost, C_s^{COM} , of multi-stage planning in a natural gas price fluctuation scenario, $s \in S$, as the objective function, including the system construction cost, C_s^I , operation cost, C_s^O , maintenance cost, C_s^M , and environmental protection cost, C_s^{ENV} :

$$C_s^{COM} = C_s^I + C_s^O + C_s^M + C_s^{ENV}, \quad (2)$$

$$C_s^I = \sum_a \frac{1}{(1+\lambda)^{T(a-1)}} \cdot \left[\mathbf{c}_a^{I,k} \cdot (\mathbf{W}_{s,a}^k - \mathbf{W}_{s,a-1}^k)^T + \mathbf{c}_a^{I,T} \cdot (I_a^{des} - I_{a-1}^{des}) \right], \quad (3)$$

$$C_s^O = \sum_y \delta_y \cdot \sum_m D_m \cdot \sum_t (c_t^E \cdot P_{s,a,m,t}^{SYS} + c_{s,a}^G \cdot G_{s,a,m,t}^{SYS} + c^S \cdot S_{s,a,m,t}^{SYS}), \quad (4)$$

$$C_s^O = \sum_y \delta_y \cdot \sum_m D_m \cdot \sum_t (c^{M,BAT} \cdot |P_{s,a,m,t}^{BAT}| + c^{M,HS} \cdot |S_{s,a,m,t}^{HS}| + c^{M,CS} \cdot |C_{s,a,m,t}^{CS}| + c^{M,k1} \cdot Q_{s,a,m,t}^{k1,T}), \quad (5)$$

$$C_s^{ENV} = \sum_y \delta_y \cdot \sum_m D_m \cdot \sum_t (\gamma^E \cdot P_{s,a,m,t}^{SYS} + \gamma^G \cdot G_{s,a,m,t}^{SYS} + \gamma^S \cdot S_{s,a,m,t}^{SYS}), \quad (6)$$

$$\delta_y = \frac{1}{(1+\lambda)^{y-1}}, \quad (7)$$

where a is the planning stage, and each stage has T years; y is the operation year of IPIES; t is 24 intraday hours; δ_y is the year discount rate; λ is the annual discount rate; $\mathbf{c}_a^{I,k}$ is the unit construction cost matrix of each device, including BAT, HS, CS, PV, CHP, GB, EB, HP, EC, HC, and AC; $\mathbf{W}_{s,a}^k$ is the total capacity matrix of each device in stage a under scenario s ; $c_a^{I,T}$ is the power transmission capacity expansion cost; I_a^{des} is the 0–1 mark for the power transmission expansion status, 1 after expansion, 0 before expansion; c_t^E is the electricity price at time t ; c_a^G is the price for a unit kWh of energy natural gas in stage a under scenario s ; c^S is the price for a unit kW·h of energy steam, and the unit kW·h energy price can be calculated by the unit cubic meter price or the unit steaming price and the low calorific value of the energy; $P_{s,a,m,t}^{SYS}$, $G_{s,a,m,t}^{SYS}$, and $S_{s,a,m,t}^{SYS}$ are the electricity, gas, and steam power, respectively, that the system interacts with in the external network at typical day m , time t in stage a under scenario s ; $c^{M,BAT}$, $c^{M,HS}$, and $c^{M,CS}$ are the unit maintenance cost of BAT, HS, and CS, respectively; $\mathbf{c}^{M,k1}$ is the unit maintenance cost matrix of the device except for energy storage in IPIES; $P_{s,a,m,t}^{BAT}$, $S_{s,a,m,t}^{HS}$ and $C_{s,a,m,t}^{CS}$ are the power exchange of the energy storage device for BAT, HS, and CS, respectively; $\mathbf{Q}_{s,a,m,t}^{k1}$ is the operating power matrix of each device except for energy storage in IPIES; and γ^E , γ^G , and γ^S are the environmental cost of emissions from unit electricity, gas, and steam power, respectively, and can be calculated from the environmental value of the pollutants discharged per kW·h of energy.

2.2.2. Constraints

The constraints in the expansion planning layer include expansion constraints, load part constraints, supply part constraints, conversion part constraints and storage part constraints.

(1) Expansion constraints

Each stage can expand the capacity of each device in the IPIES or maintain the configuration of the previous stage. Decommissioning is required for the life of the device to expire:

$$W_{s,a}^k \geq W_{s,a-1}^k - W_{s,a}^{k,out}, \quad (8)$$

$$I_a^{des} \geq I_{a-1}^{des}, \quad (9)$$

$$W_{s,a}^{k,out} = W_{s,a-n_k}^k - W_{s,a-n_k-1}^k, \quad (10)$$

where $W_{s,a}^k$ is the capacity of the device k in stage a under scenario s ; $W_{s,a}^{k,out}$ is the capacity of the device k to be decommissioned in stage a under scenario s ; and n_k is the number of planned stages that device k can serve; when $a \leq 0$, $W_{s,a}^k$ is 0.

(2) Load part constraints:

$$P_{s,a,m,t}^{PV} + P_{s,a,m,t}^{CHP} + P_{s,a,m,t}^{SYS} = P_{s,a,m,t}^{LD} + P_{s,a,m,t}^{EB} + P_{s,a,m,t}^{EC} + P_{s,a,m,t}^{EH} + P_{s,a,m,t}^{BAT}, \quad (11)$$

$$S_{s,a,m,t}^{CHP} + S_{s,a,m,t}^{EB} + S_{s,a,m,t}^{GB} + S_{s,a,m,t}^{SYS} = S_{s,a,m,t}^{LD} + S_{s,a,m,t}^{HC} + S_{s,a,m,t}^{AC} + S_{s,a,m,t}^{HS}, \quad (12)$$

$$H_{s,a,m,t}^{HC} + H_{s,a,m,t}^{EH} = H_{s,a,m,t}^{LD}, \quad (13)$$

$$C_{s,a,m,t}^{AC} + C_{s,a,m,t}^{EC} = C_{s,a,m,t}^{LD} + C_{s,a,m,t}^{CS}, \quad (14)$$

$$G_{s,a,m,t}^{SYS} = G_{s,a,m,t}^{LD} + G_{s,a,m,t}^{CHP} + G_{s,a,m,t}^{GB}, \quad (15)$$

where $P_{s,a,m,t}^{PV}$, $P_{s,a,m,t}^{CHP}$, $P_{s,a,m,t}^{LD}$, $P_{s,a,m,t}^{EB}$, $P_{s,a,m,t}^{EC}$ and $P_{s,a,m,t}^{EH}$ are the output power of the PV, CHP, the electric load power, and the electric power consumed by the EB, EC, and EH, respectively; $S_{s,a,m,t}^{CHP}$, $S_{s,a,m,t}^{EB}$, $S_{s,a,m,t}^{GB}$, $S_{s,a,m,t}^{LD}$, $S_{s,a,m,t}^{HC}$ and $S_{s,a,m,t}^{AC}$ are the output steam power of CHP, EB, GB, and the steam load power, the steam power consumed by the HC, and AC, respectively; $H_{s,a,m,t}^{HC}$, $H_{s,a,m,t}^{EH}$ and $H_{s,a,m,t}^{LD}$ are the output heat power of the HC, EH, and the heat load power, respectively; $C_{s,a,m,t}^{AC}$, $C_{s,a,m,t}^{EC}$ and $C_{s,a,m,t}^{LD}$ are the output cold power of the AC, EC, and the cold load power, respectively; $G_{s,a,m,t}^{LD}$, $G_{s,a,m,t}^{CHP}$ and $G_{s,a,m,t}^{GB}$ are

the natural gas load power, the natural gas power consumed by CHP, and GB, respectively. Considering that the accuracy requirements of the planning are not as high as the actual running, in order to improve the efficiency of the model solving, the transmission loss of power grid, gas network and steam network were neglected.

(3) Supply part constraints:

$$P_{\min}^{SYS} \leq P_{s,a,m,t}^{SYS} \leq P_{\max}^{SYS} + P_0 \cdot I_a^{des}, \quad (16)$$

$$G_{\min}^{SYS} \leq G_{s,a,m,t}^{SYS} \leq G_{\max}^{SYS}, \quad (17)$$

$$S_{\min}^{SYS} \leq S_{s,a,m,t}^{SYS} \leq S_{\max}^{SYS}, \quad (18)$$

where P_{\max}^{SYS} , G_{\max}^{SYS} , and S_{\max}^{SYS} are the upper limit of the interaction power between the system and the external electricity, gas, and steam networks, respectively; P_0 is the capacity for power transmission expansion; P_{\min}^{SYS} , G_{\min}^{SYS} , and S_{\min}^{SYS} are the lower limit of the interaction power between the system and the external electricity, gas, and steam networks, respectively;

(4) Conversion part constraints

In order to simplify the analysis, the operating efficiency of each energy conversion device is constant, and the variable operating characteristics are neglected. The constraints of GB, EB, AC, EC, HP, and HC are uniformly stated as:

$$Q_{s,a,m,t}^{k1,out} = \eta^{k1} \cdot Q_{s,a,m,t}^{k1,in} \quad (19)$$

$$\varepsilon_{\min}^{k1} \cdot W_{s,a}^{k1} \leq Q_{s,a,m,t}^{k1,in} \leq W_{s,a}^{k1}, \quad (20)$$

where $Q_{s,a,m,t}^{k1,in}$ and $Q_{s,a,m,t}^{k1,out}$ are the input and output power, respectively, of the above device, k_1 , at typical day m , time t in stage a under scenario s ; $W_{s,a}^{k1}$ is the total configuration capacity of the device in stage a under scenario s ; η^{k1} is the operating efficiency of the device; and ε_{\min}^{k1} is the lowest power factor of the device.

The CHP is coupled to both electricity and steam with the following constraints:

$$P_{s,a,m,t}^{CHP} = G_{s,a,m,t}^{CHP} \cdot \eta_{ge}^{CHP}, \quad (21)$$

$$S_{s,a,m,t}^{CHP} = G_{s,a,m,t}^{CHP} \cdot \eta_{gh}^{CHP}, \quad (22)$$

$$\varepsilon_{\min}^{CHP} \cdot W_{s,a}^{CHP} \leq P_{s,a,m,t}^{CHP} \leq W_{s,a}^{CHP}. \quad (23)$$

(5) Storage part constraints

The three types of energy storage device, including BAT, HS, and CS, have similar operating characteristics:

$$W_{s,a,m,t}^{k2} = W_{s,a,m,t-1}^{k2} (1 - \mu_{loss}^{k2}) + \left(\eta_{ch}^{k2} \cdot \max(P_{s,a,m,t}^{k2}, 0) + \frac{\min(P_{s,a,m,t}^{k2}, 0)}{\eta_{dis}^{k2}} \right) \cdot \Delta t, \quad (24)$$

$$\varphi_{\min}^{k2} \cdot W_{s,a}^{k2} \leq W_{s,m,a,t}^{k2} \leq \varphi_{\max}^{k2} \cdot W_{s,a}^{k2}, \quad (25)$$

$$-P_{\max}^{k2} \leq P_{s,m,a,t}^{k2} \leq P_{\max}^{k2}, \quad (26)$$

$$W_{s,a,m,24}^{k2} = W_{s,a,m,0}^{k2} \quad (27)$$

where k_2 is the type of energy storage device in the IPIES; $W_{s,a,m,t}^{k2}$ is the stored energy of energy storage device k_2 at typical day m , time t in stage a under scenario s ; μ_{loss}^{k2} is the self-consumption rate of the energy storage device, k_2 ; η_{ch}^{k2} and η_{dis}^{k2} are the charging efficiency and discharging efficiency of the

energy storage device k_2 , respectively; Δt is the unit scheduling time; $\varphi_{\max}^{k_2}$ and $\varphi_{\min}^{k_2}$ are the upper and lower limit coefficients, respectively, of the energy storage device, k_2 , energy stored; $P_{\max}^{k_2}$ is the upper limit of the switching power of energy storage device k_2 , related to the converter device. In order to achieve continuous scheduling, constrained energy storage stores the same energy at the beginning and end of the day.

2.3. Regret Aversion Layer

2.3.1. Optimal Alternative Schemes

The regret aversion layer can be divided into two parts: Optimal alternative schemes calculation and regret aversion optimization. The optimal alternative schemes part uses the expansion planning layer model, with the comprehensive cost in Equation (2) being lowest as the objective function, and Equations (3)–(27) as the constraint. The comprehensive costs C_s^{COM} under all natural gas price fluctuation scenarios, $s \in S$, are calculated as well as the corresponding optimal alternative schemes, ω_s , and operational plans, $\tau_s^{\omega_s}$. The calculated C_s^{COM} will then be substituted as a known parameter into the evasive optimization part.

2.3.2. Regret Aversion Optimization

In response to the regret resulting from the fact that decision-makers did not choose a better expansion planning scheme, the additional aggregate comprehensive cost was chosen as the regret value: In view of the regret aversion optimization part, the decision-maker selects the additional comprehensive cost as the regret value:

$$C_s^{REG}(\omega, \tau_s^\omega) = C_s^{COM}(\omega, \tau_s^\omega) - C_s^{COM}(\omega_s, \tau_s^{\omega_s}), \quad (28)$$

where $C_s^{REG}(\omega, \tau_s^\omega)$ is the regret value of the expansion planning scheme, ω , under scenario s ; τ_s^ω is the typical daily operation plans based on scheme ω under scenario s ; $C_s^{COM}(\omega, \tau_s^\omega)$ is the comprehensive cost of the scheme, ω , and operation plans, τ_s^ω , which is obtained during the expansion planning layer; and $C_s^{COM}(\omega_s, \tau_s^{\omega_s})$ is the lowest comprehensive cost under scenario s , which is obtained in the optimal alternative schemes part.

We used the minimum–maximum regret value under all natural gas price fluctuation scenarios considering the distribution of the scenarios as an objective to control the regret risk of the IPIES expansion planning scheme, ω , under different natural gas price fluctuation scenarios:

$$\min_{s \in S} \max \pi^s \cdot C_s^{REG}(\omega, \tau_s^\omega). \quad (29)$$

Further, the minimum–maximum regret aversion objective can be considered together with the minimum objective of the average comprehensive cost. As the optimal comprehensive cost in each scenario is known, the average regret value is equivalent to the objective of the minimum expected comprehensive cost. The objective function of the expansion planning method of the IPIES is finally constructed as:

$$\min C^{CRE}(\omega, \tau_s^\omega), \quad (30)$$

$$C^{CRE}(\omega, \tau_s^\omega) = \alpha \cdot \max_{s \in S} \pi^s \cdot C_s^{REG}(\omega, \tau_s^\omega) + \beta \cdot \sum_{s \in S} \pi^s \cdot C_s^{COM}(\omega, \tau_s^\omega), \quad (31)$$

where $C^{CRE}(\omega, \tau_s^\omega)$ is the comprehensive regret value; α and β is the weight coefficient of the minimum–maximum regret aversion objective and the minimum average regret objective, and $\alpha + \beta = 1$. When α is taken as 1, Equation (30) is equivalent to Equation (29).

The proposed method of regret aversion optimization uses Equation (30) as the objective function and Equations (2)–(28) as the constraint condition to optimize the multi-stage expansion

planning scheme of IPIES and the typical daily operation plans under multiple natural gas price fluctuation scenarios.

2.4. Method Solution

The expansion planning method of IPIES considering regret aversion proposed in this paper is a mixed integer nonlinear programming model. Considering the variables and constraints of the model, mathematical modeling was performed on the MATLAB platform through the YALMIP toolbox, and the commercial optimization solver GUROBI was used to solve the model. The model solution environment for this article was: Intel Core 2 Duo P8600 CPU; 6 GB memory; software version: MATLAB R2014A; YALMIP R20180612; GUROBI 8.1.

3. Case Study

3.1. Basic Data

Taking an economic and technological development zone that includes more than 3000 industrial enterprises in Zhejiang province in southeastern China as the case study, the planned total operating life of the IPIES is 15 years, and every 5 years is an expansion planning stage. The typical days of the industrial park can be divided into summer, winter, and ordinary days. The number of days in the whole year is 100, 60, and 200 days. There is cold load demand in summer and heat load demand in winter. There is no gas load demand. The garment industry and beverage processing industry in the park have steam demand. The typical daily energy load curve and PV output curve of the park are shown in Figures 4 and 5, respectively. In addition, consider an extreme scenario where PV units do not output power in a typical summer day. According to the high growth forecast of the park, the sustained load of the three extended planning stages is 150%, 200%, and 250% of the current load. The current electric, steam, and natural gas prices in the park are shown in Table 1. Considering the continuous advancement of China oil and gas marketization reform, referring to Figure 3, it is assumed that the future natural gas price may fluctuate by up to 50% compared with the current price, which has uniform distribution characteristics, corresponding to nine natural gas price fluctuation scenarios with the same probability: (S1) 100%-150%-150%; (S2) 100%-150%-100%; (S3) 100%-150%-50%; (S4) 100%-100%-150%; (S5) 100%-100%-100%; (S6) 100%-100%-50%; (S7) 100%-50%-150%; (S8) 100%-50%-100%; and (S9) 100%-50%-50%.

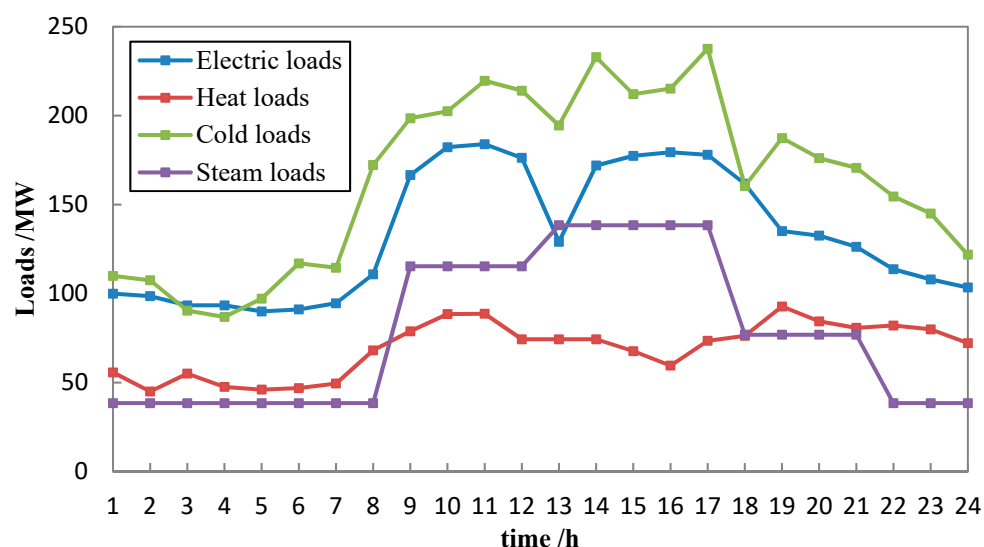


Figure 4. Typical daily electricity, steam, cold, and heat load curves.

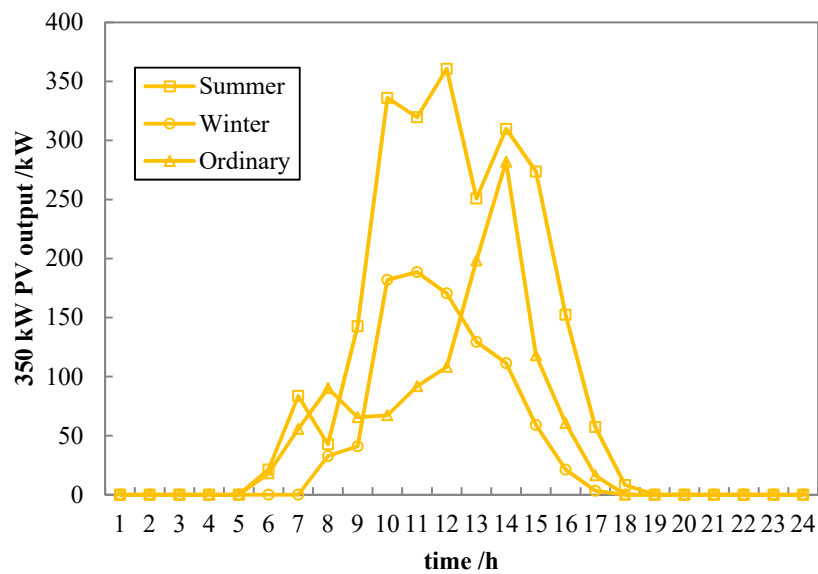


Figure 5. Typical daily 350-kW photovoltaic output curve.

Table 1. Energy peak, normal, and valley prices.

Energy Style	Unit	Peak Time	Normal Time	Vally Time
		19:00–21:00	8:00–11:00 13:00–19:00	00:00–8:00 11:00–13:00 22:00–00:00
electric	yuan/kWh	1.3097	1.0047	0.4817
gas	yuan/kWh	0.353	0.353	0.353
steam	yuan/kWh	0.312	0.312	0.312

The approximate IPIES device operating parameters, unit construction costs, and operation and maintenance costs are shown in Table 2 [44–47]. The relevant parameters of the energy storage device are shown in Table 3 [33,44,47]. The upper limits of the interaction power between the park and the grid and steam network are related to the network capacity, and they are 280 and 192.25 MW (250 T/h), respectively. The system does not output energy to the external network; that is, the lower limit of interaction between each network is 0. The minimum power factor of each device is 0. The power system in the park can be expanded to 35 MW, and the expansion cost is 5 million yuan. The environmental protection costs of electricity, natural gas, and steam using kWh energy per unit in the park are 0.07, 0.01, and 0.04 yuan/kWh, respectively [44,45]. The annual discount rate of the park is 5%, the low heat value of steam is 769 kWh/T, and the low heat value of natural gas is 9.9 kWh/m³.

Table 2. Device parameters of IPIES.

Device Style	Operating Efficiency	Unit Construction Cost (Yuan/kW)	Unit Maintenance Cost (Yuan/kWh)	Price Correction Coefficient	Critical Price Reduction Factor	Serve Years (A)
PV	-	9000	0.04	−5%	−50%	>15
CHP	Gas-electric: 0.3 Gas-steam: 0.45	6500	0.05	−5%	−50%	>15
GB	0.85	700	0.02	−3%	−20%	>15
EB	0.95	900	0.01	−3%	−20%	>15
HP	3	1000	0.01	−3%	−20%	>15
EC	4.5	1000	0.01	−3%	−20%	>15
HC	0.89	150	0.01	−2%	−10%	>15
AC	1.2	1100	0.01	−3%	−20%	>15
BAT	-	-	0.01	−10%	−80%	10
HS	-	-	0.02	−5%	−50%	>15
CS	-	-	0.02	−5%	−50%	>15

Table 3. Parameters of energy storage.

Energy Storage Style	Unit Construction Cost/yuan/kWh	Self-Consumption Rate	Charging/Discharging Efficiency	Upper/Lower Limit Coefficients	Upper Limit of the Switching Power/MW
BAT	1000	0.001	0.95/0.9	0.95/0.2	10
HS	100	0.01	0.9/0.9	1/0	10
CS	150	0.01	0.85/0.85	1/0	10

3.2. Results and Analysis

The optimized IPIES expansion planning scheme, which takes α as 0.5, is shown in Table 4. The regret value and cost of the scheme under different natural gas price fluctuation scenarios are shown in Tables 5 and 6, respectively.

Table 4. The IPIES expansion planning scheme considering regret aversion.

Capacity	PV	CHP	GB	EB	HP	EC	HC	AC	BAT	HS	CS	I
Capacity in stage 1/MW	426.15	129.43	0	39.96	77.63	126.47	68.79	37.93	44.11	8.50	426.15	0
Capacity in stage 2/MW	536.87	205.09	6.13	59.00	103.51	184.43	143.84	104.32	61.14	11.88	536.87	1
Capacity in stage 3/MW	536.87	224.06	6.13	61.97	122.01	191.41	143.84	104.32	61.14	11.88	536.87	1

Table 5. Regrets under multiple natural gas price fluctuation scenarios.

Values	S1	S2	S3	S4	S5	S6	S7	S8	S9
Regret value/ 10^6	252.19	161.07	185.70	65.47	13.97	80.32	69.49	50.09	347.41
Comprehensive regret value/ 10^6					87.40				
Maximum regret value with distribution/ 10^6					38.60				
Average regret value/ 10^6					136.19				

Table 6. Costs under multiple natural gas price fluctuation scenarios.

Case1	S1	S2	S3	S4	S5	S6	S7	S8	S9
construction cost/ 10^9 yuan					5.81				
operation cost/ 10^9 yuan	19.49	18.49	16.81	18.64	17.65	15.97	16.97	15.98	14.30
maintenance cost/ 10^9 yuan	0.57	0.62	0.70	0.64	0.70	0.77	0.72	0.78	0.85
environmental protection cost/ 10^9 yuan	1.54	1.44	1.32	1.40	1.30	1.18	1.28	1.18	1.06
comprehensive cost/ 10^9 yuan	27.41	26.36	24.64	26.50	25.46	23.74	24.80	23.75	22.03
Average comprehensive cost/ 10^9 yuan					24.97				

As seen from the expansion planning scheme in Table 4, with an increase in the load level of the park, the capacity of most energy conversion devices in the system expands. Due to the dynamic changes in the price of the system device, and the unpredictable fluctuations in the system's natural gas price from the second phase, the device capacity increase between stages 1 and 2 is greater than that between stages 2 and 3.

The PV in the system uses renewable energy and has excellent economic benefits with the most installed capacity. The CHP is the main natural gas drive device in the IPIES. At the current natural gas price, the CHP has a certain economic advantage over the grid peak hour electricity price and normal electricity price. However, in the case of natural gas price fluctuations, this situation will change. Figure 6 shows the system energy purchases of stage 2 under the scenarios of different natural gas price fluctuations. It can be seen that, when the price of natural gas rises by 50%, the purchase of natural gas in the system decreases, and the purchase of electric and steam increases. When the price of natural gas drops by 50%, the purchase of natural gas in the system increases, and the purchase of electric and steam declined, with the purchase of steam almost falling to zero.

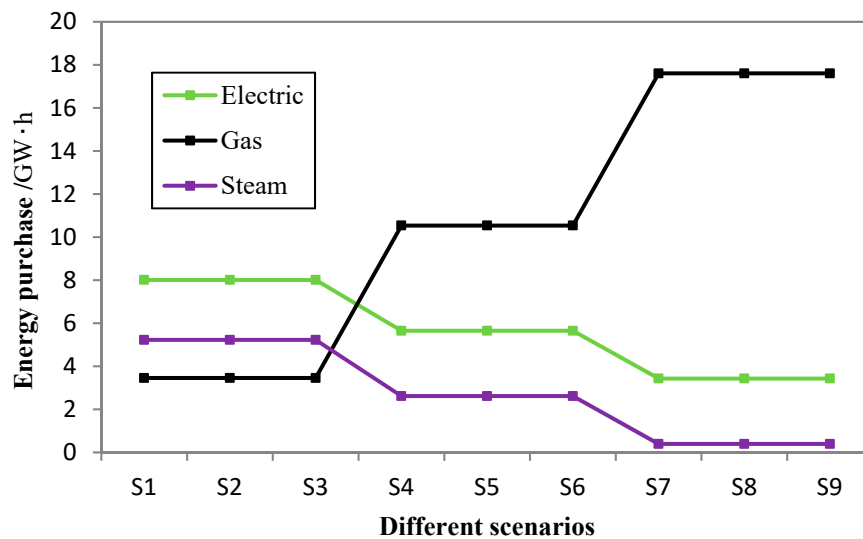


Figure 6. Stage 2 energy purchase situation under different scenarios.

As the system is connected to an external steam network, the role of the GB in supplementing the electro-thermal ratio is replaced to some extent, with fewer configurations in the system. The EB works only at the peak of the PV output, making full use of the electric energy generated by the PV and making up for the lack of steam energy caused by the reduction of the power of the CHP. Heat storage stores energy when the load demand is low and discharges it when the load demand is high. The BAT can store energy in the electricity price valley, and the energy can be released at the peak and normal time to achieve the peaking and filling of the load and the economic improvement of the system.

The absorption capacity of the AC and HC in the IPIES is matched with the CHP. It can be seen from Figure 7a that, in the normal output power of the PV, the CHP reduces the output power to make full use of the renewable energy, and the cooling power in the system is mainly provided by the EC. As the PV output power decreases after 14:00, the output power of the CHP increases, and the output cooling power of the AC increases. When entering the electricity price valley at 22:00, the system energy supply turns to the grid and the output power of the EC rises again. In the case of unexpected failure of the photovoltaic unit, the daily load needs to be supplemented by the CHP. At the same time, the output of the EC will rise when the electricity price valley is between 11:00 and 13:00, and the output of the CHP and the AC will decrease.

Comparing Figure 7a,b, it can be seen that in order to ensure the user's energy demand, the system often needs to configure other backup devices to prevent the renewable sources from fluctuating or even zero output, causing the load shedding. Thus, although photovoltaic units have high economic benefits, there are certain restrictions on the permeability of renewable energy in the system. It is necessary to consider the extreme output scenarios of some renewable energy units in the planning process to optimize the capacity of the units and other related units to ensure the safe and economic operation of the system.

Tables 5 and 6 show the regret value and cost of the plan in different natural gas price scenarios, respectively. The planning scheme has a large regret value under scenario 1 and scenario 9, and the regret value of scenario 5 is the smallest. Comparing Table 4 and optimal alternative schemes' typical device planning in stage 3 under scenarios 1, 5, and 9 in Table 7, it can be seen that the high or low natural gas price in scenario 1 and scenario 9 leads to the significant difference in the configuration capacity of the equipment between the schemes, and further causes the actual planning scheme not to match the optimal alternative, resulting in an increase in regret value.

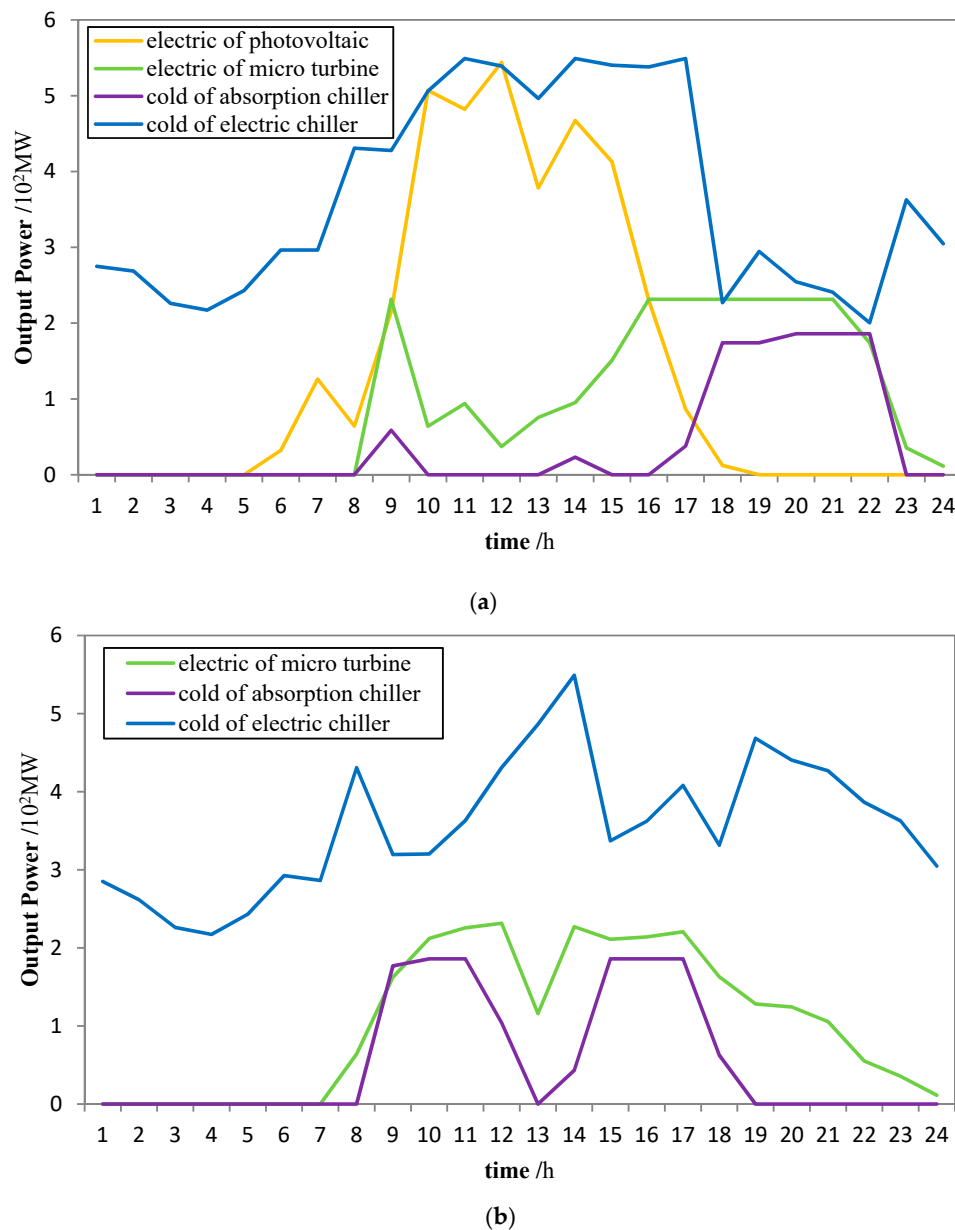


Figure 7. Summer typical day partial devices output power in stage 3 under scenario 5: (a) Typical device output power; (b) Typical device output power when the PV output is 0.

Table 7. Optimal alternative schemes' typical device planning in stage 3 under scenarios 1, 5, and 9.

Scenario	PV/MW	CHP/MW	EB/MW	HC/MW	AC/MW
1	692.21	205.80	253.37	93.29	183.70
5	536.87	220.51	93.31	181.54	128.52
9	355.05	296.35	33.86	242.28	246.23

The cost difference between the different scenarios of the planning scheme is mainly due to the difference in operating costs. The overall energy consumption of scenario 1 is high, and the running cost is high. The overall energy consumption of scenario 9 is low, and the running cost is low. Because the energy demand of phase 3 is high, the high energy cost of phase 3 has a greater impact on the overall operating cost than phase 2, and the cost of scenario 7 is higher than that of scenario 3.

4. Discussion

To verify the effectiveness of the method, we considered three planning methods for comparison:

Case1: Expansion planning method that considers regret aversion proposed in this paper;

Case2: Expansion planning method based on the lowest expected cost; and

Case3: Expansion planning method that does not consider gas price fluctuations.

The regret value of the schemes obtained by different planning methods is shown in Figure 8. The typical device expansion planning of each scheme is shown in Table 8. The regret values under multiple scenarios with different planning methods are shown in Table 9.

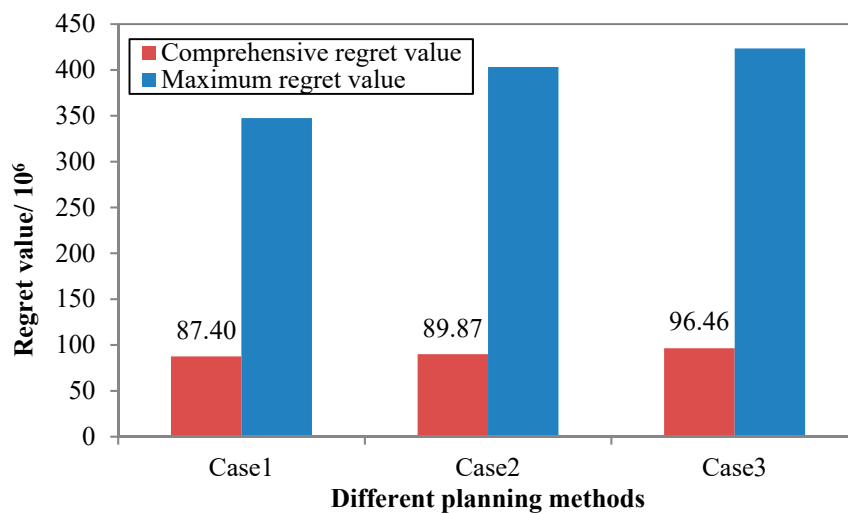


Figure 8. Regret value under different planning methods.

Table 8. Typical device expansion planning under different planning methods.

Cases	Stage	PV/MW	CHP/MW	GB/MW	EB/MW	HC/MW	AC/MW
case1	1	426.15	129.43	0	39.96	126.47	68.79
	2	536.87	205.09	6.13	59.00	184.43	143.84
	3	536.87	224.06	6.13	61.97	191.41	143.84
case2	1	426.15	129.43	0	91.13	126.47	68.79
	2	553.52	194.88	6.21	110.46	184.43	128.52
	3	553.52	220.51	6.21	110.46	184.43	128.52
case3	1	426.15	129.43	0	91.13	126.47	68.79
	2	536.87	184.56	0	93.31	181.54	113.04
	3	536.87	220.51	0	93.31	181.54	128.52

Table 9. Regret value under multiple scenarios with different planning methods.

Values	Cases	S1	S2	S3	S4	S5	S6	S7	S8	S9
Regret value/10 ⁶	Case 1	252.19	161.07	185.70	65.47	13.97	80.32	69.49	50.09	347.41
	Case 2	200.11	130.54	181.91	36.53	6.60	99.68	98.50	57.54	403.15
Comprehensive regret value/10 ⁶	Case 1					87.40				
	Case 2					89.87				
Maximum regret value with distribution/10 ⁶	Case 1					38.60				
	Case 2					44.80				
Average regret value/10 ⁶	Case 1					136.19				
	Case 2					134.95				

More PV units are deployed in the expansion plan with the lowest expected cost, showing the economic benefits of renewable energy in the system. However, in case 2 and case 3, the plan of

natural gas-related devices, such as combined heat and power (CHP), is insufficient, resulting in a large increase in regret when the price of natural gas is low. Compared to the extended planning method without consideration of the fluctuation of gas prices, the proposed method reduces the maximum regret value by 17.8% and reduces the comprehensive regret value by 9.4%.

Compared with the extended planning method based on the lowest expected cost, the method proposed in this paper has a lower regret value. The maximum regret value in case 1 is effectively constrained by the objective function. By introducing more natural gas equipment such as CHP, plan scheme in case 1 has better performance in scenario 6 to 9, especially in the worst scenario 9, but worse performance in scenario 1 to 5. The proposed method reduces the maximum regret value by 13.8% and reduces the comprehensive regret value by 2.7%. Although the average regret value increases by 0.92%, the reduction in the comprehensive regret value indicates that the benefit of controlling the maximum regret value exceeds the control of the average regret value under the decision-maker's risk control requirement.

Further considering the influence of the minimum maximum regret aversion weight coefficient, which represents the risk control requirement of the decision maker, the reduction of comprehensive regret value between case 1 and case 2 can be calculated as:

$$\frac{CCRE(\omega_2, \tau_s^{\omega_2}) - CCRE(\omega_1, \tau_s^{\omega_1})}{CCRE(\omega_2, \tau_s^{\omega_2})}, \quad (32)$$

where ω_1, ω_2 is the plan scheme in case 1 and case 2, respectively

The comprehensive regret reduction between case 1 and case 2 under different minimum–maximum regret aversion objective weights, α , are shown in Figure 9. It can be seen from Figure 9 that when the range of α is changed from 0.1 to 0.9, the comprehensive regret reduction rises, which indicates that with the increase of the decision-makers' requirement for maximum regret risk control, the planning method proposed is better than traditional method based on the lowest expected cost, making the plan more adaptive when faced with uncertain natural gas prices. If the decision makers have low demand for risk control, the planning method proposed is similar to the traditional method but still provides a little reduction in the comprehensive regret value. It shows that in the industrial park integrated energy system expansion plan, due consideration is given to the regret aversion factor, which can effectively control the regret risk of system planning decisions, and make the plan more adaptive when faced with uncertain natural gas prices.

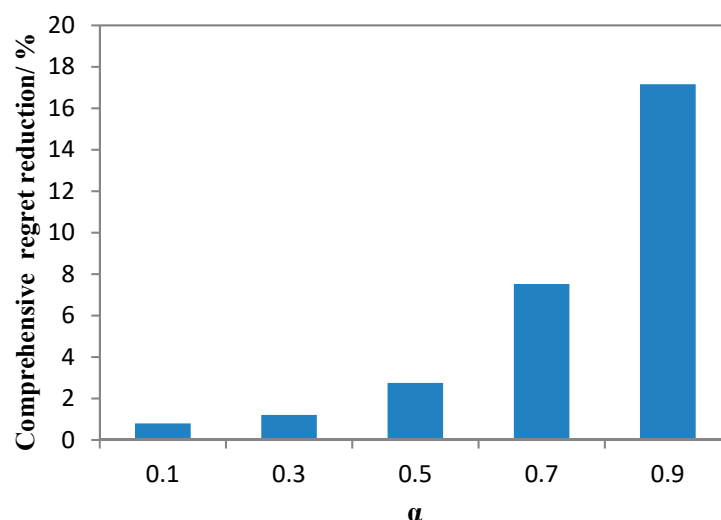


Figure 9. Comprehensive regret reduction between case1 and case 2 under different minimum–maximum regret aversion objective weights, α .

However, the model is relatively simple while the transmission loss of the power grid, gas network, and steam network were entirely neglected in the paper. The theory of how the regret value and expansion plan is affected by load growth expectation was also not put forward in this paper.

5. Conclusions

This paper proposed an expansion planning method for the industrial park integrated energy systems considering regret aversion. Based on the min–max regret aversion and the lowest average regret value, the method optimized the comprehensive cost of an expansion planning scheme in an IPIES under different natural gas price fluctuation scenarios, including costs of construction, operation and maintenance, and environmental protection. The example verifies the rationality and effectiveness of the proposed method. The optimized industrial park integrated energy system expansion plan greatly reduces the degree of decision-making regret and reduces the system cost compared with the traditional expansion plan, which does not consider natural gas price fluctuation. Compared with the expansion plan based on the lowest expected cost, it also effectively controls the system's decision-making regret risk. At the same time, the simulation results show that natural gas price fluctuations have a greater impact on system planning and operation.

With the deepening of the national power system reform, multi-regional integrated energy system collaborative planning and multi-subject integrated energy system planning and operation game theory will be the focus of future research.

Author Contributions: H.X. conceived the main idea and wrote the manuscript with guidance from Q.L., and L.L., who reviewed the work and gave helpful improvement suggestions. P.Z. and X.J. managed the project and provided case data.

Funding: This work was supported by the Science and Technology Project of the State Grid Corporation of China (No. SGZJWZ00FZJS1901007).

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Acronyms

IPIES	Industrial park integrated energy system
EH	Energy hub
CHP	Combined heat and power
CCHP	Combined cooling, heat and power
PV	Photovoltaic
EB	Electric boiler
GB	Gas boiler
HP	Heat pump
EC	Electric chiller
HC	Heat exchanger
AC	Absorption chiller
BAT	Battery
HS	Steam heat storage
CS	Cold energy storage

Symbols and matrix

s	Type of natural gas price fluctuation scenario
m	Type of typical day scenario
k	Type of device in IPIES
k_1	Type of device except for energy storage in IPIES
k_2	Type of energy storage device in IPIES
a	Planning stage
y	year
t	Time

ω	Expansion planning scheme
τ_s^ω	Operational plans based on ω under scenario s
ω_s	Optimal alternative scheme under scenario s
$\tau_s^{\omega_s}$	Operational plans based on ω_s under scenario s
S	Matrix of the natural gas price fluctuation scenario
$c_a^{I,k}$	unit construction cost matrix of device at stage a
$W_{s,a}^k$	Capacity matrix of device at stage a under scenario s
$c_{M,k1}^{I,k1}$	Unit maintenance cost matrix of the device except for energy storage in IPIES
$Q_{s,a,m,t}^{k1}$	Operating power matrix of device except for energy storage in IPIES
Variables	
Y	Operating period of the IPIES
T	The years in a planning stage
M	Total number of typical day scenario
D_m	Days of typical day scenario a whole year
g_k	Price correction coefficient of the device k
g_k^c	Critical price reduction factor of the device k
$c_y^{I,k}$	Construction price of the device k in year y
η	Amplitude of the natural gas price fluctuation
π^s	Scenario probability of the natural gas price fluctuation
C_s^{COM}	Comprehensive cost of IPIES under natural gas price fluctuation s
C_s^I	Construction cost
C_s^O	Operation cost
C_s^M	Maintenance cost
C_s^{ENV}	Environmental protection cost
δ_y	Discount rate of year y
λ	Annual discount rate
I_a^{des}	0–1 mark for power transmission expansion status in stage a
c_t^E	Electricity price at time t
c_a^G	Price for unit kW·h energy natural gas in stage a under scenario s
c^S	Price for unit kW·h energy steam
$p_{s,a,m,t}^{SYS}$	Electric power interact with the power grid at typical day m , time t in stage a under scenario s
$G_{s,a,m,t}^{SYS}$	Gas power interact with the gas network at typical day m , time t in stage a under scenario s
$S_{s,a,m,t}^{SYS}$	Steam power interact with the gas network at typical day m , time t in stage a under scenario s
$c_{M,k2}^{I,k2}$	Unit maintenance cost of energy storage device k_2
$p_{s,a,m,t}^{BAT}$	Power exchange of BAT at typical day m , time t in stage a under scenario s
$S_{s,a,m,t}^{HS}$	Power exchange of HS at typical day m , time t in stage a under scenario s
$C_{s,a,m,t}^{CS}$	Power exchange of CS at typical day m , time t in stage a under scenario s
$\gamma^E, \gamma^G, \gamma^S$	Environmental cost of emissions from unit electricity, gas, and steam power, respectively
$W_{s,a}^k$	Capacity of the device k in stage a under scenario s
$W_{s,a}^{k,out}$	Capacity of device k to be decommissioned at stage a under scenario s
n_k	Number of planned stages that device k can serve
$P_{s,a,m,t}^{k1}$	Electric power output or consumed by device k_1 at typical day m , time t in stage a under scenario s
$S_{s,a,m,t}^{k1}$	Steam power output or consumed by device k_1 at typical day m , time t in stage a under scenario s
$H_{s,a,m,t}^{k1}$	Heat power output by device k_1 at typical day m , time t in stage a under scenario s
$C_{s,a,m,t}^{k1}$	Cold power output by device k_1 at typical day m , time t in stage a under scenario s
$G_{s,a,m,t}^{k1}$	Gas power consumed by device k_1 at typical day m , time t in stage a under scenario s
$p_{s,a,m,t}^{LD}$	Electric power loads at typical day m , time t in stage a under scenario s
$S_{s,a,m,t}^{LD}$	Steam power loads at typical day m , time t in stage a under scenario s
$H_{s,a,m,t}^{LD}$	Heat power loads at typical day m , time t in stage a under scenario s
$C_{s,a,m,t}^{LD}$	Cold power loads at typical day m , time t in stage a under scenario s
$G_{s,a,m,t}^{LD}$	Gas power loads at typical day m , time t in stage a under scenario s
p_{max}^{SYS}	Upper limit of the interaction power between the IPIES and power grid

p_{\min}^{SYS}	Lower limit of the interaction power between the IPIES and power grid
G_{\max}^{SYS}	Upper limit of the interaction power between the IPIES and gas network
G_{\min}^{SYS}	Lower limit of the interaction power between the IPIES and gas network
S_{\max}^{SYS}	Upper limit of the interaction power between the IPIES and steam network
S_{\min}^{SYS}	Lower limit of the interaction power between the IPIES and steam network
P_0	Capacity for power transmission expansion
$Q_{s,a,m,t}^{k1,in}$	Input power of device k_1 at typical day m , time t in stage a under scenario s
$Q_{s,a,m,t}^{k1,out}$	Output power of device k_1 at typical day m , time t in stage a under scenario s
η^{k1}	Operating efficiency of the device k_1
ϵ_{\min}^{k1}	Lowest power factor of the device k_1
$W_{s,a,m,t}^{k2}$	Stored energy of energy storage device k_2 at typical day m , time t in stage a under scenario s
μ_{loss}^{k2}	Self-consumption rate of energy storage device k_2
$\eta_{ch}^{k2}, \eta_{dis}^{k2}$	Charging efficiency and discharging efficiency of energy storage device k_2 , respectively
Δt	Unit scheduling time
$\varphi_{\max}^{k2}, \varphi_{\min}^{k2}$	Upper and lower limit coefficients of energy storage device k_2 , respectively
P_{\max}^{k2}	Upper limit of the switching power of energy storage device k_2
$C_s^{REG}(\omega, \tau_s^\omega)$	Regret value of the based on ω and τ_s^ω under scenario s
$C_s^{COM}(\omega, \tau_s^\omega)$	Comprehensive cost based on ω and τ_s^ω under scenario s
$C_s^{COM}(\omega_s, \tau_s^{\omega_s})$	Lowest comprehensive cost based on ω_s and $\tau_s^{\omega_s}$ under scenario s
$C^{REG}(\omega, \tau_s^\omega)$	Comprehensive regret value of the based on ω and τ_s^ω under scenario s
α	Weight coefficient of the minimum–maximum regret aversion objective
β	Weight coefficient of the minimum average regret objective

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