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Investment Strategy and Benefit Analysis of Power and Heat Hybrid Energy Storage in Industrial Parks Based on Energy Performance Contracting

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Abstract: To solve the problems of a single mode of energy supply and high energy cost in the park, the investment strategy of power and heat hybrid energy storage in the park based on contract energy management is proposed. Firstly, the concept of energy performance contracting (EPC) and the advantages and disadvantages of its main modes are analyzed, and the basic scheme of EPC for parks is proposed combined with the actual demand. Furthermore, the multiple energy storage model for power and heat storage in parks is established, which includes lithium batteries and heat storage tanks. Based on this, minimizing the annual operation cost of parks is taken as the optimization goal, and the capacity optimization model for power and heat storage is constructed, which considers the investment costs, operation and maintenance costs, purchased energy costs, peak-shaving subsidy, and environmental subsidy. Finally, an industrial park is selected as an example of EPC to verify the effectiveness of our proposed investment strategy. The results show that compared with the situation before the energy-saving renovation, the park can save 35.14 ten thousand CNY in annual cost expenses. When the unit power price of the lithium battery exceeds 3900 CNY/kW, the unit capacity price exceeds 5460 CNY/kWh, the unit power price of the heat storage tank (HST) exceeds 6000 CNY/kW, and the unit capacity price exceeds 1000 CNY/kWh, the configuration of the lithium battery and HST in the park is no longer the optimal choice to perform the energy-saving renovation.

Keywords: energy performance contracting; energy service company; energy-saving renovation; energy storage investment; power and heat hybrid energy storage

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1. Introduction

Currently, energy performance contracting (EPC) has become an effective way to improve the efficiency of energy use in China [1]. Among the many modes of EPC, the shared saving model has been widely adopted. Under this mode, the energy service company (ESCO) takes the initiative to undertake all (or most) of the capital investment for the energy-saving improvement of the project and is responsible for the implementation and management of the whole project [2]. The energy-saving benefits generated from the energy-saving renovation project are shared by the ESCO and the energy users during the contract period. Since this mode can well stimulate the enthusiasm of users who lack sufficient funds for energy-saving renovation and mature energy-saving technologies, this mode has been widely promoted [3,4].

1.1. Literature Review

At present, the research related to EPC has been relatively mature, mainly focusing on the application of EPC [5–7], the main influencing factors of EPC [8–11], and the analysis of the benefits of EPC and its allocation methods [12,13]. The literature [5–7] focused on the application of EPC in developing countries, and the study showed that the application of EPC can effectively improve the energy utilization rate. The literature [8] analyzed the main factors affecting the application of an EPC business model, pointing out that the most significant factor is the degree of understanding of the model on the demand side. The literature [9] studied the implementation process of EPC, and the study showed that improving the management chain can effectively stimulate the incentive mechanism of both sides, promoting the effective utilization of energy and cooperation between the two sides. The literature [10] pointed out that the size of the benefits of EPC depends on the perfection of the financing mechanism. The literature [11] took the Russian energy market as the object and made a risk prediction on the multiple factors affecting EPC, and the results showed that the risks from finance and regulation are most likely to affect the EPC program. The literature [12] analyzed the benefits of EPC companies by integrating policies related to the development of EPC marketization. The literature [13] analyzed the distribution of energy-saving benefits in the EPC projects based on a shared saving model by using Rubinstein's bargaining game theory. In summary, EPC has been applied in many industries more maturely, but the application of EPC in the power industry is still in its initial stage.

The earliest practice of EPC in China originated from the "China Energy Conservation Promotion Project" jointly implemented by the Chinese government, the World Bank, and the Global Environment Facility in 1997 [14,15]. To accomplish this project, three ESCOs were set up in Beijing, Liaoning, and Shandong provinces to implement EPC projects in the fields of textile, machinery, light industry, power, building materials, metallurgy, chemical industry, papermaking, and other industries. At present, EPC is often applied to projects such as building energy efficiency, green lighting, boiler retrofitting, and industrial waste energy recovery [15].

ESCOs can provide a wide variety of energy-saving services based on their characteristics as well as provide space for the implementation of EPC mechanisms. According to statistics, the number of companies engaged in energy-saving service business in China reached 11,835 by 2022 [16]. Under the fierce competition in the market environment, energy-saving service companies are mainly categorized into service-oriented ESCOs, technology-oriented ESCOs, and companies affiliated with public utilities [16,17].

The core of EPC is to improve the efficiency of using energy so that the ESCO and energy users can both obtain benefits. Energy storage has good energy time-shift characteristics, which can effectively meet the energy demand in different periods. It is an important way to ensure the profitability of a contracted energy management program. However, there are many difficulties in the existing energy storage investment projects, which seriously lag behind the development of energy storage [18–20]. Among them, the realization of the optimal allocation of energy storage is one of the key issues that needs to be resolved first and foremost, and it is also a prerequisite for the realization of large-scale investment in energy storage [21–23].

For the optimal configuration of energy storage, scholars at home and abroad have carried out several studies. The literature [24] proposed a resilience-oriented planning method for the optimal configuration of distribution multi-energy systems by integrating multiple types of energy storage resources into generalized energy storage resources. The literature [25] compared the advantages of different approaches to the configuration of energy storage system capacity and proposed an optimal capacity configuration of a hybrid energy storage system based on an improved moving average and ensemble empirical mode decomposition method. The literature [26] considered the lifetime of the energy storage equipment and presented a new home energy storage system configuration scheme based on lithium-ion batteries. Based on the battery life loss model, a two-layer optimization model of electric/thermal hybrid energy storage capacity was constructed for the integrated energy system in the park in the literature [27]. The literature [28] took the multi-energy microgrid containing wind power generation and power/heat/gas loads as the research object and proposed an optimal configuration method of multiple energy storage systems for micro-energy networks considering coupled electricity/heat/gas demand response.

To support the development and application of energy storage, both domestic and foreign countries have formulated a series of policies for energy storage [29–32]. Taking China as an example, in July 2021, the National Development and Reform Commission (NDRC) and the Energy Bureau (EB) of China issued the "Guiding Opinions on Accelerating the Development of New Energy Storage", proposing that by 2025, new energy storage will be transformed from the early stage of commercialization to large-scale development with an installed capacity of more than 30 million kW [30]. Since then, the provincial "14th Five-Year Plan" has been introduced, and more than 20 provinces and municipalities set the "14th Five-Year Plan" period of new energy storage development goals, the total development scale of more than 6000 kW, including Shanxi, Hebei, Shandong, Gansu, Qinghai, and Ningxia province. In March 2022, the NDRC and EB issued the "Modern energy system planning for the 14th five-year plan", proposing to carry out new energy storage key technologies to focus on research, accelerate the realization of the autonomy of the core technology of energy storage, and promote the continuous decline in the cost of energy storage and its application at scale [31]. Then, in June 2022, the NDRC and EB further issued the "Notice on Further Promoting the Participation of New-type Energy Storage in the Electricity Market and Dispatching Application", which stated that independent energy storage power stations that send power to the grid, and the corresponding charging power, will not be subject to transmission and distribution tariffs and governmental funds and surcharges [32].

From the above studies, we can summarize the following problems. Firstly, there are fewer studies on the application of EPC in the power industry, especially for energy-saving renovation in the industrial park. Secondly, the studies on energy storage investment are mainly focused on the technical level, not combined with the energy-saving renovation in the industrial park. Moreover, with the increasing heat demand in the industrial park, the application of heat storage equipment is also more and more crucial, and the joint optimization of power storage and heat storage configuration is particularly important.

1.2. Aims and Contributions

To address the above challenges, this paper proposes an investment strategy for power and heat hybrid energy storage in parks based on EPC. Firstly, the concept of EPC is introduced and combined with practical problems to put forward the basic scheme of energy-saving renovation in the park. Secondly, the model of power and heat hybrid energy storage in the park containing lithium batteries and heat storage tanks is established. Then, a power and heat energy storage investment optimization model aimed at minimizing the annual operation cost of the park is constructed. Finally, taking the EPC project of an industrial park as an example, the benefits that can be obtained by the park and the ESCO are analyzed, as well as the influence of the energy storage price on the results of the energy storage allocation and the economy of the EPC project.

The contributions of this paper are as follows:

1. This study first closely combines EPC with energy-saving renovation and energy storage investment in the industrial park. By utilizing the good energy time-shift characteristics of energy storage, we can achieve the purpose of energy saving.
2. This study considers the joint optimization configuration of power storage and heat storage, facilitating the application of heat storage in the industrial park. In addition, the constructed optimization model considers the main costs and revenues of energy storage, thus enhancing the practicability of the model.
3. This study analyzes the revenue potential of energy-saving renovation and the benefits available to the energy users and ESCO in depth, together with the impact of the energy storage equipment price on the economy of energy-saving renovation projects, providing effective guidance for the investment decisions of the energy users.

2. Energy Performance Contracting (EPC)

2.1. Concept and Main Models of EPC

EPC is a new type of commercialized energy management operation, the essence of which is a kind of energy-saving service method that pays for the full cost of the energy-saving project and the benefits of the related parties with the reduced energy costs [33]. By signing energy-saving contracts, the ESCO provides users with the whole process of energy-saving services, including energy audits, the program design of energy-saving renovation, energy-saving project financing, and the procurement, monitoring, training, operation, and management of equipment [34]. In recent years, since EPC can promote the development of the energy-saving industry from the high-technology level, more and more industries have begun to introduce this specialized energy management service.

The main models of EPC can be divided into the following three types [35]:

(1) Guaranteed saving model

The guaranteed saving model refers to the EPC project invested in by the energy users and implemented by the ESCO, and the ESCO promises a certain percentage of energy savings. During the contract period, regardless of the actual energy savings generated by the EPC project, energy users will obtain the guaranteed energy savings. When the EPC project fails to meet the energy-saving standard guaranteed by the ESCO, the ESCO will pay the energy users for the shortfall in benefits.

(2) Energy-cost trust model

The energy-cost trust model is that the ESCO is responsible for the renovation of high energy-consuming equipment of energy users, as well as the operation and management of the renovated equipment and facilities. In addition, the ESCO is required to undertake energy costs and operating costs and promise to achieve the specified energy-saving effects. The energy-saving benefits generated by the energy-saving renovation and the benefits brought about by the improvement in the operation and management level are the sources of benefits shared by the energy users and the ESCO.

(3) Shared saving model

The shared saving model refers to the EPC program in which both partners share the energy-saving revenues according to a certain percentage in the contract. The EPC program is invested in by the energy users and implemented by the ESCO. At the termination of the EPC program, the energy users will own all the energy-saving facilities and alone enjoy the energy-saving benefits.

2.2. Description of Practical Problem

The main business of industrial park A is manufacturing, the working area includes industrial buildings, office buildings, and warehouses, with a total floor area of 10,000 square meters. Currently, the energy demand of industrial park A consists of power demand and heat demand, and the sources of energy are mainly from the power grid and heat network.

However, due to the peak prices of power and heat, the cost of energy consumption exceeds the expected expenses. As can be seen from Table 1, the average costs of purchasing power and heat in the three years are 243.85 and 155.82 ten thousand CNY. To reduce the cost of energy consumption, the ESCO called B is commissioned to upgrade and maintain the energy supply system of the park, and to build a specialized power and heat storage system for industrial park A. Note that the configuration heat storage can reduce the heat costs, but can also improve the flexibility of using heat, especially when the heat network has insufficient heat supply.

Table 1. Purchased energy costs of industrial park A from 2021–2023.

Year	Purchased Power Costs/Ten Thousand CNY	Purchased Heat Costs/Ten Thousand CNY
2021	223.14	141.61
2022	249.47	157.34
2023	258.93	168.52

Industrial park A commissions ESCO B to carry out the energy-saving renovation of the park's energy supply system. Industrial park A is responsible for all the costs of the project renovation, and ESCO B is responsible for the selection, installation, operation, and maintenance of the energy-saving equipment. Specifically, it includes the construction, operation, and maintenance of the power and heat storage systems, and the operation and maintenance of the power supply lines and heat supply pipelines. The invested energy storage equipment needs to be manufactured according to specifications, reliable, and durable. In terms of operation and maintenance, ESCO B should establish an operation and maintenance management system for power and heat storage equipment, including a duty operation and management plan, an inspection management system, an energy-saving operation plan, a safety management plan, and an equipment emergency plan.

The provision of an energy storage equipment guarantee and technician duty service must be strengthened during sensitive periods and special climates. ESCO B is responsible for carrying out free technical training once a year; the training content includes equipment structure, performance, operation, equipment maintenance, and other knowledge, and provides real-time fault acceptance service.

As the benefits and risks of the shared saving model are shared between the energy users and the ESCO jointly, this model is more widely used, and we also take this model as an example for this study. Specifically, industrial park A provides all the costs of the energy-saving renovation project, and ESCO B is responsible for the implementation of the energy-saving renovation project. When the energy-saving renovation is completed, all energy-saving facilities are owned by the industrial park. The energy-saving benefits in the life cycle of the equipment are shared by industrial park A and ESCO B in the proportion of k_1 and k_2, respectively. If the energy-saving benefits are negative, the loss will be undertaken by industrial park A and ESCO B in the proportion of k_1 and k_2.

3. Methods and Models

3.1. Modeling of Heat Storage System

Before the energy-saving renovation, the park meets its heat demand only by purchasing heat. The configuration of the heat storage system can not only meet the heat load demand of the park, but also improve the flexibility of heat consumption. Specifically, when the price of the heat supply is low, the heat load of the industrial park is satisfied directly through the heat network, and the heat storage tank (HST) starts to store heat at the same time. When the price of the heat supply is high, the HST releases heat to maintain the balance of the heat supply and demand in the system, and the shortfall is then satisfied by the purchased heat. The charging and discharging characteristics of the HST can be expressed by [36]

$$E_{\mathrm{HST},t} = E_{\mathrm{HST},t-1} + (\eta_{\mathrm{HST,C}} P_{\mathrm{HST,C},t} - \frac{P_{\mathrm{HST,D},t}}{\eta_{\mathrm{HST,D}}})\Delta t \quad (1)$$

where $E_{\mathrm{HST},t}$, $E_{\mathrm{HST},t-1}$ are the heat storage capacity of the HST during period t and $t-1$, respectively, $\eta_{\mathrm{HST,C}}$, $\eta_{\mathrm{HST,D}}$ are the heat storage efficiency and heat release efficiency of the HST, respectively, and $P_{\mathrm{HST,C},t}$, $P_{\mathrm{HST,D},t}$ are the heat storage power and heat release power of the HST during period t, respectively. Δt is the time step.

The operation of the HST needs to satisfy the following constraints [36]:

(1) Heat storage state of the HST.

$$\alpha_{\min} E_{\text{HST,Rate}} \leq E_{\text{HST},t} \leq \alpha_{\max} E_{\text{HST,Rate}} \quad (2)$$

where $\alpha_{\max}$, $\alpha_{\min}$ are the upper and lower limits of the heat storage proportion of the HST. $E_{\text{HST,Rate}}$ is the maximum heat storage capacity of the HST.

(2) Charging and discharging heat of the HST.

$$\begin{cases} 0 \leq P_{\text{HST,C},t} \leq U_{\text{HST,C},t} P_{\text{HST,Rate}} \\ 0 \leq P_{\text{HST,D},t} \leq U_{\text{HST,D},t} P_{\text{HST,Rate}} \\ U_{\text{HST,C},t} + U_{\text{HST,D},t} \leq 1 \end{cases} \quad (3)$$

where $P_{\text{HST,Rate}}$ is the rated power of the HST, $U_{\text{HST,C},t}$, $U_{\text{HST,D},t}$ are the heat storage and heat release state of the HST during period t, respectively, and they are 0–1 variables.

(3) Capacity and power ratio constraint of the HST.

The relationship between the rated capacity and the rated power of the HST can be expressed as

$$E_{\text{HST,Rate}} = \gamma_{\text{HST}} P_{\text{HST,Rate}} \quad (4)$$

where γ_{HST} is the energy rate of the HST.

3.2. Modeling of Power Storage System

Similar to the heat storage system, the power storage system significantly reduces the cost of power while meeting the power demand in the park through "charging at low load periods and discharging at high load periods". Lithium batteries have the advantages of small land area, low maintenance costs, long service life, and are easy to install in industrial parks. Hence, it is the preferred choice for the construction of power storage systems. The charging and discharging characteristics of lithium batteries can be described as [36]

$$E_{\text{Bat},t} = E_{\text{Bat},t-1} + (\eta_{\text{Bat,C}} P_{\text{Bat,C},t} - \frac{P_{\text{Bat,D},t}}{\eta_{\text{Bat,D}}})\Delta t \quad (5)$$

where $E_{\text{Bat},t}$, $E_{\text{Bat},t-1}$ are the storage power of the lithium battery during period t and $t-1$, respectively, $\eta_{\text{Bat,C}}$, $\eta_{\text{Bat,D}}$ are the charging efficiency and discharging efficiency of the lithium battery, respectively, and $P_{\text{Bat,C},t}$, $P_{\text{Bat,D},t}$ are the charging power and discharging power of the lithium battery during period t, respectively.

The following constraints need to be satisfied for the operation of the lithium battery [36]:

(1) Power storage state of the lithium battery.

$$\beta_{\min} E_{\text{Bat,Rate}} \leq E_{\text{Bat},t} \leq \beta_{\max} E_{\text{Bat,Rate}} \quad (6)$$

where $\beta_{\max}$, $\beta_{\min}$ are the upper and lower limits of the power storage proportion of the lithium battery, respectively, and $E_{\text{Bat,Rate}}$ is the maximum power storage capacity of the lithium battery.

(2) Charging and discharging power of the lithium battery.

$$\begin{cases} 0 \leq P_{\text{Bat,C},t} \leq U_{\text{Bat,C},t} P_{\text{Bat,Rate}} \\ 0 \leq P_{\text{Bat,D},t} \leq U_{\text{Bat,D},t} P_{\text{Bat,Rate}} \\ U_{\text{Bat,C},t} + U_{\text{Bat,D},t} \leq 1 \end{cases} \quad (7)$$

where $P_{\text{Bat,Rate}}$ is the rated power of the lithium battery, $U_{\text{Bat,C},t}$, $U_{\text{Bat,D},t}$ are the power storage and power release state of the lithium battery during period t, respectively, and they are 0–1 variables.

(3) Capacity and power ratio constraint of the lithium battery.

The relationship between the rated capacity and the rated power of the lithium battery can be expressed as

$$E_{\mathrm{Bat,Rate}} = \gamma_{\mathrm{Bat}} P_{\mathrm{Bat,Rate}} \tag{8}$$

where γ_{Bat} is the energy rate of the lithium battery.

3.3. Hybrid Energy Storage Capacity Optimization Model

3.3.1. Objective Function

In the energy supply system of industrial park A, the power and capacity of the lithium battery and HST are to be planned so that their annual operating costs during the operating period are minimized. At the same time, the time value of capital is considered, and all costs are normalized to equal annual values.

The expenditures of the energy-saving renovation project include the investment costs, operation and maintenance costs of the lithium battery and HST, and the costs of purchasing power from the external grid and heat network. The benefits obtained include the peak-shaving subsidy, environmental subsidy of the lithium battery, and the environmental subsidy of the HST. Residual value recovery and equipment loss are not considered. The annual operating costs of the park are provided in Figure 1 and can be expressed as

$$\min f = C - R \tag{9}$$

$$C = C_{\mathrm{HST}} + C_{\mathrm{Bat}} + C_{\mathrm{OM}} + C_{\mathrm{Buy,Ele}} + C_{\mathrm{Buy,Heat}} \tag{10}$$

$$R = R_{\mathrm{Sub,Peak}} + R_{\mathrm{Sub,Envi}} \tag{11}$$

where C_{HST}, C_{Bat}, C_{OM}, $C_{\mathrm{Buy,Ele}}$, and $C_{\mathrm{Buy,Heat}}$ are the annual investment costs of the HST, the annual investment costs of the lithium battery, the annual operation and maintenance costs of the HST and the lithium battery, the annual costs of purchasing power, and the annual costs of purchasing heat, respectively, and $R_{\mathrm{Sub,Peak}}$ and $R_{\mathrm{Sub,Envi}}$ are the annual peak-shaving subsidy of the lithium battery and the annual environmental subsidy of the lithium battery and the HST, respectively.

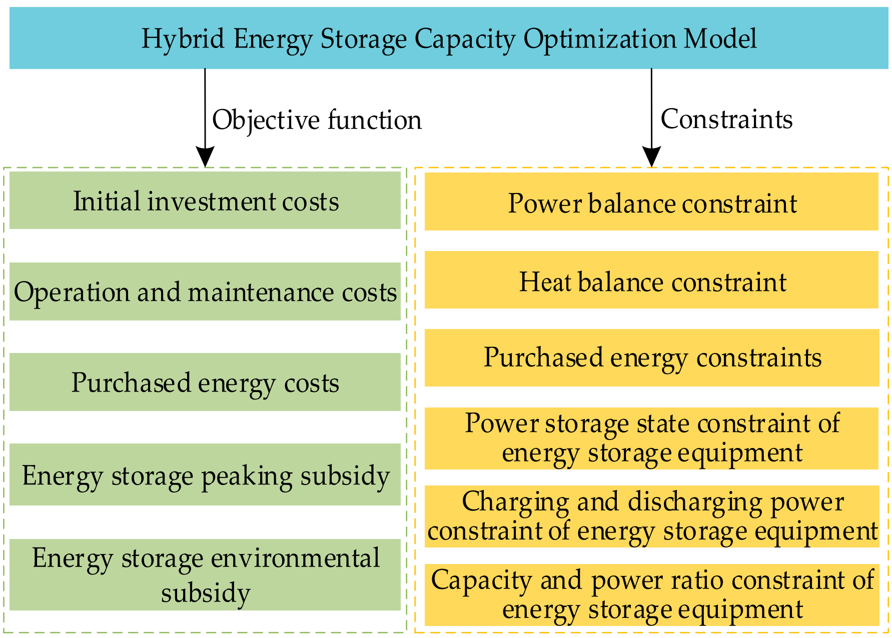

Figure 1. The structure of hybrid energy storage capacity optimization model.

(1) Initial investment costs.

Since other equipment has been built, the industrial park only needs to invest to construct the lithium battery and HST in the initial stage, and the initial investment costs of the lithium battery and HST are denoted by [36]

$$C_{\mathrm{HST}} = k_{\mathrm{CO}}(c_{\mathrm{HST,P}}P_{\mathrm{HST,Rate}} + c_{\mathrm{HST,E}}E_{\mathrm{HST,Rate}}) \tag{12}$$

$$C_{\mathrm{Bat}} = k_{\mathrm{CO}}(c_{\mathrm{Bat,P}}P_{\mathrm{Bat,Rate}} + c_{\mathrm{Bat,E}}E_{\mathrm{Bat,Rate}}) \tag{13}$$

where $c_{\mathrm{HST,P}}$, $c_{\mathrm{HST,E}}$ are the unit power price and unit capacity price of the HST, respectively, $c_{\mathrm{Bat,P}}$, $c_{\mathrm{Bat,E}}$ are the unit power price and unit capacity price of the lithium battery, respectively, and k_{CO} is the coefficient for the conversion of the present value into an annual value. At a discount rate of r and a life cycle of N years for the energy storage equipment, the expression is

$$k_{\mathrm{CO}} = \frac{(1+r)^N - 1}{r(1+r)^N} \tag{14}$$

(2) Operation and maintenance costs.

Operation and maintenance costs refers to the funds dynamically invested to ensure the normal operation of energy storage in the service life, and the annual operation and maintenance costs of the lithium battery and HST can be expressed as [36]

$$C_{\mathrm{OM}} = \rho_{\mathrm{HST}}P_{\mathrm{HST,Rate}} + \rho_{\mathrm{Bat}}P_{\mathrm{Bat,Rate}} \tag{15}$$

where ρ_{HST}, ρ_{Bat} are the annual operation and maintenance prices of the HST and lithium battery, respectively.

(3) Purchased energy costs.

The industrial park needs to purchase power from the power grid and heat from the heat network to meet its energy demand. The purchased energy costs are represented as

$$\begin{cases} C_{\mathrm{Buy,Ele}} = T_{\mathrm{d}}\rho_{\mathrm{Ele}}P_{\mathrm{Ele,buy}} \\ C_{\mathrm{Buy,Heat}} = T_{\mathrm{d}}\rho_{\mathrm{Heat}}P_{\mathrm{Heat,buy}} \end{cases} \tag{16}$$

where ρ_{Heat}, ρ_{Ele} are the purchased heat price and purchased power price of the park, respectively, and T_{d} is the number of operating days of the park in a year.

(4) Energy storage peak-shaving subsidy.

The energy storage peak compensation can be calculated based on the "Notice on Promoting the Participation of Electric Energy Storage in Peak-shaving Auxiliary Services in the Three North Areas" issued by the National Energy Administration in 2016 [37]. It can be expressed as

$$R_{\mathrm{Sub,Peak}} = T_{\mathrm{d}}\rho_{\mathrm{Peak}}\sum_{t=1}^{T_{\mathrm{h}}} P_{\mathrm{Bat,D},t} \tag{17}$$

where ρ_{Peak} is the peak compensation price, T_{h} is the number of periods in a day.

(5) Energy storage environmental subsidy.

Environmental subsidy refers to the environmental benefits brought by the reduction in SO_2, NO_2, and other gas emissions after the substitution of coal-fired units and coal-fired boilers by power and heat storage systems, which is subsidized by the government and can be expressed as

$$R_{\mathrm{Sub,Envi}} = T_{\mathrm{d}}(\rho_{\mathrm{Sub,Bat}}\sum_{t=1}^{T_{\mathrm{h}}} P_{\mathrm{Bat,D},t} + \rho_{\mathrm{Sub,HST}}\sum_{t=1}^{T_{\mathrm{h}}} P_{\mathrm{HST,D},t}) \tag{18}$$

where $\rho_{\mathrm{Sub,HST}}$, $\rho_{\mathrm{Sub,Bat}}$ are the environmental subsidized price of the HST and lithium battery, respectively.

3.3.2. Constraints

(1) System power balance constraint.

$$P_{\mathrm{Bat,D},t} + P_{\mathrm{Ele,buy},t} = P_{\mathrm{LEle},t} + P_{\mathrm{Bat,C},t} \tag{19}$$

where $P_{\mathrm{Ele,buy},t}$, $P_{\mathrm{LEle},t}$ are the purchased power and power load demand of the park during period t, respectively.

(2) System heat balance constraint.

$$P_{\mathrm{HST,D},t} + P_{\mathrm{Heat,buy},t} = P_{\mathrm{LHeat},t} + P_{\mathrm{HST,C},t} \tag{20}$$

where $P_{\mathrm{Heat,buy},t}$, $P_{\mathrm{LHeat},t}$ are the purchased heat and heat load demand of the park during period t, respectively.

(3) Purchased energy constraints.

$$\begin{cases} 0 \le P_{\mathrm{Ele,buy},t} \le P_{\mathrm{Ele,max}} \\ 0 \le P_{\mathrm{Heat,buy},t} \le P_{\mathrm{Heat,max}} \end{cases} \tag{21}$$

where $P_{\mathrm{Ele,max}}$, $P_{\mathrm{Heat,max}}$ are the upper limit of the purchasing power and heat, respectively.

3.3.3. Model Solution

Due to the nonlinear terms in Formulas (3) and (7), the hybrid energy storage capacity optimization model is a nonlinear optimization problem. The decision variables include the rated capacity and rated power of the lithium battery and HST, the charging and discharging power at each period, and the charging and discharging states.

Using the Big-M method, this nonlinear optimization problem can be transformed into a mixed-integer linear programming problem by transforming the nonlinear terms into linear terms. Taking Formula (3) as an example, the transformation is provided in Formula (22). Then, the transformed model is solved in Matlab 2018a via the Yalmip toolbox and CPLEX solver.

$$\begin{cases} 0 \le P_{\mathrm{HST,C},t} \le P_{\mathrm{HST,Rate}} \\ 0 \le P_{\mathrm{HST,C},t} \le U_{\mathrm{HST,C},t} M \\ 0 \le P_{\mathrm{HST,D},t} \le P_{\mathrm{HST,Rate}} \\ 0 \le P_{\mathrm{HST,D},t} \le U_{\mathrm{HST,D},t} M \\ U_{\mathrm{HST,C},t} + U_{\mathrm{HST,D},t} \le 1 \end{cases} \tag{22}$$

Based on the above derivation and analysis, the process of energy-saving renovation for industrial parks based on EPC is given in Figure 2.

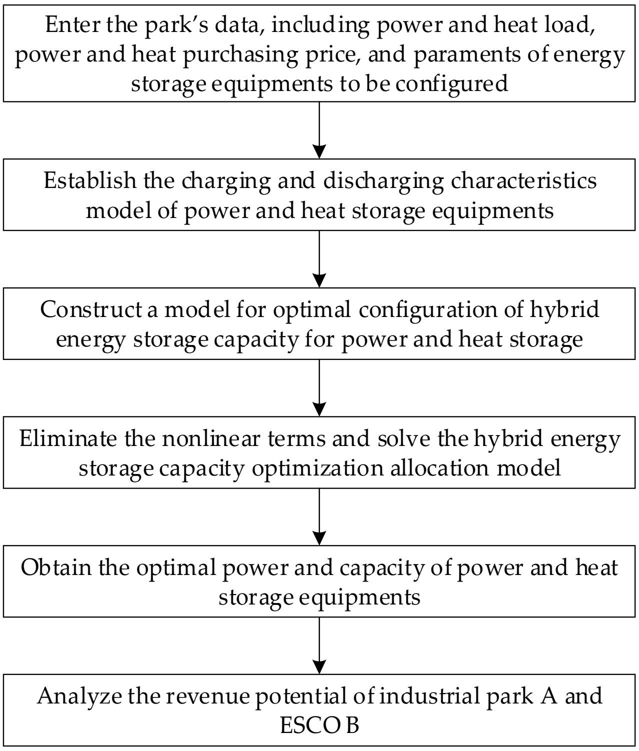

Figure 2. The process of energy-saving renovation for industrial park based on EPC.

4. Case Study

4.1. Case Introduction

In this section, industrial park A in Section 2.2 is selected as an example. The typical daily power and heat load demand of this park is shown in Figure 3. T_h = 24, and the time step Δt is 1 h. The park is on a double weekly basis, T_d = 260. The unit power price and the unit capacity price of the lithium battery and HST are from the literature [36], and the annual operation and maintenance price of the two are 72 CNY/(year·kW) and 56 CNY/(year·kW), respectively. $\eta_{HST,C} = \eta_{HST,D} = \eta_{Bat,C} = \eta_{Bat,D} = 0.92$, $\alpha_{max} = \beta_{max} = 0.9$, and $\alpha_{min} = \beta_{min} = 0.1$. The purchased power price and the heat price adopt the TOU price [38], as shown in Figure 4.

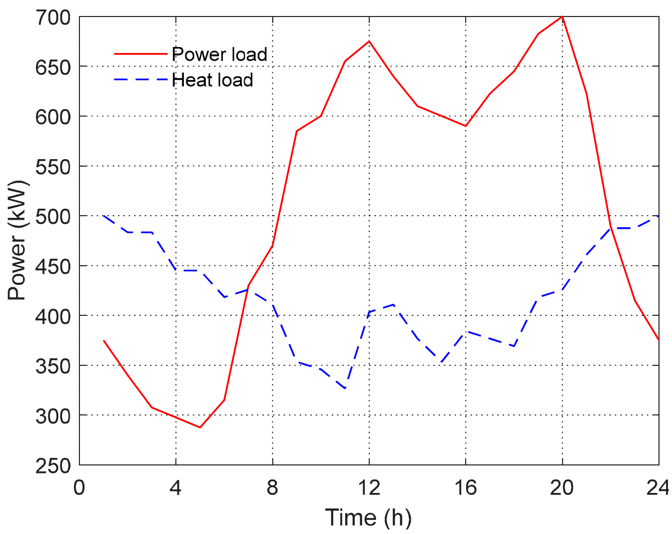

Figure 3. Power and heat load in a typical day.

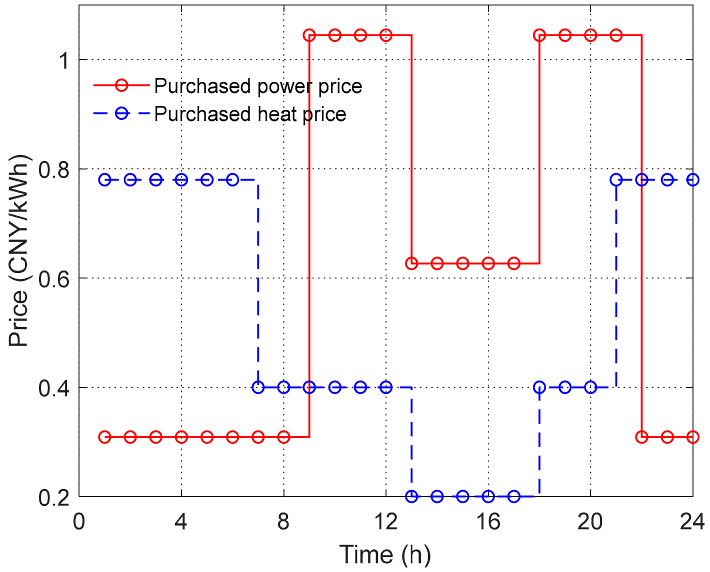

Figure 4. The price of purchasing power and heat.

4.2. Results and Analysis

The optimal configuration of the lithium battery and HST in the park after the implementation of EPC are as follows: the rated power of the lithium battery is 375 kW, the rated capacity is 999.68 kWh, the rated power of the HST is 698.49 kW, and the rated capacity is 1862.04 kWh.

Before the energy-saving renovation, the energy costs of the park mainly come from the costs of purchasing power and heat, and the annual cost of purchasing energy is 364.75 ten thousand CNY. After the energy-saving renovation, the park needs to invest a total cost of 356.60 ten thousand CNY initially. Then, it can obtain the benefits of 26.99 ten thousand CNY, and the net investment costs are 329.61 ten thousand CNY.

Compared with the situation before the energy-saving renovation, the park can save 35.14 ten thousand CNY in annual cost expenses, which can bring significant economic benefits. The cost comparison of the park before and after the energy-saving renovation is shown in Figure 5.

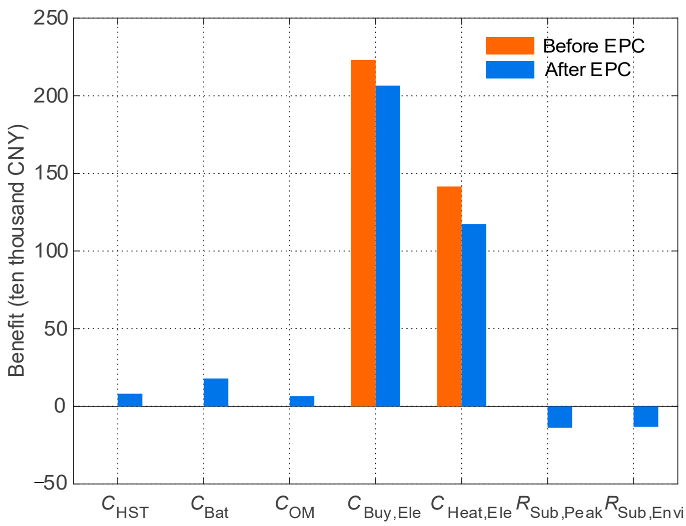

Figure 5. Comparison of the various costs of the park before and after energy-saving renovation.

As can be seen from Figure 5, the energy storage investment, operation, and maintenance costs (32.64 ten thousand CNY) are added after the energy-saving renovation. Due to the good energy time-shift characteristics of energy storage, the construction of energy storage in the park can significantly reduce the demand for purchasing power and heat in high-price hours. Moreover, the construction of energy storage can bring considerable peak subsidies and environmental benefits, which reduce the annual operating costs of the park by 35.14 ten thousand CNY after the energy-saving renovation. Note that the park's purchased power and heat costs were reduced by 16.59 and 24.21 ten thousand CNY, respectively. The park received 13.83 ten thousand CNY and 13.16 ten thousand CNY of peak-shaving subsidies and environmental subsidies, respectively.

Since the contract between the ESCO and industrial park states that, during the life cycle of the equipment, the energy-saving benefits generated by the energy-saving renovation project will be enjoyed by the ESCO and industrial park as a proportion of k_1 and k_2, respectively, if the energy-saving benefits are negative, the loss will be undertaken by both. Assuming that k_1 takes the value [0.1, 0.2, 0.3, . . ., 0.9], the annual benefits available to the industrial park and ESCO are shown in Figure 6.

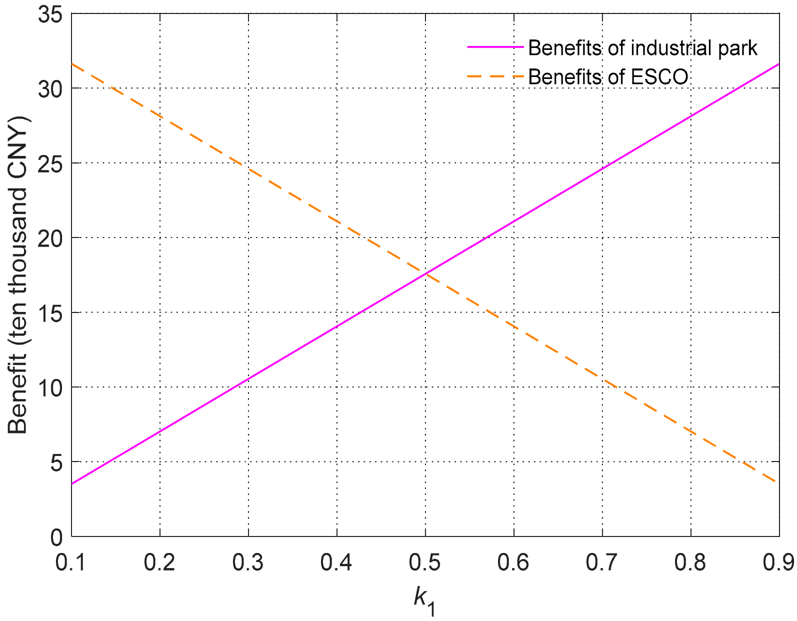

Figure 6. Benefits of the park and ESCO after energy-saving renovation.

As can be seen from Figure 6, when signing the energy-saving service contract, the park needs to determine the benefit-sharing ratio k_1 according to its own expected energy-saving target. For example, if the expected energy-saving benefits are a minimum of 20 ten thousand CNY, then $k_1 \geq 0.569$, and if the expected energy-saving benefits are a minimum of 10 ten thousand CNY, then $k_1 \geq 0.285$. Similarly, the ESCO can determine its benefit-sharing ratio k_2 in this way.

After the energy-saving renovation, the charging and discharging power and storage capacity of the lithium battery during each period are shown in Figure 7. The storage and release heat, and heat storage capacity of the HST during each period are shown in Figure 8.

As seen in Figure 7, the charging time of the lithium battery is mainly concentrated in the low load time in the early morning and 1:00–6:00 p.m., which is because the price of purchasing power in the park is lower at this time, and the costs of purchasing power to be paid for charging is lower. In other periods, the lithium battery is discharging to maintain the balance of the system's power supply and demand, and its storage capacity always meets the constraints of the power storage state. Among them, the maximum charging and discharging power of the lithium battery is 375 kW.

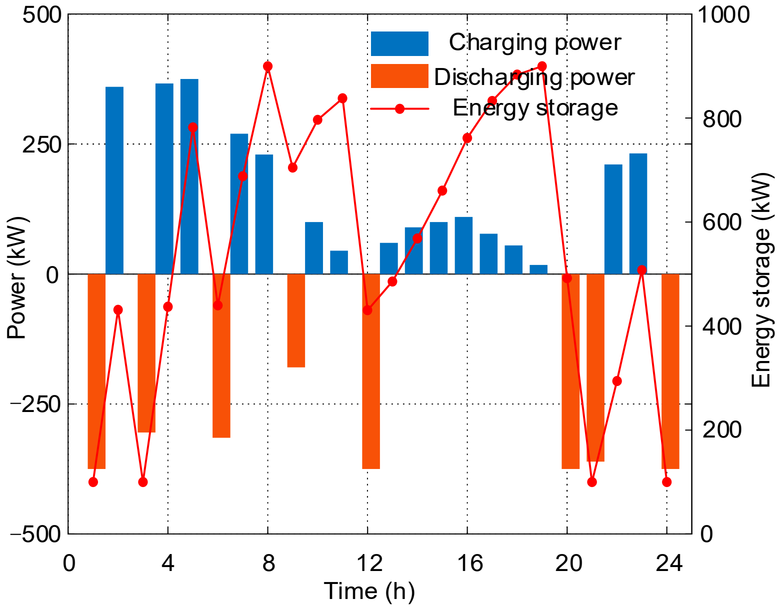

Figure 7. Charging and discharging power, and storage capacity of lithium battery.

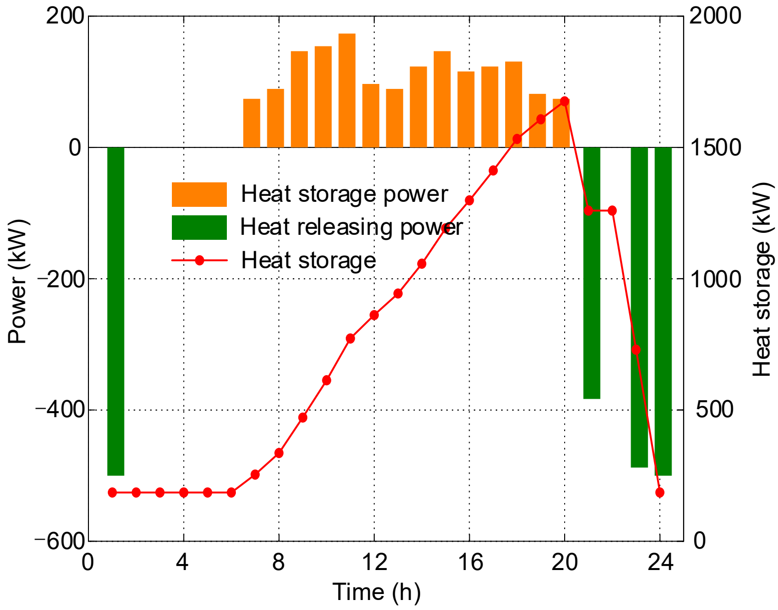

Figure 8. Heat storage, release power, and heat storage capacity of HST.

From Figure 8, due to the low heat load demand and the low price of purchasing heat during 7:00–20:00, the HST is always working in the heat storage state, and the amount of stored heat rises from 186.20 kWh to 1675.84 kWh. The HST starts to release a large amount of heat to satisfy the heat load demand of the park from 7:00–20:00. It can be seen that the good energy time-shift characteristics of the energy storage equipment can greatly improve the flexibility of energy use in the park.

To analyze the impact of the changes in energy storage prices on the results of energy storage configuration, parks, and ESCO's revenues, we have carried out the following studies. The relationship between the rated capacity, rated power of the lithium battery, and its unit price is shown in Figure 9. The comparison of the annual operating costs of the park before and after the energy-saving renovation is shown in Figure 10. Among them, the annual operating costs of the park before energy-saving renovation are the purchased energy costs. The lithium battery unit power price and unit capacity price are $k_{\mathrm{Bat,var}}c_{\mathrm{Bat,P}}$ and $k_{\mathrm{Bat,var}}c_{\mathrm{Bat,E}}$, respectively.

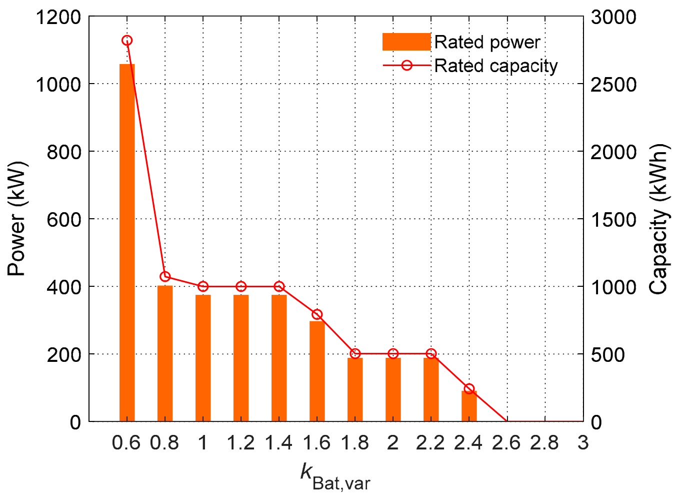

Figure 9. The relationship between the rated capacity, rated power of lithium battery, and its unit price.

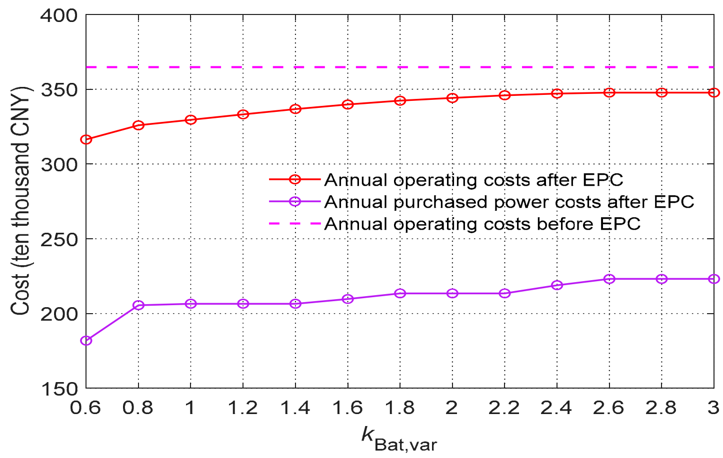

Figure 10. The comparison of the annual operating costs of the park before and after the energy-saving renovation when the price of lithium battery varies.

As can be seen from Figure 9, with the lithium battery price coefficient $k_{\mathrm{Bat,var}}$ increase, the lithium battery rated capacity and rated power are gradually reduced. When $k_{\mathrm{Bat,var}} = 2.6$, that is, the lithium battery unit power price is 3900 CNY/kW and unit capacity price is 5460 CNY/kWh, the investment costs of the lithium battery have exceeded the costs of purchasing power for the energy supply, meaning the park does not need to configure energy storage.

As can be seen in Figure 10, with the lithium battery price change coefficient $k_{\mathrm{Bat,var}}$ increases, the annual operating costs and annual power purchased costs are a gradually growing trend. This is because the rated capacity and rated power of the lithium battery have been reduced, but its unit price is growing rapidly, making the total investment costs of energy storage higher. Moreover, the purchased power costs are still increasing.

Similarly, when the unit power price and unit capacity price of the HST are $k_{\mathrm{HST,var}}c_{\mathrm{HST,P}}$ and $k_{\mathrm{HST,var}}c_{\mathrm{HST,E}}$, the relationship between the rated capacity and rated power of the HST with its unit price is shown in Figure 11. The comparison of the annual operating costs of the park before and after the energy-saving renovation is shown in Figure 12.

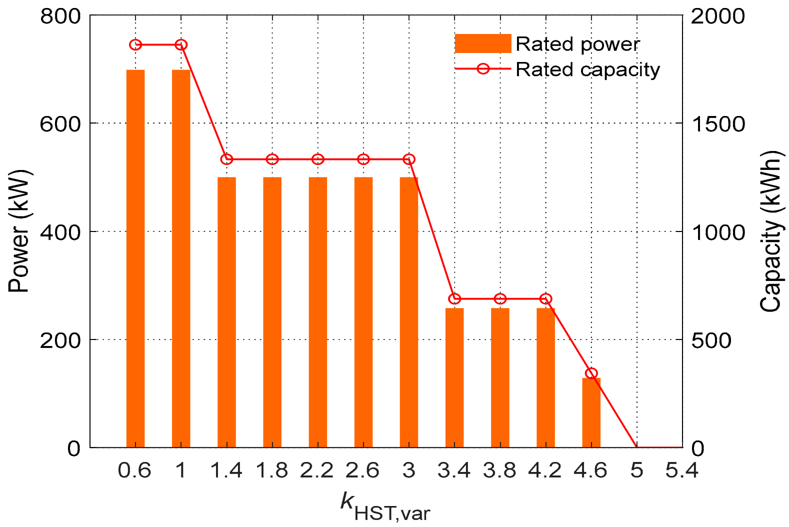

Figure 11. The relationship between the rated capacity, rated power of HST, and its unit price.

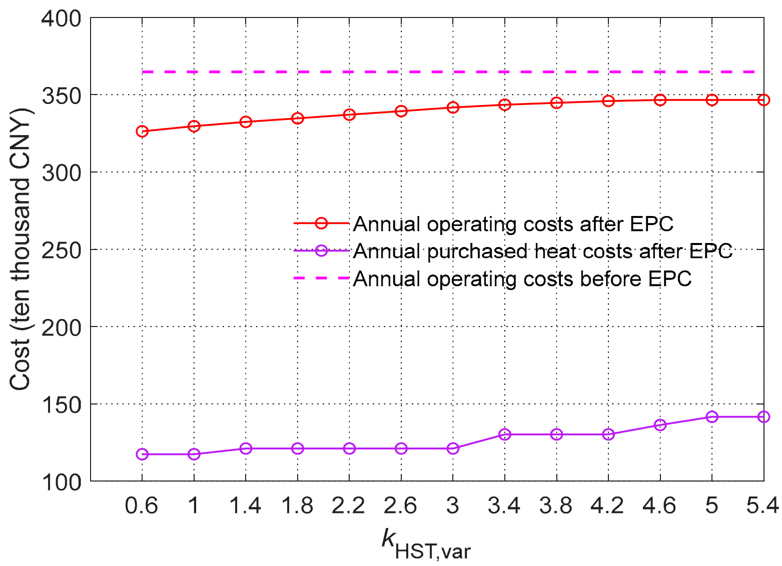

Figure 12. The comparison of the annual operating costs of the park before and after the energy-saving renovation when the price of HST varies.

As can be seen from Figures 11 and 12, the rated capacity and rated power of the HST are negatively correlated with its price. When the unit power price of the HST is 6000 CNY/kW, and the unit capacity price is 1000 CNY/kWh, the configuration of the HST in the park is no longer the optimal choice to meet the heat demand. In addition, as the rated capacity and rated power of the HST decrease, the annual costs of heat purchased and operating costs of the park after the energy-saving renovation increase, both of which have a maximum value of 141.61 ten thousand CNY and 346.63 ten thousand CNY, respectively.

It can be seen that the economy of energy storage investment is closely related to its capital costs. With the development of energy storage technology, the construction cost of energy storage equipment will be gradually reduced. Power and heat energy storage has a broader application prospect.

When state policies change and there are no peak-shaving subsidies and environmental subsidies for energy storage, the relationship between the rated capacity, rated power of the lithium battery, and its unit price is shown in Figure 13. The relationship between the rated capacity and rated power of the HST with its unit price is shown in Figure 14.

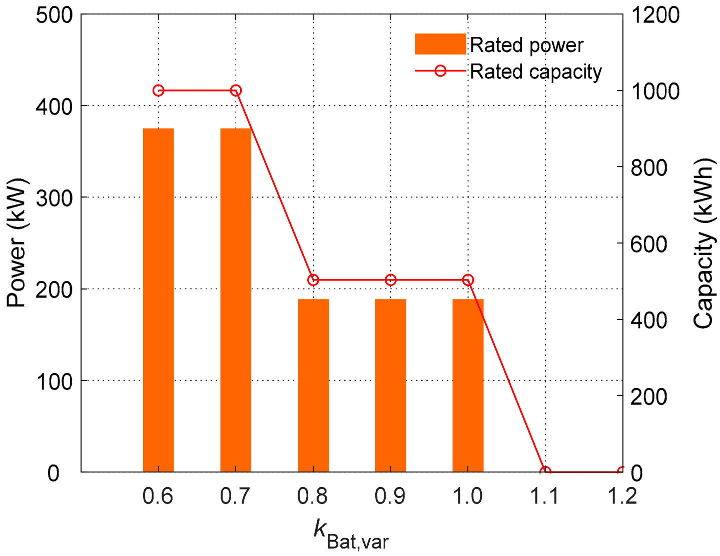

Figure 13. The relationship between the rated capacity, rated power of lithium battery, and its unit price without peak-shaving subsidy and environmental subsidy.

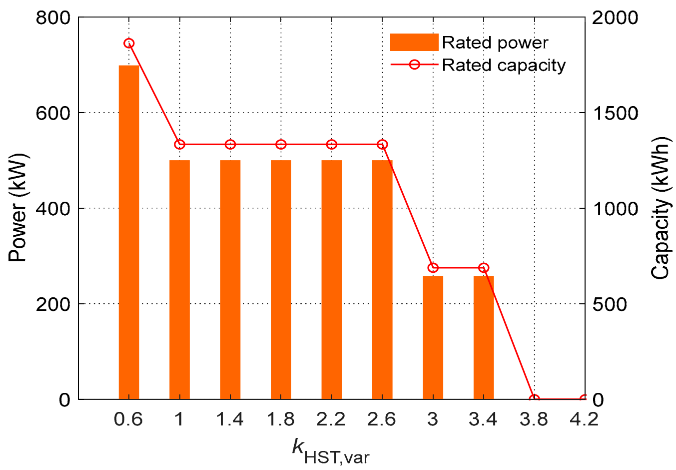

Figure 14. The relationship between the rated capacity, rated power of HST, and its unit price without peak-shaving subsidy and environmental subsidy.

As can be seen from Figure 13, the rated capacity and rated power of the lithium battery are negatively correlated with its price coefficient $k_{\mathrm{Bat,var}}$. When $k_{\mathrm{Bat,var}} = 1.1$, that is, when the unit power price of the lithium battery is 1650 CNY/kW, and the unit capacity price is 2310 CNY/kWh, the economy of the lithium battery investment is already lower than the economy of purchasing power. This means that the unit power price of 1650 CNY/kW and the unit capacity price of 2310 CNY/kWh is the price threshold that influences whether or not a park invests in a lithium battery.

In Figure 14, when the unit power price of the HST is 5040 CNY/kW, and the unit capacity price is 840 CNY/kWh, the economy of the HST investment is lower than the economy of purchasing heat. This price threshold is much lower than the price threshold when energy storage subsidies were available. It can be concluded that in the current market environment, subsidies for energy storage have a significant impact on its development and application.

5. Conclusions

This paper combines EPC with energy-saving renovation in the industrial park and constructs a hybrid power and heat energy storage capacity optimization model, which considers the investment costs, operation and maintenance costs, purchased energy costs, peak-shaving subsidy, and environmental subsidy. The case study analyzes the impact of the energy storage price on the configuration results and the economy of energy-saving renovation project, and draws the following conclusions:

(1) Compared with only meeting the energy demand through purchasing energy, the configuration of power and heat energy storage can significantly improve the flexibility and economic efficiency of the park's energy use. At the same time, the ESCO can also obtain benefits. The total annual benefits of the ESCO and industrial park are 35.14 ten thousand CNY.
(2) If the level of subsidy and the price of energy storage remain constant, the park can obtain a certain amount of revenue when investing in energy storage for energy-saving renovation. Therefore, parks that need energy-saving renovation can give priority to investing in energy storage to achieve this goal.
(3) When the unit power price and the unit capacity price of the lithium battery exceed 3900 CNY/kW, and 5460 CNY/kWh, and the unit power price and the unit capacity price of the HST exceed 6000 CNY/kW and 1000 CNY/kWh, the investment costs of the lithium battery and HST have been more than the costs of purchasing energy to meet the needs of the park. The construction of energy storage is no longer the optimal investment strategy for energy-saving renovation in parks.
(4) The reasons why parks are interested in the investment of energy storage for energy-saving renovation include the following two aspects. On the one hand, energy storage equipment can reduce the demand during peak-price hours, thus reducing the cost of energy significantly. On the other hand, investing in energy storage can obtain peak-shaving subsidies and environmental subsidies.
(5) Under the current subsidy level, enterprises are able to obtain a certain amount of revenue through energy-saving renovation. If the amount of peak-shaving subsidies and environmental subsidies provided by the government can be further increased, it will further enhance the motivation of enterprises to carry out energy-saving renovation and promote the large-scale application of energy storage. Hence, issuing more subsidy policies on energy storage is an effective way to stimulate energy-saving renovation on the user side and accelerate the application of energy storage.

6. Limitations and Outlook

This paper does not consider the impact of the lifetime loss of energy storage on its investment strategy. In fact, there is a certain lifetime loss of energy storage equipment in each charging or discharging cycle, especially the deep discharging of batteries. In addition, this paper only considers the joint configuration of power and heat storage in a deterministic environment, but the uncertainty of demand and price will increase the complexity of energy storage configuration. Subsequent research will be centered on the uncertainty of demand and price.

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