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Optimal Configuration of Power-to-Heat Equipment Considering Peak-Shaving Ancillary Service Market

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Abstract: The serious problem of wind power curtailment in northern China has created a pressing need to enhance the peak-shaving ability of the power system. As the main source of power supply in northern China, combined heat and power (CHP) units have significant potential for peak-shaving. Currently, the Chinese government encourages CHP plants to increase their peak-shaving capacity by installing power-to-heat (P2H) equipment. In addition, the government has implemented auxiliary service market policies to encourage CHP plants to provide peak-shaving services. In order to maximize economic benefits for CHP plants, this paper proposes an optimal configuration method of P2H equipment with the static payback time (SPT) as the objective function. Cost and income models of installing the P2H equipment are constructed by taking into account the auxiliary service market policies. The peak-shaving income model of the CHP plant is derived emphatically as a key part of the proposed method. Finally, the district heating region in Jilin province is used as a case study example. The results show that adding the P2H equipment is significantly effective in improving the peak-shaving ability of CHP units, and investing in heat pumps is more cost-effective than electric boilers. The proposed method can be applied to other northern regions relying on CHP units for central heating, providing a valuable solution to the problem of wind power curtailment in these regions.

Keywords: combined heat and power; power-to-heat equipment; peak-shaving ancillary service market; optimal configuration; wind power integration

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1. Introduction

In China, the vast majority of wind power generators are installed in northern regions [1,2], posing a significant challenge to the power system's ability to accommodate wind power. The peak-shaving ability of the power system in northern China is primarily dependent on coal-fired combined heat and power (CHP) units, as these units generate a high proportion of power. However, the CHP units are operated in a "heat-led" mode that prioritizes space-heating, and the generated electric power is dominated by thermal power, resulting in the limited flexibility of the power system [3,4]. Therefore, there is an urgent need to enhance the peak-shaving ability of CHP units to increase the flexibility of the entire system.

This study aims to investigate the optimal configuration of auxiliary heating equipment to enhance the peak-shaving ability and willingness of CHP units. The peak-shaving ability of CHP units can be improved by decoupling the constraints between thermal power and electric power through the use of auxiliary heating equipment [5]. The CHP plants are more likely to actively participate in the peak-shaving ancillary service market for potential economic benefits [6,7].

Many studies have proven that power-to-heat (P2H) equipment, especially the electric boiler (EB) and heat pump (HP), are outstanding at promoting the flexibility of CHP units [8–10]. Yan et al. [11] investigated the performance of four technologies with respect to the flexibility improvement of the CHP system and claimed that the EB is the most effective piece of equipment for improving renewable energy integration. Lv et al. [12] proposed an evaluation model of wind power integration in consideration of the CHP units, EB, and heat storage. It was demonstrated that the electric power produced by CHP units can be reduced to the second level of down-regulation subsidy with the help of the EB. Lei et al. [13] proposed a multi-level input/exit operation mode of heat storage electric boilers to consume the curtailed wind power for space heating in northern China. The authors claimed that the wind power accommodation capacity can be improved effectively. In addition, the contribution of the EB to better system flexibility has been confirmed in previous work [14–16]. The HP has also been discussed by many scholars with respect to its ability to consume surplus wind power [17]. In [18], an electrified energy system is created by combining a high temperature heat pump and wind turbine to supply super-heated steam. The operational costs and CO_2 emissions are reduced effectively. In [19], HPs were utilized to relieve the heating pressure of CHP units by heating the return water in the district heating network. Dengiz et al. [20] proposed a heuristic control strategy for modulating HPs to reduce heating costs and wasted renewable energy. In [21], the authors claimed that the HP is more cost-effective than the EB for consuming surplus wind energy. Liu et al. [22] proposed new operation scheduling steady-state models of CHP units integrated with an EB and an HP for energy saving and economic benefits.

Based on the studies mentioned above, the EB and HP promote the operation flexibility of CHP units, but their economic potential is significantly affected by the capacity, efficiency, and price in the electricity market [23,24]. Therefore, it is necessary to optimize the configuration of the EB or the HP if a CHP plant expects to participate in the peak-shaving ancillary service market to achieve better economic benefits. In recent years, several studies have investigated the configuration of auxiliary heating equipment. For instance, Wang et al. [25] and Østergaard et al. [26] both discussed capacity planning of heat storage. Liu et al. [27] investigated the optimal capacity of the EB with the goal of maximizing economic and environmental benefits. Yi et al. [28] proposed a two-stage configuration strategy for distributed EB and heat storage to simultaneously enhance wind power integration and minimize construction costs. Optimal planning of electric heater and heat storage was investigated considering the capacity and distribution in a previous study [28,29]. However, very few works have researched the configuration of the EB or the HP in consideration of the peak-shaving ancillary service market, which is a key factor of the economy [30].

The aim of this study is to investigate the optimal configuration of the EB and the HP added by the CHP plant, with a focus on the economic benefits influenced by the ancillary service market policy. This paper provides a detailed analysis of the deep peak-shaving income of the CHP plant considering the peak-shaving capacity required by the power grid under different levels of wind power generation. Based on this analysis, income and cost models are developed for adding the P2H equipment. The optimal capacity of the P2H is determined with the static payback time (SPT) as the objective function. Finally, numerical case studies are carried out with the power system in Jilin province as an example, and the results verify the effectiveness of the proposed method.

The rest of this paper is organized as follows. In Section 2, the deep peak-shaving ability of the CHP plant is analyzed, and the deep peak-shaving income model is established. In Section 3, the optimal configuration model is developed with the SPT as the objective index based on the analysis of income and cost of adding the P2H equipment. Numerical studies are described in Section 4 and conclusions are presented in Section 5.

2. Deep Peak-Shaving Income of the CHP Plant

2.1. Deep Peak-Shaving Capacity Provided by the CHP Plant

The CHP unit is operated in “heat-led” mode, and its operation region is shown in Figure 1a. To meet the deep peak-shaving demand of the power grid, especially during the heating season, the Chinese government encourages CHP plants to install P2H equipment to harness the peak-shaving potential of CHP units. P2H equipment can serve as an interruptible load to participate in the peak-shaving auxiliary service market. The heat load can be jointly undertaken by the CHP units and P2H equipment:

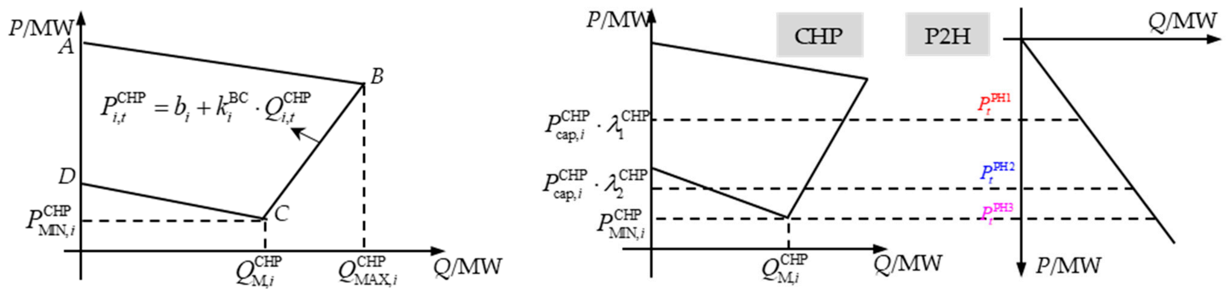
$$\sum_{i=1}^{N1} Q_{i,t}^{\mathrm{CHP}} + P_t^{\mathrm{PH}} \cdot \eta = Q_t^{\mathrm{H}} \tag{1}$$

$$0 \le Q_{i,t}^{\mathrm{CHP}} \le Q_{\mathrm{MAX},i}^{\mathrm{CHP}} \tag{2}$$

$$0 < P_t^{\mathrm{PH}} \le P_{\max,t}^{\mathrm{PH}} \tag{3}$$

$$P_{\max,t}^{\mathrm{PH}} = \max\left\{0\,,\ \min\left\{P_{\mathrm{cap}}^{\mathrm{PH}},\, (Q_t^{\mathrm{H}} - \sum_{i=1}^{N1} Q_{\mathrm{M},i}^{\mathrm{CHP}}) \Big/ \eta\right\}\right\} \tag{4}$$

where t is the index of scheduling time interval; $N1$ is the total number of CHP units; $Q_{i,t}^{\mathrm{CHP}}$ and $Q_{\mathrm{MAX},i}^{\mathrm{CHP}}$ are the output and maximum thermal power of the i-th CHP unit, respectively; $Q_{\mathrm{M},i}^{\mathrm{CHP}}$ is the thermal power at point C in Figure 1; P_t^{PH}, $P_{\max,t}^{\mathrm{PH}}$, and $P_{\mathrm{cap}}^{\mathrm{PH}}$ are the actual running power, maximum running power, and power capacity of the P2H equipment, respectively; η is the coefficient of performance (COP); and Q_t^{H} is the heat load.



(**a**) (**b**)

Figure 1. (**a**) Operation region of a CHP unit. (**b**) Relationship between the electric power output of the CHP unit and the P2H equipment.

CHP units are usually operated in back-pressure mode, denoted as segment BC, to minimize electric power output during the heating season. Under this mode of operation, the electric power produced by the CHP units is expressed as follows [7,31]:

$$\sum_{i=1}^{N1} P_{i,t}^{\mathrm{CHP}} = \sum_{i=1}^{N1} (k_i^{\mathrm{BC}} \cdot Q_{i,t}^{\mathrm{CHP}} + b_i) \approx k_{\mathrm{av}} \cdot \sum_{i=1}^{N1} Q_{i,t}^{\mathrm{CHP}} + \sum_{i=1}^{N1} b_i = k_{\mathrm{av}}(Q_t^{\mathrm{H}} - P_t^{\mathrm{PH}} \cdot \eta) + \sum_{i=1}^{N1} b_i \tag{5}$$

Then, the minimum electric power produced by the CHP plant can be derived as:

$$\Big(\sum_{i=1}^{N1} P_{i,t}^{\mathrm{CHP}}\Big)_{\min} = \max\left\{\sum_{i=1}^{N1} P_{\mathrm{MIN},i}^{\mathrm{CHP}}\ ,\ k_{\mathrm{av}}(Q_t^{\mathrm{H}} - P_{\max,t}^{\mathrm{PH}} \cdot \eta) + \sum_{i=1}^{N1} b_i\right\} \tag{6}$$

where $P_{i,t}^{\mathrm{CHP}}$ and $P_{\mathrm{MIN},i}^{\mathrm{CHP}}$ are the generated and minimum electric power of the i-th CHP unit, respectively; k_i^{BC} and b_i are the expression coefficients; and k_{av} is the approximate value of the electrothermal ratio.

From Equation (5), when the CHP units are operated at different power levels, the running power of the P2H equipment is constrained by the following equations:

$$\sum_{i=1}^{N1} P_{\text{cap},i}^{\text{CHP}} \cdot \lambda_1^{\text{CHP}} = k_{\text{av}}(Q_t^{\text{H}} - P_t^{\text{PH1}} \cdot \eta) + \sum_{i=1}^{N1} b_i \tag{7}$$

$$\sum_{i=1}^{N1} P_{\text{cap},i}^{\text{CHP}} \cdot \lambda_2^{\text{CHP}} = k_{\text{av}}(Q_t^{\text{H}} - P_t^{\text{PH2}} \cdot \eta) + \sum_{i=1}^{N1} b_i \tag{8}$$

$$\sum_{i=1}^{N1} P_{\text{MIN},i}^{\text{CHP}} = k_{\text{av}}(Q_t^{\text{H}} - P_t^{\text{PH3}} \cdot \eta) + \sum_{i=1}^{N1} b_i \tag{9}$$

where $P_{\text{cap},i}^{\text{CHP}}$ is the power capacity; λ_1^{CHP} and λ_2^{CHP} are the first base line and second base line of deep peak-shaving, respectively; and P_t^{PH1}, P_t^{PH2}, and P_t^{PH3} are the running powers of the P2H equipment. The relationship of electric power output between the CHP unit and the P2H equipment is displayed in Figure 1b. If $P_t^{\text{PH1}} \leq 0$, then set $P_t^{PH1} = 0$; if $P_t^{\text{PH2}} \leq 0$, set $P_t^{\text{PH2}} = 0$; and if $P_t^{\text{PH3}} \leq 0$, set $P_t^{\text{PH3}} = 0$.

According to the policy of the peak-shaving ancillary service market, the available deep peak-shaving capacities of the CHP plant at the first and second levels are expressed as follows:

$$P_t^{\text{sup1}} = \max\left\{ \min\left\{ \sum_{i=1}^{N1} P_{\text{cap},i}^{\text{CHP}} \cdot (\lambda_1^{\text{CHP}} - \lambda_2^{\text{CHP}}) \,,\, \sum_{i=1}^{N1} P_{\text{cap},i}^{\text{CHP}} \cdot \lambda_1^{\text{CHP}} - \left(\sum_{i=1}^{N1} P_{i,t}^{\text{CHP}}\right)_{\min} \right\} ,\, 0 \right\} \tag{10}$$

$$P_t^{\text{sup2}} = \max\left\{ \sum_{i=1}^{N1} P_{\text{cap},i}^{\text{CHP}} \cdot \lambda_2^{\text{CHP}} - \left(\sum_{i=1}^{N1} P_{i,t}^{\text{CHP}}\right)_{\min} ,\, 0 \right\} \tag{11}$$

If $P_t^{\text{sup1}} = 0$, it means that the CHP plant lacks the ability to provide a deep peak-shaving service. In addition to the deep peak-shaving capacity provided by the CHP units, the increased power load, namely the power consumed by the P2H equipment, is also helpful for enhancing wind power integration. From Equations (6)–(11), the power consumed by the P2H equipment is calculated corresponding to P_t^{sup1} and P_t^{sup2}:

$$if\ P_t^{\text{sup1}} = \sum_{i=1}^{N1} P_{\text{cap},i}^{\text{CHP}} \cdot (\lambda_1^{\text{CHP}} - \lambda_2^{\text{CHP}}) \,, \qquad \Delta P_t^{\text{E1}} = P_t^{\text{PH2}} \tag{12}$$

$$if\ P_t^{\text{sup1}} = \sum_{i=1}^{N1} P_{\text{cap},i}^{\text{CHP}} \cdot \lambda_1^{\text{CHP}} - \left(\sum_{i=1}^{N1} P_{i,t}^{\text{CHP}}\right)_{\min} ,\quad \Delta P_t^{\text{E1}} = P_{\max,t}^{\text{PH}} \tag{13}$$

$$if\ P_t^{\text{sup2}} = \sum_{i=1}^{N1} P_{\text{cap},i}^{\text{CHP}} \cdot \lambda_2^{\text{CHP}} - \left(\sum_{i=1}^{N1} P_{i,t}^{\text{CHP}}\right)_{\min} ,\quad \Delta P_t^{\text{E2}} = \min\left\{ P_t^{\text{PH3}}, P_{\max,t}^{\text{PH}} \right\} \tag{14}$$

$$if\ P_t^{\text{sup2}} = 0 \,, \quad \Delta P_t^{\text{E2}} = \Delta P_t^{\text{E1}} \tag{15}$$

2.2. Deep Peak-Shaving Capacity Required by the Power Grid

Deep peak-shaving is required by the power grid if wind power remains excessive when coal-fired units have been operated at the first base line of deep peak-shaving and non-coal-fired units have been operated at minimum power output. The deep peak-shaving capacity required by the power grid, which is denoted as P_t^{G}, depends on the level of wind power generation and is equal to the difference between the total produced electric power and the heat load:

$$P_t^{\text{G}} = P_t^{\text{WF}} + P_{\text{MIN}}^{\text{OTH}} + \sum_{i=1}^{N1} P_{\text{cap},i}^{\text{CHP}} \cdot \lambda_1^{\text{CHP}} + \sum_{j=1}^{N2} P_{\text{cap},j}^{\text{CON}} \cdot \lambda_1^{\text{CON}} - P_t^{\text{E}} \tag{16}$$

where P_t^{WF} is the generated wind power; $P_{\mathrm{MIN}}^{\mathrm{OTH}}$ is the minimum power output of non-coal-fired units; $P_{\mathrm{cap},j}^{\mathrm{CON}}$ is the power capacity of the j-th coal-fired condensing (CON) unit; $N2$ is the total number of CON units; λ_1^{CON} is the first base line of deep peak-shaving of the CON unit; and P_t^{E} is the electric power load. If $P_t^{\mathrm{G}} \leq 0$, there is no need for deep peak-shaving.

Depending on the amount of wind power, P_t^{G} can be divided into five scenarios. As shown in Figure 2, P_t^{G} satisfies different conditions in each scenario:

Scenario 1 (S1):
$$0 < P_t^{\mathrm{G}} \leq P_t^{\mathrm{PH1}} \tag{17}$$

Scenario 2 (S2):
$$P_t^{\mathrm{PH1}} < P_t^{\mathrm{G}} \leq P_t^{\mathrm{sup1}} + \Delta P_t^{\mathrm{E1}} \tag{18}$$

Scenario 3 (S3):
$$\begin{aligned} & P_t^{\mathrm{sup1}} + \Delta P_t^{\mathrm{E1}} < P_t^{\mathrm{G}} \leq P_t^{\mathrm{sup1}} + \Delta P_t^{\mathrm{E1}} + P_{\Sigma 1}^{\mathrm{CON}} \\ & P_{\Sigma 1}^{\mathrm{CON}} = \sum_{j=1}^{N2} P_{\mathrm{cap},j}^{\mathrm{CON}} \cdot (\lambda_1^{\mathrm{CON}} - \lambda_2^{\mathrm{CON}}) \end{aligned} \tag{19}$$

Scenario 4 (S4):
$$P_t^{\mathrm{sup1}} + \Delta P_t^{\mathrm{E1}} + P_{\Sigma 1}^{\mathrm{CON}} < P_t^{\mathrm{G}} \leq P_t^{\mathrm{sup1}} + P_{\Sigma 1}^{\mathrm{CON}} + P_t^{\mathrm{sup2}} + \Delta P_t^{\mathrm{E2}} \tag{20}$$

Scenario 5 (S5):
$$P_t^{\mathrm{G}} > P_t^{\mathrm{sup1}} + P_{\Sigma 1}^{\mathrm{CON}} + P_t^{\mathrm{sup2}} + \Delta P_t^{\mathrm{E2}} \tag{21}$$

where $P_{\Sigma 1}^{\mathrm{CON}}$ is the deep peak-shaving capacity at the first level available from the CON plant; and λ_2^{CON} is the second base line of deep peak-shaving of the CON unit.

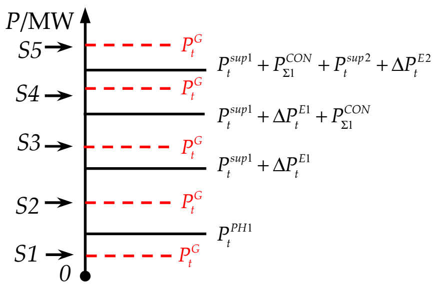


Figure 2. P_t^G under different scenarios.

2.3. Deep Peak-Shaving Income of the CHP Plant

The peak-shaving income of the CHP plant depends on the actual deep peak-shaving capacity utilized by the power grid. The income is calculated in each scenario.

S1: In this scenario, the running power of the P2H equipment is P_t^{PH1} when the CHP units reduce the power output to the first base line of deep peak-shaving. In fact, there is no need for the CHP units to run at the first base line of deep peak-shaving because the power consumed by the P2H equipment is much greater than P_t^{G}. Thus, the running power of the CHP units and the P2H equipment are regulated simultaneously to make the redundant wind power equal to zero.

$$P_t^{\mathrm{WF}} + P_{\mathrm{MIN}}^{\mathrm{OTH}} + k_{\mathrm{av}}(Q_t^{\mathrm{H}} - P_t^{\mathrm{PH}}|_{S1} \cdot \eta) + \sum_{i=1}^{N1} b_i + \sum_{j=1}^{N2} P_{\mathrm{cap},j}^{\mathrm{CON}} \cdot \lambda_1^{\mathrm{CON}} - P_t^{\mathrm{E}} - P_t^{\mathrm{PH}}|_{S1} = 0 \tag{22}$$

The actual running power of the P2H equipment is derived as:

$$P_t^{\mathrm{use1}}\Big|_{S1} = 0 \tag{23}$$

$$P_t^{\mathrm{use2}}\Big|_{S1} = 0 \tag{24}$$

$$P_t^{\mathrm{PH}}|_{S1} = \frac{k_{\mathrm{av}} \cdot Q_t^{\mathrm{H}} + \sum_{i=1}^{N1} b_i + \sum_{j=1}^{N2} P_{\mathrm{cap},j}^{\mathrm{CON}} \cdot \lambda_1^{\mathrm{CON}} + P_t^{\mathrm{WF}} + P_{\mathrm{MIN}}^{\mathrm{OTH}} - P_t^{\mathrm{E}}}{1 + k_{\mathrm{av}} \cdot \eta} \tag{25}$$

where P_t^{use1} and P_t^{use2} are the first and second levels of deep peak-shaving capacities actually provided by the CHP units in S1, respectively.

S2: In this scenario, P_t^{G} is equal to the sum of the deep peak-shaving capacity provided by the CHP units and the power consumed by the P2H equipment.

$$P_t^{\mathrm{use1}}|_{S2} + P_t^{\mathrm{PH}}|_{S2} = P_t^{\mathrm{G}} \tag{26}$$

$$P_t^{\mathrm{use1}}|_{S2} = \sum_{i=1}^{N1} P_{\mathrm{cap},i}^{\mathrm{CHP}} \cdot \lambda_1^{\mathrm{CHP}} - \left(k_{\mathrm{av}} \left(Q_t^{\mathrm{H}} - P_t^{\mathrm{PH}}|_{S2} \cdot \eta \right) + \sum_{i=1}^{N1} b_i \right) = k_{\mathrm{av}} \cdot \eta \cdot \left(P_t^{\mathrm{PH}}|_{S2} - P_t^{\mathrm{PH1}} \right) \tag{27}$$

The actual deep peak-shaving capacity provided by the CHP units and the actual running power of the P2H equipment are derived as follows:

$$P_t^{\mathrm{use1}}|_{S2} = \frac{k_{\mathrm{av}} \cdot \eta \cdot \left(P_t^{\mathrm{G}} - P_t^{\mathrm{PH1}} \right)}{1 + k_{\mathrm{av}} \cdot \eta} \tag{28}$$

$$P_t^{\mathrm{use2}}|_{S2} = 0 \tag{29}$$

$$P_t^{\mathrm{PH}}|_{S2} = \frac{P_t^{\mathrm{G}} + k_{\mathrm{av}} \cdot \eta \cdot P_t^{\mathrm{PH1}}}{1 + k_{\mathrm{av}} \cdot \eta} \tag{30}$$

S3: In this scenario, the total power capacity of the first deep peak-shaving level of the CHP units and the power capacity provided by the P2H equipment are used, and some of the power capacity in the first deep peak-shaving region of the CON units is required. The actual deep peak-shaving capacity provided by the CHP units and the actual running power of the P2H equipment are derived as follows:

$$P_t^{\mathrm{use1}}|_{S3} = P_t^{\mathrm{sup1}} \tag{31}$$

$$P_t^{\mathrm{use2}}|_{S3} = 0 \tag{32}$$

$$P_t^{\mathrm{PH}}|_{S3} = \Delta P_t^{\mathrm{E1}} \tag{33}$$

S4: In this scenario, apart from the total power capacity of the first deep peak-shaving level of the CHP units and the CON units, a part of the power capacity of the second deep peak-shaving level of the CHP units is required by the power grid.

$$P_t^{\mathrm{sup1}} + P_{\Sigma 1}^{\mathrm{CON}} + P_t^{\mathrm{use2}}|_{S4} + P_t^{\mathrm{PH}}|_{S4} = P_t^{\mathrm{G}} \tag{34}$$

$$P_t^{\mathrm{use2}}|_{S4} = k_{\mathrm{av}} \cdot \eta \cdot \left(P_t^{\mathrm{PH}}|_{S4} - P_t^{\mathrm{PH2}} \right) \tag{35}$$

The actual deep peak-shaving capacity provided by the CHP units and the actual running power of the P2H equipment are derived as follows:

$$P_t^{\mathrm{use1}}|_{S4} = P_t^{\mathrm{sup1}} \tag{36}$$

$$P_t^{\text{use2}}|_{S4} = \frac{k_{\text{av}} \cdot \eta \cdot (P_t^{\text{G}} - P_t^{\text{sup1}} - P_{\Sigma 1}^{\text{CON}} - P_t^{\text{PH2}})}{1 + k_{\text{av}} \cdot \eta} \tag{37}$$

$$P_t^{\text{PH}}|_{S4} = \frac{P_t^{\text{G}} - P_t^{\text{sup1}} - P_{\Sigma 1}^{\text{CON}} + k_{\text{av}} \cdot \eta \cdot P_t^{\text{PH2}}}{1 + k_{\text{av}} \cdot \eta} \tag{38}$$

S5: In this scenario, the total deep peak-shaving capacity of the CHP units is used. The actual deep peak-shaving capacity provided by the CHP units and the actual running power of the P2H equipment are derived as follows:

$$P_t^{\text{use1}}|_{S5} = P_t^{\text{sup1}} \tag{39}$$

$$P_t^{\text{use2}}|_{S5} = P_t^{\text{sup2}} \tag{40}$$

$$P_t^{\text{PH}}|_{S5} = \Delta P_t^{\text{E2}} \tag{41}$$

Considering S1–S5, the peak-shaving income of the CHP plant is derived from the peak-shaving service provided by the CHP units and the P2H equipment. The income of each scenario is given by:

$$B_{s,t}^{\text{get}} = [P_t^{\text{PH}} \cdot U_d^{\text{PH}} + P_t^{\text{use1}} \cdot U_d^1 + P_t^{\text{use2}} \cdot U_d^2] \cdot \Delta t \tag{42}$$

where s is the serial number of each scenario; U_d^{PH} is the transaction price of the power capacity provided by the P2H equipment on the d-th day in heating season; and U_d^1 and U_d^2 are transaction prices of the deep peak-shaving capacity at the first and second level, respectively.

On the d-th day in heating season, the total deep peak-shaving income of the CHP plant, denoted as $B_{\text{get},d}^{\text{CHP}}$, is given by

$$B_{\text{get},d}^{\text{CHP}} = \sum_{s=1}^{5} \sum_{t \in T_s} B_{s,t}^{\text{get}} \tag{43}$$

where T_s is the set of scheduling time intervals of the s-th scenario.

3. Optimal Configuration of the P2H Equipment

When investors decide whether to invest in a new project, they tend to focus on the payback period [32]. Therefore, the static payback time (SPT) is used as the core index to measure the comprehensive benefit the CHP plant can obtain by installing the P2H equipment:

$$\min \quad \text{SPT} = \frac{C_{\text{sum}}^{\text{PH}}}{\sum\limits_{d=1}^{D} B_d^{\text{PH}}} \tag{44}$$

where $C_{\text{sum}}^{\text{PH}}$ is the total fixed cost; B_d^{PH} is the daily income of the P2H equipment; and D is the total number of days in the heating season. If the SPT is smaller than the lifetime, it means that a return on investment can be obtained during the life cycle of the P2H equipment. The smaller the SPT, the higher the return on investment.

3.1. Total Fixed Cost of the P2H Equipment

The total fixed cost consists of the initial construction cost and fixed maintenance cost:

$$C_{\text{sum}}^{\text{PH}} = (1 + y^{\text{PH}} \cdot \varepsilon_{\text{safe}}^{\text{PH}}) \cdot P_{\text{cap}}^{\text{PH}} \cdot c^{\text{PH}} \tag{45}$$

where y^{PH} is the lifetime of the P2H equipment; $\varepsilon_{\text{safe}}^{\text{PH}}$ is the ratio of maintenance cost; and c^{PH} is the unit price of the P2H equipment, including auxiliaries.

3.2. Operation Income of the P2H Equipment

The coal cost, carbon trading cost, and apportioned compensation cost of deep peak-shaving paid by the CHP plant can be reduced by installing the P2H equipment for auxiliary heating. In addition, the deep peak-shaving income is expected to increase as the CHP plant gets more opportunities to participate in the peak-shaving ancillary service market. Thus, the operation income generated by the P2H equipment during the heating season can be expressed as follows:

$$\sum_{d=1}^{D} B_d^{\mathrm{PH}} = \sum_{d=1}^{D} (B_d^{\mathrm{coal}} + B_d^{\mathrm{co}_2} + \Delta B_{\mathrm{get},d}^{\mathrm{CHP}} + \Delta B_{\mathrm{pay},d}^{\mathrm{CHP}}) \tag{46}$$

where B_d^{coal}, $B_d^{\mathrm{co}_2}$, and $\Delta B_{\mathrm{pay},d}^{\mathrm{CHP}}$ are the reduced coal cost, carbon trading cost, and apportioned compensation cost of deep peak-shaving, respectively; and $\Delta B_{\mathrm{get},d}^{\mathrm{CHP}}$ is the increased deep peak-shaving income.

According to the operation rules of the peak-shaving ancillary service market, the reduced electric power of the CHP plant during the heating season should be compensated during other months within the same year. This means that the total electric power produced by the CHP plant remains unchanged over one year. Therefore, the saved coal cost and carbon trading cost only depend on the actual thermal power of the CHP units replaced by the P2H equipment:

$$B_d^{\mathrm{coal}} = \Delta Q_{\mathrm{coal}} \cdot U_{\mathrm{coal}} \tag{47}$$

$$B_d^{\mathrm{co}_2} = \Delta Q_{\mathrm{coal}} \cdot \alpha_{\mathrm{co}_2} \cdot U_{\mathrm{co}_2} \tag{48}$$

$$\Delta Q_{\mathrm{coal}} = (\sum_{s=1}^{5} \sum_{t \in T_s} P_t^{\mathrm{PH}}) \cdot \eta \cdot \Delta t \cdot Q_{\mathrm{coal}} \tag{49}$$

where U_{coal} and U_{co_2} are the unit prices of coal and carbon trading, respectively; α_{co_2} is the carbon emission coefficient of standard coal; and ΔQ_{coal} is the total reduced coal for thermal power production.

The operation rules of the peak-shaving ancillary service market stipulate that the coal-fired units, which are unable to provide deep peak-shaving capacity, must share in the compensation cost of deep peak-shaving paid to other units that have fulfilled the deep peak-shaving mandate. The compensation cost shared by the CHP plant is given by

$$B_{\mathrm{pay},d}^{\mathrm{CHP}} = \frac{B_{\mathrm{get},d}^{\mathrm{CON}} \cdot \sum_{i=1}^{N1} E_{i,d}^{\mathrm{CHP}}}{\sum_{i=1}^{N1} E_{i,d}^{\mathrm{CHP}} + E_d^{\mathrm{WF}} + E_d^{\mathrm{SO}} + E_d^{\mathrm{NU}}} \tag{50}$$

$$\sum_{i=1}^{N1} E_{i,d}^{\mathrm{CHP}} = \sum_{t=1}^{T_w} (\sum_{x=1}^{3} \sum_{i=1}^{N1} P_{\mathrm{MIN},i,t}^{\mathrm{CHP}} \cdot \Delta t \cdot k_x) \tag{51}$$

$$B_{\mathrm{get},d}^{\mathrm{CON}} = \begin{cases} \sum_{t=1}^{T_w} P_t^{\mathrm{G}} \cdot \Delta t \cdot U_d^1 & \text{, if } P_t^{\mathrm{G}} \le P_{\Sigma 1}^{\mathrm{CON}} \\ \sum_{t=1}^{T_w} [P_{\Sigma 1}^{\mathrm{CON}} \cdot \Delta t \cdot U_d^1 + \min\left\{ P_t^{\mathrm{G}} - P_{\Sigma 1}^{\mathrm{CON}}, \sum_{j=1}^{N2} P_{\mathrm{cap},j}^{\mathrm{CON}} \lambda_2^{\mathrm{CON}} - P_{\mathrm{MIN}}^{\mathrm{CON}} \right\} \cdot \Delta t \cdot U_d^2] & \text{, if } P_t^{\mathrm{G}} > P_{\Sigma 1}^{\mathrm{CON}} \end{cases} \tag{52}$$

where $E_{i,d}^{\mathrm{CHP}}$, E_d^{WF}, E_d^{SO}, and E_d^{NU} are the daily modified power production values of the CHP units, wind power generators, solar power generators, and nuclear power generators, respectively; k_x is the correction factor; T_w is the set of scheduling time intervals during which $P_t^{sup} = 0$; and P_{MIN}^{CON} is the minimum power generated by the CON plant. Then, $\Delta B_{pay,d}^{CHP}$ can be calculated based on Equations (50)–(52):

$$\Delta B_{pay,d}^{CHP} = B_{pay,d}^{CHP}\_0 - B_{pay,d}^{CHP}\_1 \quad (53)$$

where $B_{pay,d}^{CHP}\_1$ and $B_{pay,d}^{CHP}\_1$ are the compensation costs apportioned by the CHP plant with and without the P2H equipment, respectively.

Next, $\Delta B_{get,d}^{CHP}$ can be calculated based on Equation (43):

$$\Delta B_{get,d}^{CHP} = B_{get,d}^{CHP}\_1 - B_{get,d}^{CHP}\_0 \quad (54)$$

where $B_{get,d}^{CHP}\_1$ and $B_{get,d}^{CHP}\_0$ are the deep peak-shaving incomes achieved by the CHP plant with and without the P2H equipment, respectively.

4. Case Studies

Jilin province is a typical region that depends on CHP units for central heating, and it is also a pioneering pilot area for implementing the auxiliary service market policy. Thus, a simplified region power system based on the power system of Jilin province is used in case studies. The installed capacities of the CHP unit, CON unit, wind power generator, and other types of generators are 600 MW (40.54%) (300 MW × 2), 350 MW (23.65%), 250 MW (16.89%), and 280 MW (18.92%), respectively. The typical load curves of thermal power and electric power are shown in Figure 3. The curve in Figure 3a is the typical daily load curve in winter. The heating period is from 5 October 2021 to 10 April 2022 with a total of 168 days. Curves in Figure 3b represent the average thermal load per month. The scheduling period is 24 h and each time interval is 15 min. In the northeast region, the first and second deep peak-shaving base lines of the CHP unit are 50% and 40%, respectively. The first and second deep peak-shaving base lines of the CON unit are 48% and 40%, respectively. To simplify calculations, the quotations for the deep peak-shaving services provided by the CHP units and CON units are assumed to be the same, namely, $U_d^1 = 0.32$ ¥/kWh and $U_d^2 = 0.8$ ¥/kWh. The quotation for the power capacity provided by the P2H equipment is $U_d^{PH} = 0.2$ ¥/kWh. Other parameters are listed in Table 1.

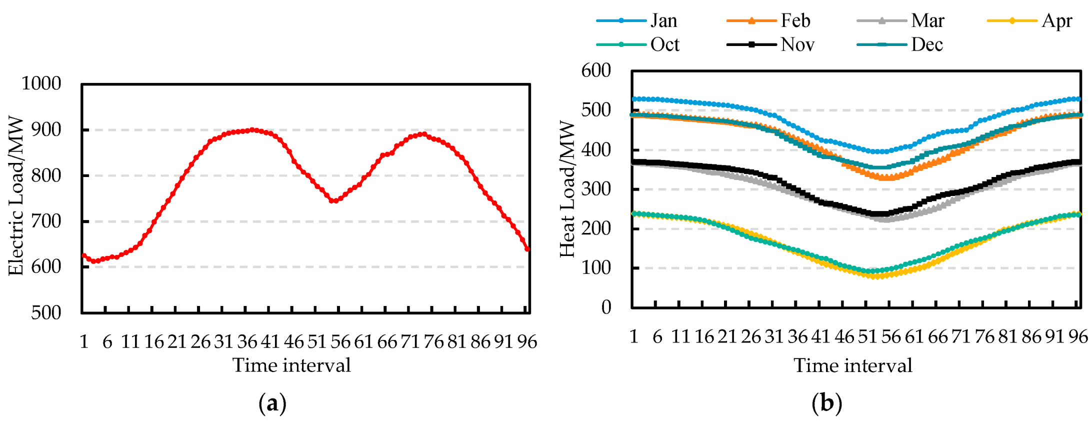


Figure 3. (**a**) Electric power curves; (**b**) Thermal power curves.

Table 1. Technical and economic parameters.

Parameters	P_{MIN}^{CHP}	P_{MIN}^{CON}	P_{MIN}^{OTH}	Q_M^{CHP}	U_{coal}	Q_{coal}	U_{co_2}	α_{co_2}	k_{av}
Value	114 MW	105 MW	56 MW	73.4 MW	840 ¥/ton	135 kg/kWh	56 ¥/ton	2.66	0.45

4.1. Analysis of the Deep Peak-Shaving Ability of the CHP Plant without the P2H Equipment

The P_t^G of each time interval during the heating season is calculated according to Equation (16), and the distribution diagram is displayed in Figure 4. The color bar on the right side of Figure 4 presents the magnitude of P_t^G. The demand for deep peak-shaving is mainly concentrated in time intervals of 1–21 and 86–96, namely 0:00–5:00 and 21:30–0:00. Sometimes—such as on days 90–94—redundant wind power could also be presented during time intervals of 49–63 except early morning and night. Moreover, sometimes—such as on days 163–168—there is little redundant wind power all day. There are 16,128 time intervals during the heating season, including 5696 time intervals where deep peak-shaving is needed. Overall, the demand for deep peak-shaving is high.

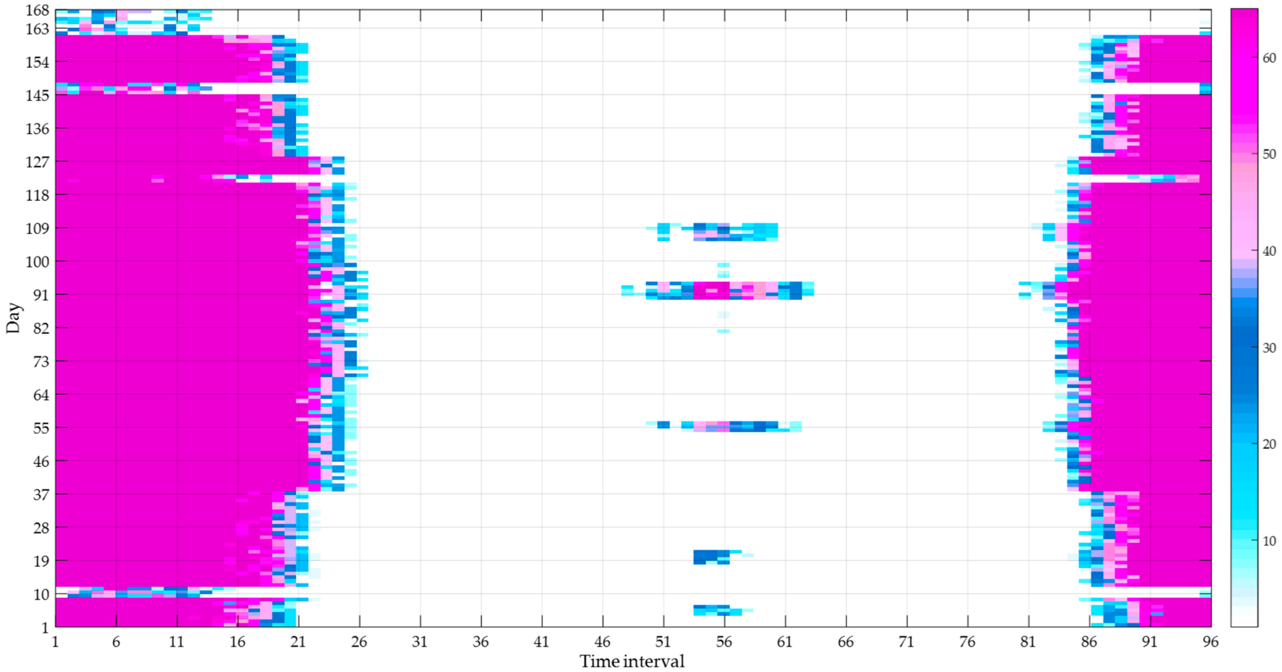


Figure 4. P_t^G of each time interval during the heating season.

In Figure 5, the deep peak-shaving income and apportioned cost of the CHP plant without P2H equipment are evaluated. For most of the time, the CHP plant has to share the deep peak-shaving compensation paid to the CON plant since the CHP units are unable to provide a deep peak-shaving service without the assistance of P2H equipment. The total apportioned cost is up to 1952.36 k¥, but the deep peak-shaving income is only 81.03 k¥. The time intervals when deep peak-shaving is required by the power grid are equal to the time intervals when the heating demand is high. The CHP units have to prioritize the need for heating, and this inflexibility causes them to lose opportunities to compete in the ancillary service market.

4.2. Analysis of Economic Benefits with Different P2H Equipment

Since the P2H equipment acts as an auxiliary heater, the CHP units can reduce their electric power and thermal power outputs. The EB and HP are recognized as excellent auxiliary heating devices. To choose the most suitable equipment for the CHP plant, comparative analysis is carried out in the following case studies. The parameters of the EB and HP are listed in Table 2.

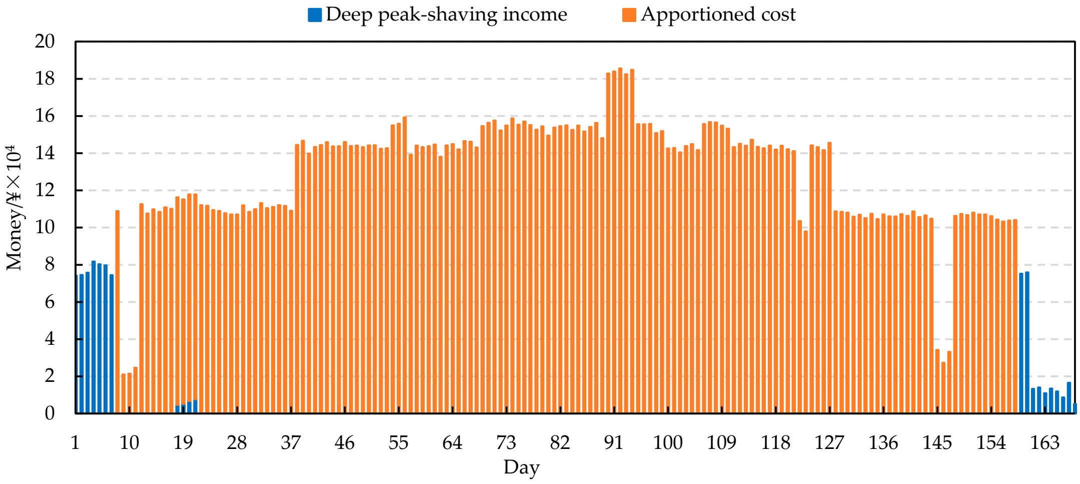


Figure 5. Deep peak-shaving income and apportioned cost of the CHP plant without P2H equipment.

Table 2. Parameters of the EB and HP.

Parameters	η	y^{PH}	ε^{PH}_{safe}	c^{PH}
EB	95%	20 years	30%	980 k¥/MW
HP	3.5	20 years	15%	4500 k¥/MW

The enumeration method is used to get the optimal value. Considering that the average heat load of seven heating months is about 328 MW and the total thermal power produced by the CHP units is about 173 MW when they are running at the second base line of deep peak-shaving, the thermal power provided by the P2H equipment is 155 MW. The searching upper limits for optimizing the capacities of the EB and HP are set as 163 MW and 48 MW, respectively. To make the result more precise, the optimal value is first found with a step size of 1 MW, and then the step size is narrowed down to 0.1 MW for secondary optimization calculation.

It can be seen from Figure 6 that the optimal SPTs are 15.9 and 17.9 when the HP and EB are set as 19 MW and 67 MW, respectively. For the HP, the SPTs are less than 20 most of the time. In contrast, for the EB, the SPTs are greater than 20 most of the time. Therefore, adding the HP as an auxiliary heater may help the CHP plant achieve a better economy.

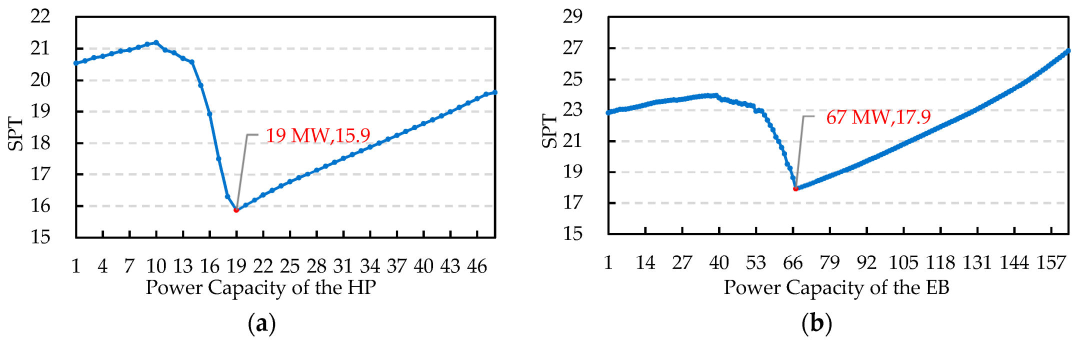


Figure 6. (**a**) SPT of the HP with different capacities; (**b**) SPT of the EB with different capacities.

The key economic parameters are given in Table 3. Compared to the situation without P2H equipment, both the EB and the HP improve the deep peak-shaving ability of the CHP units, contributing to the reduction of apportioned compensation cost and the increase of deep peak-shaving income. Due to the larger capacity of the EB compared to the HP, the trading power and peak-shaving income of the EB in the ancillary service market are greater than those of the HP. However, the energy efficiency of the HP is significantly higher than that of the EB, and the thermal power produced by the HP is greater than that of the EB. Thus, the saved coal cost and carbon trading cost resulting from the thermal power of the CHP units replaced by the HP exceed those of the EB. Although the total operation income, denoted by $\sum B_d^{\text{PH}}$, of the EB is slightly higher than that of the HP, the power capacity of the EB is much greater, leading to a higher total cost of the EB. Overall, it is preferable to invest in the HP rather than the EB.

Table 3. Economic comparison between the EB and HP.

Parameters	$\sum B_{\text{get},d}^{\text{CHP}}$/¥ × 10⁴	$\sum B_{\text{pay},d}^{\text{CHP}}$/¥ × 10⁴	$\sum B_d^{\text{coal}}$/¥ × 10⁴	$\sum B_d^{\text{co}_2}$/¥ × 10⁴	$\sum B_d^{\text{PH}}$/¥ × 10⁴	$C_{\text{sum}}^{\text{PH}}$/¥ × 10⁴
Without P2H	81.03	1952.36	0	0	0	0
EB = 67 MW	563.15	787.18	780.33	138.38	2566.01	45,962
HP = 19 MW	293.91	1074.30	904.04	160.32	2155.30	34,200

The optimal capacity of the HP is 19 MW when the step size is 1 MW. In order to obtain a more accurate value, the step sizes are set to 0.1 MW and 0.01 MW for second- and third-round optimizations, respectively. The search range of the second-round optimization is 18 MW to 20 MW and the results are shown in Figure 7a. The optimal value is 18.1 MW. Hence, the search range of the third-round optimization is 18 MW to 18.2 MW and the results are shown in Figure 7b. The optimal value is still 18.1 MW. Finally, the optimal capacity of the HP is set as 18.1 MW.

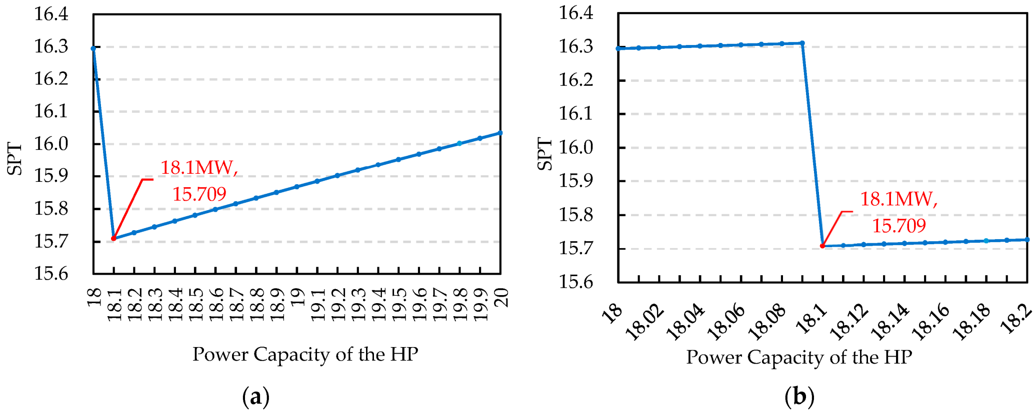


Figure 7. (**a**) Enumeration optimization result with a step size 0.1 MW; (**b**) Enumeration optimization result with a step size 0.01 MW.

Due to the fact that the results obtained by the enumeration method are discrete values, there exists a certain amount of error in the results. The smaller the step size set, the smaller the error will be. As the focus of this article is on exploring the optimization model of the P2H equipment rather than the solution methods, more detailed solutions will not be provided in this case study.

4.3. Analysis of Deep Peak-Shaving Ability of the CHP Plant with an HP

The deep peak-shaving capacities of the first and second levels that can be provided by the CHP units without the P2H equipment are 33.16 kWh × 10^6 and 2.09 kWh × 10^6, respectively. In Figure 8a, the available deep peak-shaving capacities from the CHP units with different capacities of the HP are plotted. The deep peak-shaving ability of the CHP cannot be released if the capacity of the HP is too small. The deep peak-shaving capacity of the first level available from the CHP units tends to increase when the capacity of the HP is greater than 8 MW, especially when the capacity is greater than 16 MW. From Equations (7)–(9), the P_t^{PH2} is much higher than 48 MW during the peak heating periods, so the deep peak-shaving capacity of the second level is not increased when the HP is set as 1–48 MW. Hence, in Figure 8b, only the deep peak-shaving capacity of the first level provided by the CHP units is plotted. The deep peak-shaving ability of the CHP is gradually improved along with the growth of the HP capacity. When the HP capacity is greater than 18 MW, the CHP units can provide deep peak-shaving capacity of the first level under different scenarios, leading to more deep peak-shaving income. Furthermore, from Figure 9, it can be seen that the deep peak-shaving capacity of the second level available from the CHP units is very limited, and P_t^{sup2} is equal to zero most of the time. This is why there are no data grouped into S4 in Figure 8b.

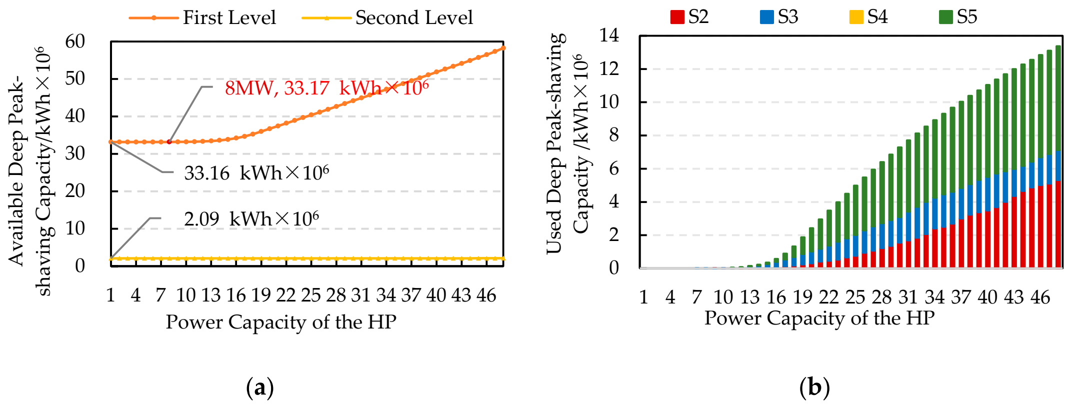


Figure 8. (**a**) Available deep peak-shaving capacity of the CHP units; (**b**) Actually used deep peak-shaving capacity of the first level provided by the CHP units.

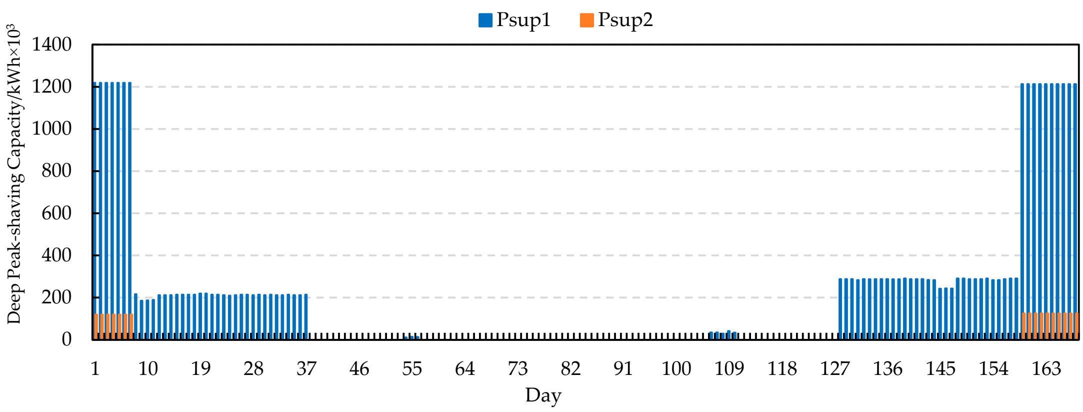
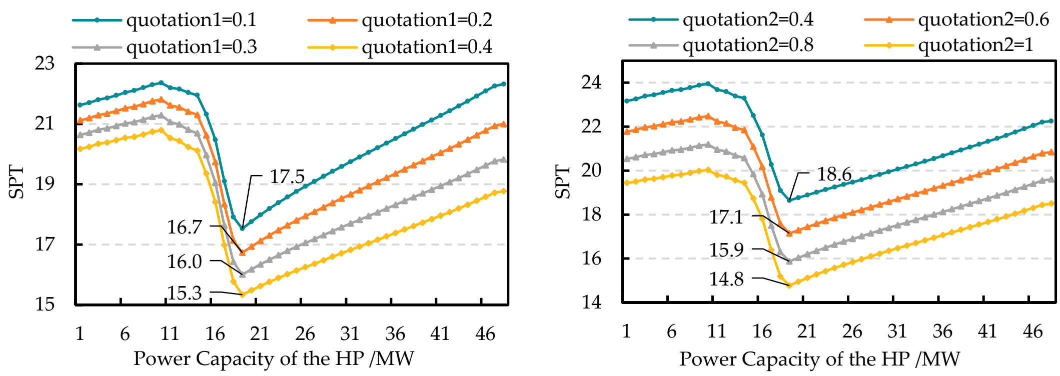


Figure 9. Deep peak-shaving capacity can be supplied by the CHP units when the HP is 19 MW.

4.4. Analysis of Influence Factors of the Optimal P2H Equipment Capacity

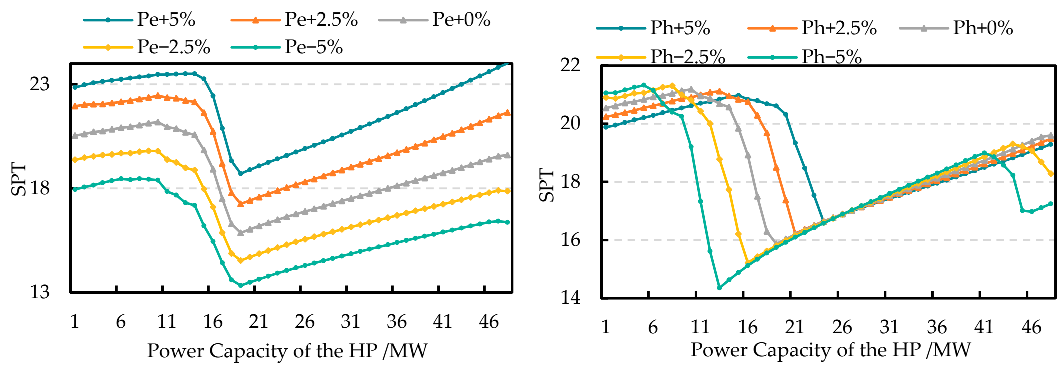
From Equations (44)–(54), the optimal P2H equipment capacity is related to several factors. Considering that the correlation of the maintenance cost and the equipment price of the HP with the peak-shaving ancillary service market is weak, this paper mainly discusses the effects of the quotation, power load, heat load, and wind power variation on the SPT. The first level quotation varies from 0.1 ¥/kWh to 0.4 ¥/kWh with the step size set as 0.1 ¥/kWh. The second level quotation varies from 0.4 ¥/kWh to 1 ¥/kWh with the step size set as 0.1 ¥/kWh. The level of power load varies from −5% to +5% with the step size set as 2.5%, and the variations of the heat load and the wind power are the same. For simplicity, only one round of optimization is conducted in the subsequent analysis.

It can be concluded from Figure 10 that the SPT is positively correlated with the quotation. Even when the quotation is at a minimum, the SPT remains lower than the lifetime of the HP, indicating that the CHP plant can achieve a positive return. Thus, installing the HP to improve the peak-shaving ability will enhance the CHP plant's participation in the peak-shaving ancillary service market. Figure 11a shows that the SPT is higher when the level of power load is lower. In contrast, Figure 12 indicates that the SPT is higher when the level of wind power is higher. This is because when the level of power load decreases or the wind power increases, the deep peak-shaving capacity required by the power grid will increase. Then, the deep peak-shaving capacity provided by the CHP plant will be utilized more, contributing to greater peak-shaving income. Therefore, the economic benefit of investing in HP is likely to increase over time due to the growing trend of wind power.



(**a**) (**b**)

Figure 10. (**a**) Effect of the first level quotation variation on the SPT; (**b**) Effect of the second level quotation variation on the SPT.



(**a**) (**b**)

Figure 11. (**a**) Effect of power load variation on the SPT; (**b**) Effect of heat load variation on the SPT.

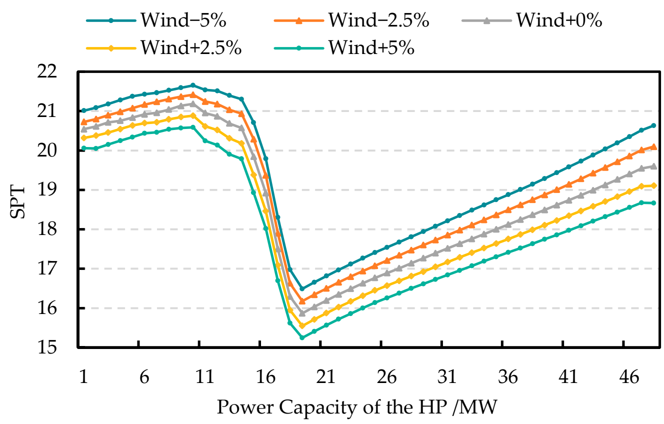


Figure 12. Effect of wind power variation on the SPT.

In Figure 11b, we can observe a significant change in the optimal value when the heat load changes. However, in reality, the level of heat load served by the CHP plant will not change in the short term unless the scale of the CHP plant is expanded. Therefore, the impact of heat load on the optimization result can be ignored. Apart from the heat load, when other factors vary, the optimal capacity of the HP remains constant at 19 MW. Therefore, even if there is a deviation between historical and real-time data of quotation values, power load, and wind power, it will not affect the optimization results. This indicates that the optimization model proposed in this study is feasible and stable.

Currently, most areas in northern China have implemented the ancillary service market peaking. Moreover, many regions in northern China, such as Jilin province, rely on CHP units for central heating. Therefore, the proposed method is applicable to most northern regions of China.

5. Conclusions

Aiming to solve the problem of wind power curtailment caused by the limited peak-shaving ability of the power system, this study explores the feasibility of installing P2H equipment at the CHP plant side to improve the peak-shaving ability of CHP units. An optimal configuration model of the P2H equipment is established considering the economic benefits of the CHP plant in the ancillary service market. Case studies are carried out using the CHP system of Jilin province as a typical example. The impact of the P2H equipment on the peak-shaving ability and economic benefits of the CHP plant is discussed in detail with numerical studies. Several conclusions are drawn as follows:

(1) It is necessary for the CHP plant to invest in P2H equipment in order to improve the peak-shaving ability of the CHP units.
(2) It is beneficial for the CHP plant to invest in P2H equipment considering the economic benefits that may be obtained in the ancillary service market.
(3) Due to higher energy conversion efficiency of the HP, investing in the HP has better economic benefits than investing in the EB. Furthermore, with the trend of continuous growth in wind power scale, the CHP plant will achieve higher investment returns.
(4) The optimal capacity of the HP will not be affected by the deviation between historical and real-time data of quotation value, power load, and wind power. The optimization model proposed in this study is feasible and stable.

In summary, it is beneficial for the CHP plant to promote its deep peak-shaving ability and enthusiasm simultaneously by installing HP, thereby fundamentally helping to address the peak-shaving problem of the power grid.

In this study, the CHP plants in the power system are regarded as an investment portfolio. In the future, we intend to conduct advanced studies on the economic benefits of investing in HP for individual CHP plants. Details of deep peak-shaving benefits of each CHP plant will be discussed, and the optimal allocation strategy of the HP capacity among different CHP plants will be explored.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to that most of the data comes from the power grid company and the data is required to be confidential.

Conflicts of Interest: The authors declare that they have no conflict of interest.

Nomenclature

$Q_{i,t}^{\mathrm{CHP}}$	thermal power output of the *i*-th CHP unit, MW
$Q_{\mathrm{MAX},i}^{\mathrm{CHP}}$	maximum thermal power output of the *i*-th CHP unit, MW
$Q_{\mathrm{M},i}^{\mathrm{CHP}}$	maximum thermal power output of the *i*-th CHP when the unit is operated at the minimum running power, MW
P_t^{PH}	running power of the P2H equipment, MW
$P_{\max,t}^{\mathrm{PH}}$	maximum running power of the P2H equipment, MW
$P_{\mathrm{cap}}^{\mathrm{PH}}$	power capacity of the P2H equipment, MW
Q_t^{H}	heat load, MW
$P_{i,t}^{\mathrm{CHP}}$	generated electric power of the *i*-th CHP unit, MW
$P_{\mathrm{MIN},i}^{\mathrm{CHP}}$	minimum electric power output of the *i*-th CHP unit, MW
$P_{\mathrm{cap},i}^{\mathrm{CHP}}$	power capacity of the *i*-th CHP unit, MW
P_t^{PH1}	running power of the P2H equipment when CHP units running at the first base line of deep peak-shaving, MW
P_t^{PH2}	running power of the P2H equipment when CHP units running at the second base line of deep peak-shaving, MW
P_t^{PH3}	running power of the P2H equipment when CHP units running at the minimum power output, MW
P_t^{sup1}	deep peak-shaving capacity at the first level available from the CHP plant, MW
P_t^{sup2}	deep peak-shaving capacity at the second level available from the CHP plant, MW
P_t^{G}	deep peak-shaving capacity required by the power grid, MW
P_t^{WF}	generated wind power, MW
$P_{\mathrm{MIN}}^{\mathrm{OTH}}$	minimum power output of non-coal-fired units, MW
$P_{\mathrm{cap},j}^{\mathrm{CON}}$	power capacity of the *j*-th CON unit, MW
P_t^{E}	electric power load, MW
$P_{\Sigma 1}^{\mathrm{CON}}$	deep peak-shaving capacity at the first level available from the CON plant, MW
P_t^{use1}	first level of deep peak-shaving capacity actually provided by CHP units, MW
P_t^{use2}	second level of deep peak-shaving capacity actually provided by CHP units, MW
U_d^{PH}	transaction price of the power capacity provided by the P2H equipment on the *d*-th day in heating season, ¥/kWh
U_d^1	transaction price of the deep peak-shaving capacity at the first level, ¥/kWh
U_d^2	transaction price of the deep peak-shaving capacity at the second level, ¥/kWh
E_d^{WF}	daily modified power production value of wind power generators, MW
E_d^{SO}	daily modified power production value of solar power generators, MW
E_d^{NU}	daily modified power production value of nuclear power generators, MW
$B_{\mathrm{pay},d-1}^{\mathrm{CHP}}$	compensation cost apportioned by the CHP plant with the P2H equipment, ¥
$B_{\mathrm{get},d-1}^{\mathrm{CHP}}$	deep peak-shaving income of the CHP plant with the P2H equipment, ¥
$P_{\mathrm{MIN}}^{\mathrm{CON}}$	minimum power generated by the CON plant, MW
t	index of scheduling time interval
$N1$	total number of CHP units
η	coefficient of performance
k_i^{BC}	expression coefficient
b_i	expression coefficient
k_{av}	approximate value of the electrothermal ratio

λ_1^{CHP}	first base line of deep peak-shaving set for the CHP unit
λ_2^{CHP}	second base line of deep peak-shaving set for the CHP unit
$N2$	total number of CHP units
λ_1^{CON}	first base line of deep peak-shaving set for the CON unit
λ_2^{CON}	second base line of deep peak-shaving set for the CON unit
D	total days of the heating season
y^{PH}	lifetime of the P2H equipment
$\varepsilon_{\mathrm{safe}}^{\mathrm{PH}}$	ratio of maintenance cost
$\alpha_{\mathrm{co_2}}$	carbon emission coefficient of standard coal
k_x	correction factor
T_w	set of scheduling time intervals during which $P_t^{sup} = 0$
$B_{\mathrm{get},d}^{\mathrm{CHP}}$	deep peak-shaving income of the CHP plant, ¥
B_d^{PH}	daily income of the P2H equipment, ¥
$C_{\mathrm{sum}}^{\mathrm{PH}}$	total fixed cost of the of the P2H equipment, ¥
c^{PH}	unit price of the P2H equipment, ¥/MW
B_d^{coal}	reduced coal cost, ¥
$B_d^{\mathrm{co_2}}$	reduced carbon trading cost, ¥
$\Delta B_{\mathrm{pay},d}^{\mathrm{CHP}}$	reduced compensation cost of deep peak-shaving apportioned by the CHP plant, ¥
$\Delta B_{\mathrm{get},d}^{\mathrm{CHP}}$	increased deep peak-shaving income, ¥
U_{coal}	unit price of coal, ¥/ton
$U_{\mathrm{co_2}}$	unit price of carbon trading, ¥/ton
ΔQ_{coal}	reduced coal for thermal power production, ton
$E_{i,d}^{\mathrm{CHP}}$	daily modified power production value of CHP units, MW
$B_{\mathrm{pay},d-}^{\mathrm{CHP}}0$	compensation cost apportioned by the CHP plant without the P2H equipment, ¥
$B_{\mathrm{get},d-}^{\mathrm{CHP}}0$	deep peak-shaving income of the CHP plant without the P2H equipment, ¥

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