

Article

Optimal Dispatch of Multi-Type CHP Units Integrated with Flexibility Renovations for Renewable Energy Accommodation

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Abstract: Driven by the goals of carbon neutral and carbon peak, coal power units need increased flexibility in peak shaving to accommodate intermittent renewables, especially for a region with a large proportion of combined heat and power (CHP) units in China. In this study, the data-mining-based method is proposed for revealing and utilizing the heat–power coupling mechanism of CHP units, which can be used to solve the mentioned issues. Specifically, extraction-condensing (EC) units, high-back-pressure (HBP) units and low-pressure turbine zero power output (LZPO) units are introduced into the proposed dispatch model for maximizing renewable energy accommodation. The operation schemes and the feasible minimum output power of the CHP system under one certain heat load are obtained via the genetic algorithm. Results show that the CHP system is capable of reducing its output power by 18.7% to 41.7% in the heating season, compared with the actual operation data. Furthermore, the influence of multi-type units' combination on peak-shaving flexibility is discussed. This study can be utilized for the optimal load dispatch scheme of multiple CHP units and guide the power dispatching department in making reasonable generation plans.

Keywords: combined heat and power; load dispatch; renewable energy accommodation; genetic algorithm



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1. Introduction

1.1. Research Background

Driven by the goals of carbon neutral and carbon peak in China, the role of renewables such as wind power and photovoltaic power in the restructuring of Chinese electricity is becoming increasingly prominent. Wind power and solar power are developing rapidly in China and will become the main energy source of the Chinese power system in the future. Due to the intermittent and uncontrollable nature of wind and solar energy, it will bring serious challenges to the grid [1], and renewables are also vulnerable to natural disasters and extreme weather. In the period of the energy transition process, coal power should fully cooperate with renewables and gradually change from the role of basic power supply to the role of integrated energy services, power auxiliary services, etc. Therefore, conventional coal power units are strongly required to improve their flexibility, especially peak-shaving capability, to ensure more intermittent renewables can be securely accommodated by the grid.

1.2. Literature Reviews

For the northern region of China, there is a large demand for heating in winter, so there is a relatively large proportion of combined heat and power (CHP) units. The proportion of CHP units in the northeast region, Shandong province and Shanxi province are over 50%. The amount of CHP units will continue to increase as the heating renovation proceeds. Since CHP units provide heat for civil or industrial use, their adjustable output power would be remarkably limited, which is named the heat–power coupling mechanism. For

regions with a high proportion of CHP units, the flexibility of the CHP system is severely constrained during the heating season [2]. How to overcome the heat–power coupling constraint, further depress the overall power output and improve its own power auxiliary service capacity to adapt to the growing renewables are urgent issues.

For a single CHP unit, heat–power decoupling (HPD) renovations, including thermal energy storage (TES) [3], power-to-heat (P2H) [4], low-pressure turbine (LPT) renovations [5] and high-pressure–low-pressure (HP-LP) bypass heating [6] devices, are carried out to improve the flexibility of the CHP unit. Through HPD techniques, the flexibility range of CHP units is expected to enlarge and the minimum power load decrease further. The power load can be balanced by the electrical energy storage between the production and consumption sides [7,8]. Thermal energy storages can be applied to heat load shaving [9,10]. Heat pumps and electric boilers have been widely used in HPD [11]. Blarke [12] concluded that a well-designed heat pump is more cost-effective than an electric boiler after comparing electric boilers and heat pumps in distributed cogeneration. Levihn [13] proposed a CHP plant integrated with heat pumps to balance renewable sources. Furthermore, steam turbine renovations have become popular in recent years. High-back-pressure (HBP) renovation and the low-pressure turbine zero power output (LZPO) renovation are effective techniques to improve the heating capacity of the unit or reduce the minimum power load of the unit. Wang et al. [14] established the operation region of HBP renovated units in consideration of the heating network parameters. Liu et al. [15] described that LPT renovations, such as zero-output renovation and those with a bladeless shaft, have a potential range for reducing the feasible minimum power load.

The adjustable range of a single unit is limited, and the types and operating characteristics of different CHP units are also different [16]. From the perspective of the whole CHP plant, there is more valuable space for scheduling multiple types of CHP units. Yuan et al. [17] developed an integrated weighted dispatching optimization model for five units and optimize the economic dispatching of the electric power system by particle swarm optimization algorithm. Wang et al. [18] optimized the heat–power load dispatch strategy of the CHP plant by particle swarm optimization and revealed the potential heat–power load adjustable range of the case CHP plant. Lu et al. [19] developed a robust optimization model for the load dispatch of a community energy hub, considering the electrical and thermal demand response programs. There will be the optimal heat load dispatch scheme among multiple units under a certain heat load to maximize the downward-adjustment range of the whole power load. The minimum operation mode of CHP units focuses on the start-up mode of units for the whole system and the downward-adjustment range for the power load according to dispatching the heat load rationally during the heating season. Under the current policy and environmental situation, it is of practical significance for the CHP unit to maximize the adjustable range of the system-level power loads in order to enhance the flexibility of units.

1.3. Novelty and Contributions

As mentioned in Section 1.2, previous studies established the thermodynamic systems of CHP units using design data or simulation software. However, most CHP units have been in operation for several years and have undergone several overhauls; thus, their real heat–power coupling characteristics inevitably deviate from design or simulated values. Hence, there are research gaps in modeling based on actual operational data to veritably reveal the operation characteristics of multi-type CHP units. Moreover, the above-mentioned dispatch strategies are mainly carried out for extraction–condensing (EC) units, and hardly include multi-type CHP units, i.e., HBP units and LZPO units.

In this study, the data-mining-based method is proposed for revealing and utilizing the heat–power coupling mechanism of CHP units, which reveals the operation characteristics of multi-type CHP units. According to the empirical knowledge, the relevant variables which affect the power load of different types of units should be selected. Then, the working conditions are divided according to the different operating boundaries and operating

conditions of the unit. A Gaussian process regression model is used to establish the analysis model of heat–power coupling characteristics for each type of unit. A dispatch model obtaining the feasible minimum output power is constructed, and each type of unit’s optimal load is calculated through the genetic algorithm. The optimization enables the CHP system to operate at the minimum power output while meeting the heat load for accommodating the potential increased renewables. The optimization results can not only provide a method for optimizing CHP systems which have different types of units or several renovated units, but also for selecting suitable dispatch strategies for multi-CHPs.

The rest of this study is summarized as follows. Section 2 presents the data-mining-based method and the dispatch model for multi-CHP units. In Section 3, the CHP system consisting of EC units, HBP units and LZPO units is taken as a case study. The quantitative results and useful outcomes are discussed in Section 4.

2. Methodology

2.1. Thermodynamic Modelling

CHP units mainly include back-pressure (BP) units and adjustable extraction units. To improve the flexibility of unit load adjustment, high-back-pressure modified technologies and low-pressure turbine zero-output modified technologies were proposed. The characteristics of units are changed after flexibility renovation, and the corresponding analytical model of heat–power coupling characteristics needs to be established. The system schematic of BP is shown as Figure 1a. After the steam working at all levels of the turbine, the exhaust steam is directly heating the circulating water of the heat network in the turbine condenser. The system can provide a steady heat load, whose power is determined according to the heat load. So, the system shows a strong heat–power coupling. By adjusting the heat load, the power load adjustment within a certain range can be achieved. The power load can be expressed as

$$P = f(m) \quad (1)$$

where m is the main steam mass flow rate, t/h. The heat load can be expressed as

$$w = m_c \cdot \Delta h \quad (2)$$

where m_c the flow rate of circulating water, t/h; Δh is the enthalpy drop of heating.

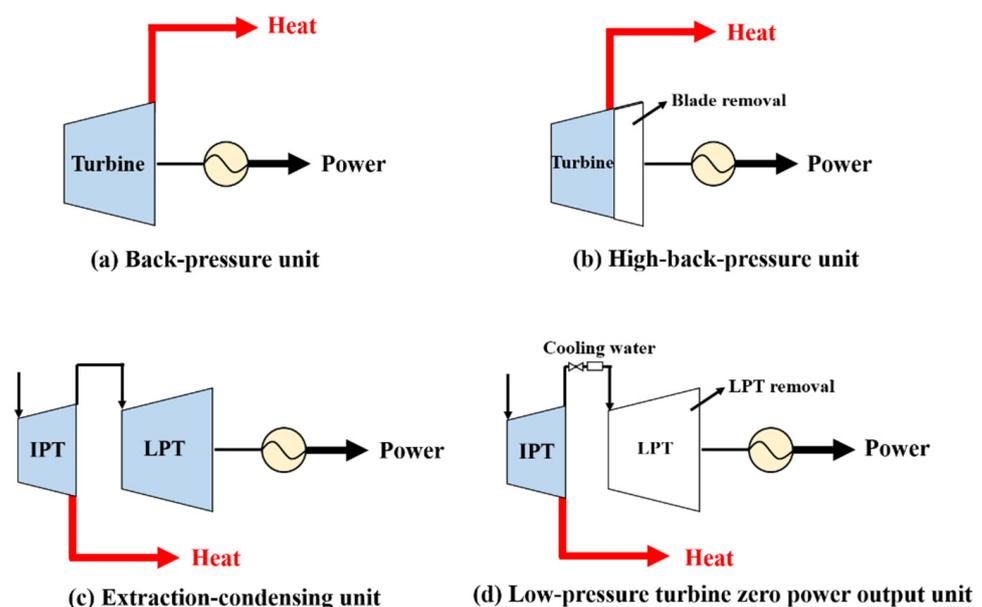


Figure 1. Different types of units.

As Figure 1c shows, in the extraction–condensing (EC) unit, a portion of steam is extracted from the intermediate turbine for heating, and the rest of the steam continues to enter the subsequent turbine in order to perform its function, and then enters the condenser. The power load of the EC unit is the sum of the power produced by steam in the high-pressure section and low-pressure section of the turbine. In practice, a certain amount of steam must flow through the LPT into the condenser in order to cool the LPT and take away the heat generated due to frictional losses of the blower [20]. At a certain amount of heat extraction, there is a certain range of adjustable space for the power load. For the EC unit, the power load can be expressed as

$$P = f(m, m_h) \quad (3)$$

where m_h is the mass flow rate of heating extraction steam, t/h. The heat load can be expressed as

$$Q = m_h \cdot \Delta h \quad (4)$$

As Figure 1b shows, the HBP unit increases the exhaust steam pressure of the LPT according to reducing the number of turbine extraction stages. Because of the exhaust steam temperature being raised, the exhaust steam directly heats the circulating water of the heat network entering the condenser. It makes full use of the latent heat of vaporization of the exhaust steam to heat the circulating water of the heat network, reduces the loss of cold source and improves the energy utilization efficiency of the unit [21]. At the same time, it recovers the spent heat of the exhaust steam to increase the heating capacity of the unit.

As Figure 1d shows, the LZPO renovation adds a water spray cooler to the inlet pipeline of the LPT. After the LZPO renovation, the required steam flow to cool the LPT is reduced significantly. Most of the IPT exhaust steam is used for heating, except a small portion of steam flows into the LPT to cool the rotors [22]. The steam hardly performs its function in the low-pressure part of the turbine and the exhaust steam of IPT directly heats the circulating water of the heat network entering the condenser. This technology uses the original LPT working steam for heating, reduces the unit cooling source loss and lowers the coal consumption rate of the unit for power generation. Under the same boiler heat load condition, it can improve the heating capacity of the unit. Under the condition of unchanged heat load, it can reduce the power load of the unit to a certain extent.

2.2. Data-Mining Analysis for the Heat–Power Coupling Mechanism

Each CHP unit in operation has accumulated rich historical operation data, as well as real-time operation data, which can reflect the unit's heat–power coupling characteristics. Nowadays, data-mining technology provides an effective way to establish an accurate model of heat–power coupling characteristics. The data-mining method obtains the operation regions of CHP units based on the historical operation data. Therefore, every operation point within the operation regions can be realized in actuality, which proves that the research results of this paper are reliable. Compared with the conventional theoretical modeling method, the data-mining method more effectively reflects the realistic operating characteristics of CHP units. The minor limitation of this approach is that a large amount of data is required to support the precise model.

2.2.1. Steady State Identification

The historical data of the CHP units contain complex data such as unit start-up and shutdown conditions, steady working conditions and adjustment working conditions. The operating parameters change rapidly during the start-up and shutdown of units and the adjustment of the operating conditions. The load of units will transition between different steady operating states, and the data generated by its transition process belong to the non-stationary data. Therefore, a large part of the entire operating cycle of the CHP unit is considered within the non-stationary state. In order to ensure the accuracy and credibility

of the calculation, it is also necessary to obtain the operating data under steady operating conditions while analyzing data.

For the steady-state operating conditions of units, the several key variables related to power load, main steam pressure, main steam temperature, reheat steam temperature, feed water flow, heating extraction steam flow rate and heating extraction steam temperature are taken as the key judgment parameters. The differentiation criterion of the steady-state operating conditions of CHP units is provided in Ref. [23]. The concept of the steady-state threshold is introduced, which is expressed as

$$\delta = \frac{A_{max} - A_{min}}{A_0} < \delta_k \quad (5)$$

where A_{max} and A_{min} are the maximum and minimum values of the studied parameters in a particular period of time, respectively. A_0 is the design value of above studied parameters. δ is the steady-state threshold and the δ_k is the key threshold, which is shown in Table 1. The value of δ reflects the operation stability of CHP units. If δ is less than δ_k , the CHP unit can be considered to operate in a steady state.

Table 1. The thresholds of steady-state detection parameters [23].

Items	δ_k
Power load/MW	$\pm 10\%$
Main steam pressure/MPa	$\pm 2\%$
Main steam temperature/ $^{\circ}\text{C}$	$\pm 10\%$
Reheat steam temperature/ $^{\circ}\text{C}$	$\pm 10\%$

2.2.2. Prediction of Heat–Power Coupling Mechanism Based on Gaussian Process

In this paper, different parameters are selected as input variables and power load of unit as output variables according to unit types. The input parameters for each type of unit are shown in Table 2.

Table 2. The input parameters for different type of unit.

Extraction Condensing Type	Back Pressure Type
Feedwater flow rate/ th^{-1}	Feedwater flow rate/ th^{-1}
Main steam pressure/MPa	Main steam pressure/MPa
Main steam temperature/ $^{\circ}\text{C}$	Main steam temperature/ $^{\circ}\text{C}$
Heating extraction steam flow rate/ th^{-1}	Condensing water flow rate/ th^{-1}
Heating extraction steam temperature/ $^{\circ}\text{C}$	Condensing water inlet temperature/ $^{\circ}\text{C}$
Heating extraction steam pressure/MPa	Condensing water exit temperature/ $^{\circ}\text{C}$ /MPa

The Gaussian process model method is used to establish the prediction model of heat–power coupling mechanism under different operating conditions.

The principle of Gaussian process regression is as follows: given a training data set $D = \{(x_i, y_i), i = 1, \dots, n\}$, where $x_i = \{x_{i1}, \dots, x_{id}\}$ is a d-dimensional input variable, y is the output variable. If there exists some mapping function f that constitutes the set $Q = \{f(x_1), \dots, f(x_n)\}$, where $f(x)$ is determined by the mean function $m(x)$ and the variance function $k(x, x')$ and obeys a Gaussian distribution, then the process is defined as a Gaussian process.

$$f(x) \sim GP(m(x), k(x, x')) \quad (6)$$

In practice, white noise ε with mean 0 and variance σ_2 are introduced.

$$y = f(x) + \varepsilon \quad (7)$$

For convenience, take $m(x) = 0$.

$$y \sim N(0, K(X, X) + \sigma^2 I) \quad (8)$$

where $X = (x_1, \dots, x_n)$, $K_{ij} = k(x_i, x_j)$; I is the unit matrix. For the test data x^* , its corresponding output y^* .

$$\begin{bmatrix} y \\ y^* \end{bmatrix} \sim N\left(0, \begin{bmatrix} K(X, X) + \sigma^2 I & K(X, x^*) \\ K(x^*, X) & K(x^*, x^*) \end{bmatrix}\right) \quad (9)$$

The expression for the predicted value y^* is shown in Equation (10).

$$y^* | X, y, x^* \sim N(m, \Sigma) \quad (10)$$

where $m = K(x^*, X)(K(X, X) + \sigma^2 I)^{-1}$, $\Sigma = k(x^*, x^*) - K(x^*, X)[K(X, X) + \sigma^2 I]^{-1}K(X, x^*)$. The squared exponential covariance function is chosen as the kernel function.

2.2.3. Work Condition Division

Many factors affect the heat–power coupling mechanism of the CHP unit. It is difficult that the factors are accurately quantified and analyzed. In order to exclude the other interference factors, the unit power loads are clustered and analyzed, and different working conditions are classified according to the different power load categories obtained. The prediction of unit heat–power coupling mechanism based on Gaussian process regression model can be performed separately for different operating conditions.

In this paper, K-means clustering method is used to cluster power load indicators. In the original data set, k data points are randomly selected, and their initial values are used as the centers of each cluster. The distance from the data of the remaining non-centers to the center of each nest is calculated and assigned to the cluster with the closest distance to cluster, and then the mean value of each cluster is recalculated, the cluster class centers are reselected and repeated until the objective criterion function converges. The criterion function is defined as

$$E = \sum_{i=1}^k \sum_{x \in C_i} (x - \bar{x}_i)^2 \quad (11)$$

where E is the sum of the distances from the data in each cluster to its corresponding cluster center, x is a point in the data space and \bar{x}_i is the arithmetic mean of the clusters.

The optimal number of clusters for the K -means algorithm is determined by the elbow method: as the number of clusters k increases, the sample division will be finer, and the degree of aggregation of each cluster will gradually increase, then the final criterion function E corresponding to k will naturally become gradually smaller. Additionally, when k is less than the optimal number of clusters, the decrease of E will be large because the increase of k will significantly increase the degree of aggregation of each cluster, and when k reaches the optimal number of clusters, the return of the degree of aggregation obtained by increasing k will rapidly become smaller, so the decrease of E will plummet, and then level off as the value of k continues to increase, and when the decrease is not obvious, the corresponding value of k is the true number of clusters of the data.

2.3. Optimal Load Dispatch Model

As shown in Section 2.1, different types of CHP units have different capacities and heat–power coupling characteristics. In this study, the research subject is the CHP system consisting of multi-type CHP units. The optimal load dispatch enables the CHP system to operate at the minimum power output while meeting heat load for accommodating the potential increased renewables.

2.3.1. Objective

Based on the analysis of the heat–power coupling mechanism of different types of CHP units, the lower limit function of the power load of each unit is obtained, and the heat load among units is dispatched under the boundary condition of meeting the units' safety operation to minimize power load of the whole CHP system. The load dispatching optimization target can be described as follows:

$$\min P = f(w_1, w_2, \dots, w_n) = \sum_{i=1}^n P_{i,\min}(w_i) \quad (12)$$

where $P_{i,\min}$ is the lower limit of power load of the No. i unit, MW; w_i is heat load of the No. i unit, t/h; n is the number of CHP units in the case system.

2.3.2. Constraints

The power load of CHP units is influenced by the demand of heat load and the operating limit of units. The constraints for the model are as follows.

- (1) The CHP system including multi-units needs to meet the demand of heating in the heating season. The total heat load of multi-CHP units is equal to the sum of the units' heat load.

$$Q_t = \sum_{i=1}^n m_i (h_i - h_{is}) \quad (13)$$

where Q_t is the heat demand, MW; h_i is the heating extraction steam enthalpy of the No. i unit, kJ/kg; h_{is} is the drainage water enthalpy of the No. i unit, kJ/kg; n is the unit number of the CHP system in operation.

- (2) Due to the design and manufacture of each unit, there are different heating restrictions for each unit, and there is a maximum amount of heating extraction.

$$0 \leq w_i \leq w_{i\max} \quad (14)$$

where $w_{i\max}$ is the maximum heat load of the No. i unit, MW.

- (3) The operation region constraint is considered as well. The research subject is the CHP system consisting of multi-type CHP units. Therefore, for guaranteeing that there is an operating point of the CHP system, the operating points of various CHP units are required to be within their operation regions. The operation region constraints for various types of CHP units can be expressed simply as follows. For EC units, the power load has an adjustable region when the heat load is given because the heating extraction flow can be regulated. For HBP units and LZPO units, the power load is uniquely determined once the heat load is designated.

2.3.3. Solving Method

The genetic algorithm (GA) is used to solve the model in this paper, which has no special requirements on the objective function, and is not bound by the restrictive assumptions of the search space. During the solving progress, the assumptions of continuity, existence of derivatives and single peak, etc., are not required. GA only needs the fitness function to evaluate individuals, has strong generality and operability and is widely used in load dispatch problems [24,25].

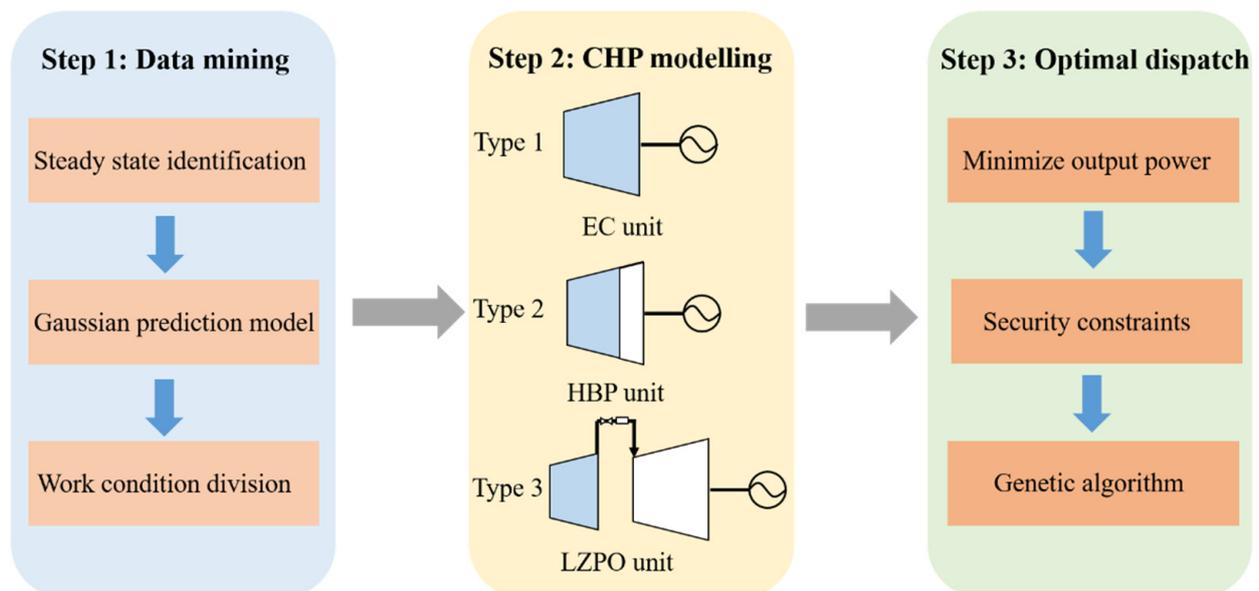
As the units in operation are determined, the objective function of Equation (12) can be obtained under the different total heat load according to dispatching the heat load. In this study, the GA is performed via the optimization toolbox provided by MATLAB. According to the Ref. [26], the parameters of the used GA are set as Table 3.

Table 3. Parameters setting of the used GA [26].

Items	Value
Number of iterations	200
Number of population size	40
Crossover probability	0.5
mutation probability	0.15

2.4. Standard Solution Procedure

In this section, a standard solution procedure for dispatching multi-CHP units is proposed, as shown in Figure 2. In step 1, vast amounts of realistic operation data are fed into the data-mining system, which includes the steady state identification, Gaussian prediction and work condition division. Then, the thermodynamic models and the heat–power coupling characteristics of multi-type CHP units are established in step 2. In step 3, the optimal dispatch is carried out via GA. The minimum output power of the entire CHP system is the objective function and the heat–power coupling characteristics can be considered as the constraints.

**Figure 2.** Standard solution procedure for dispatching multi-CHP units.

3. Case Study

In this paper, a CHP system is selected as the case study, including three different types of units. The #1 unit is the 330 MW EC unit, the #2 unit is the 330 MW HBP modified unit and the #3 is the 330 MW LZPO modified unit.

The historical data from May 2020 to April 2021 were selected and analyzed as a sampling; a total of 75,085 operating data samples were obtained. Taking EC unit #1 as an example, the sliding window technique was used to filter the historical operation data to obtain the steady-state operation data, setting the width of the sliding window to 30 and the sliding step of the window to 1. So, 12,715 sets of steady-state operation data were obtained by screening. Figure 3 shows the historical operating data and the screened steady-state data over a period of time.

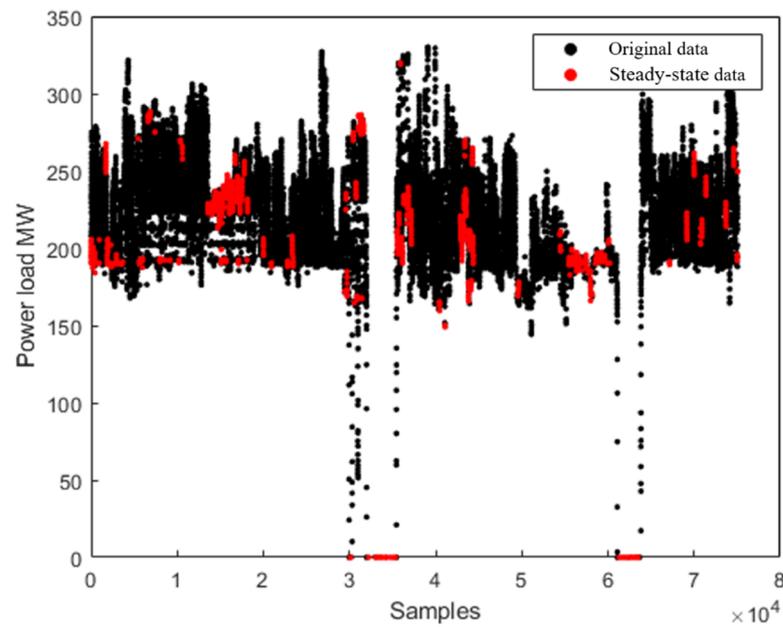


Figure 3. The results of steady-state data screening.

Under each type of steady-state operating conditions, the Gaussian process regression method introduced in Section 2.2.2 is used to develop the prediction model of the heat–power coupling mechanism. The results of the predicted power load and actual power load are shown in Figure 4. In Figure 4, the mean absolute error (MAE) of the case unit predicted model is 0.63 MW, which is acceptable because the actual power load is often between 150 MW and 300 MW. Therefore, the predicted results can be used in load dispatch. In detail, the prediction based on data mining establishes a quantitative relationship between the output power and the input parameters of the unit. Next, the operation regions of CHP units can be obtained by setting input parameter values such as the boundary value of the main steam flow. Then, the operation regions can be considered as the constraints of the multi-type CHP units dispatch models, which restricts the adjustment range of heat and power loads.

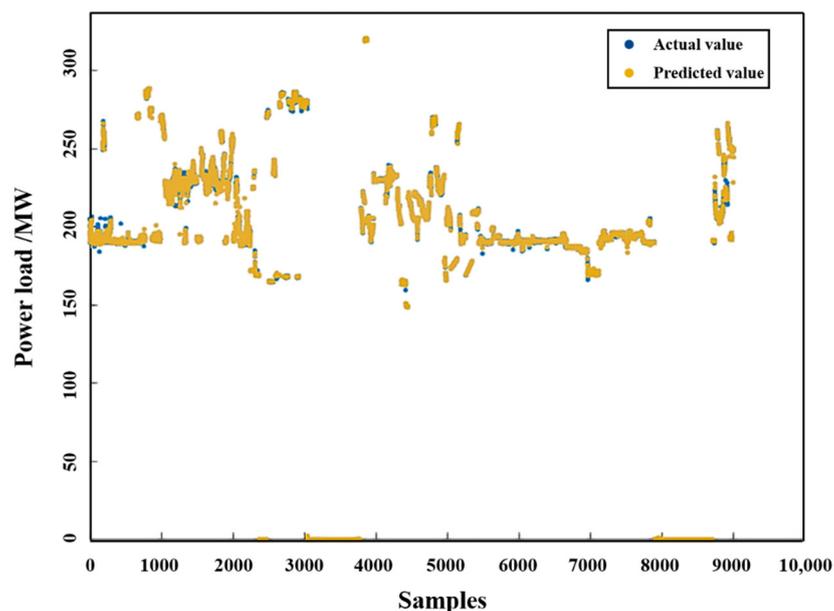


Figure 4. Comparison between the predicted load and actual load.

4. Results and Discussion

4.1. Operation Region

The heat–power coupling mechanism of three different types of units can be analyzed with the method presented in Section 2.2.

The #1 unit is the 330 MW EC unit. By limiting the main steam flow rate to the two limit conditions of TMCR and 40% THA, the power load function will be converted to Equation (15).

$$P = f(w) \quad (15)$$

The operation region of the unit for heat and power load can be obtained, which is shown as Figure 5. If the heat load is given, the power load will have the corresponding adjustment range. The lower limit of the power load shows two different linear trends with increasing heat load, decreasing at first and then increasing. Line AB and Line CD show the constraints of the maximum and minimum main flow rate, respectively. Line BE shows the constraint of the maximum heating extraction flow rate. Line DE shows the constraint of the minimum flow rate to cool the LPT. Moreover, the grey area in the Figure 5 is the operation region of the #1 unit, which shows the adjustment range of power and heat loads.

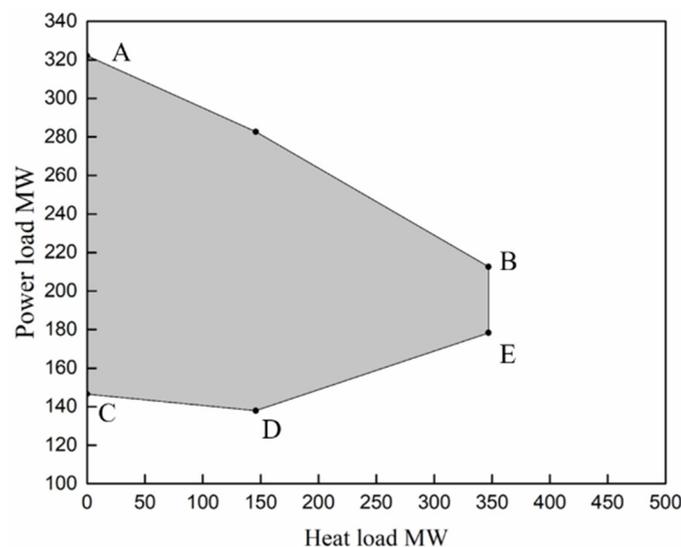


Figure 5. Operation region of #1 unit.

The adjustable lower limit of the power load of the EC unit is influenced by the heating extraction steam of the unit, the minimum main steam flow and the minimum low-pressure turbine exhaust steam flow. So, a critical heating extraction steam flow should exist corresponding to the critical heat load. When the heat load does not reach the critical heat load, the unit can always operate at the minimum main steam flow. Under this situation, as the heating extraction steam flow increases, the LPT exhaust steam flow gradually decreases and the unit power load decreases accordingly. When the LPT exhaust steam flow is reduced to the minimum value for safe operation, the main steam flow rate needs to be increased to meet the requirements of heat load increase, which will lead to the rise of the adjustable lower limit of the power load. The relationship between the minimum main steam flow and the heating extraction steam flow is shown in Figure 6.

Taking the critical heat load as the dividing point, the trend in the lowest power load for EC units is different on both sides of the dividing point, which has important influence on the heat load dispatch.

The #2 unit is an HBP unit renovated from an EC unit like the #1 unit. By limiting the main steam flow rate to the two limit conditions of TMCR and 40% THA, the power load function can be converted as Equation (15). If the heat load is given, the power load is one

uniquely certain value. As shown in Figure 7, the operation region of the unit for heat and power load can be obtained.

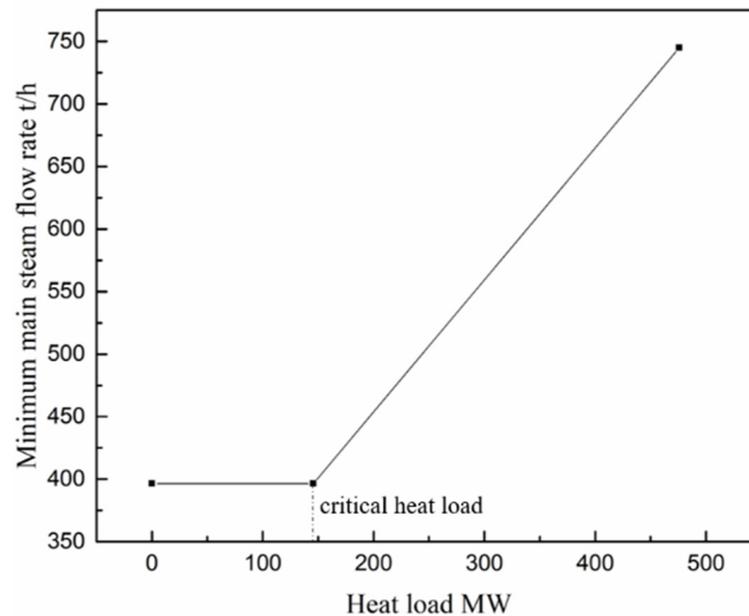


Figure 6. Variation of the minimum main steam flow with the heat extraction steam flow.

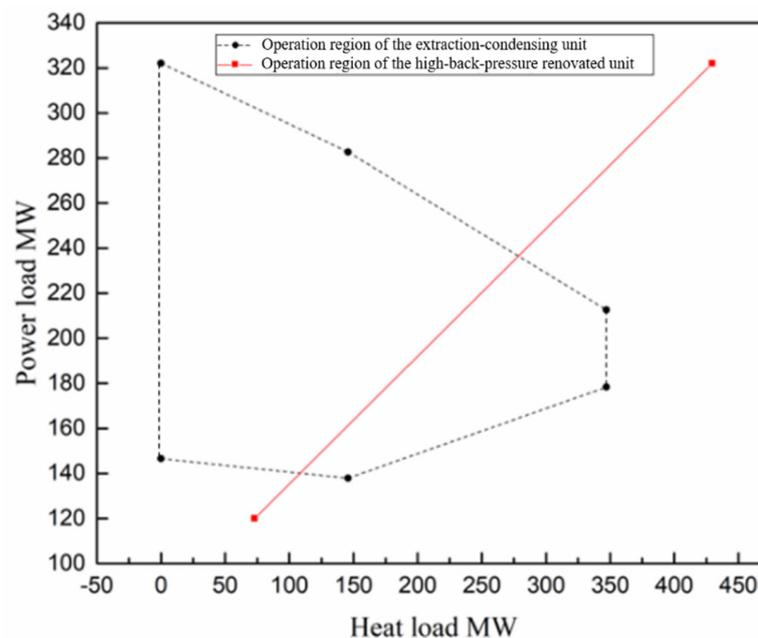


Figure 7. Operation region of #2 unit.

After HBP renovation, the maximum heat load is increased from 347.0 MW to 429.5 MW, and the minimum power load is reduced from 145.8 MW to 120.0 MW. The heating supply capacity of the unit is enhanced.

The #3 unit is a LZPO unit renovated from an EC unit like the #1 unit. By limiting the main steam flow rate to the two limit conditions of TMCR and 40% THA, the power load function can be converted as Equation (15). As shown in Figure 8, the operation region of unit for heat and power load can be obtained. If the heat load is given, the power load is one uniquely certain value.

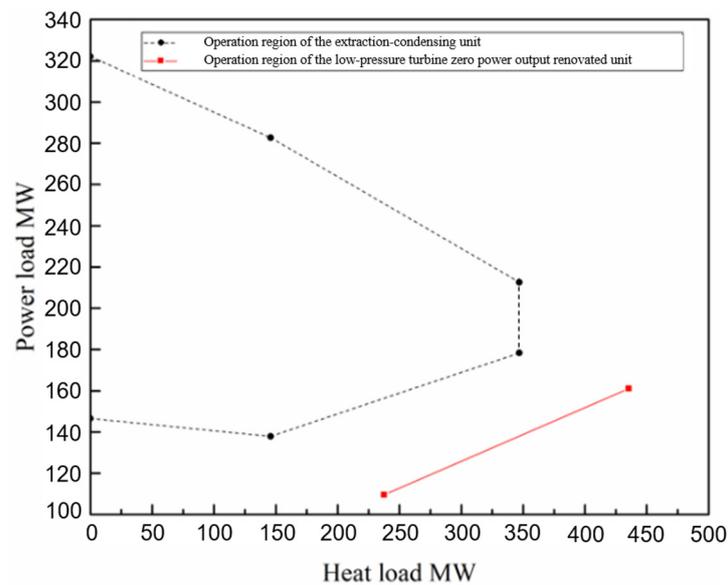


Figure 8. Operation region of #3 unit.

After LZPO renovation, with the same main steam flow, the power load of the unit is further reduced. The minimum power load is reduced from 137.9 MW to 109.5 MW. The heat supply capacity of the unit is significantly increased. The maximum heat load is increased from 347.0 MW to 429.5 MW.

4.2. Optimization Results and Multi-Type Units Load Dispatch Strategy

The multi-type units' system is studied through the load dispatch model to explore load dispatch strategies. The relevant heating season data in the CHP system from 15 November 2020 to 15 March 2021 is chosen. In Figure 9, the relevant loads of the case system in a heating season are shown. The power load before and after the optimized dispatch is shown in Figure 10a.

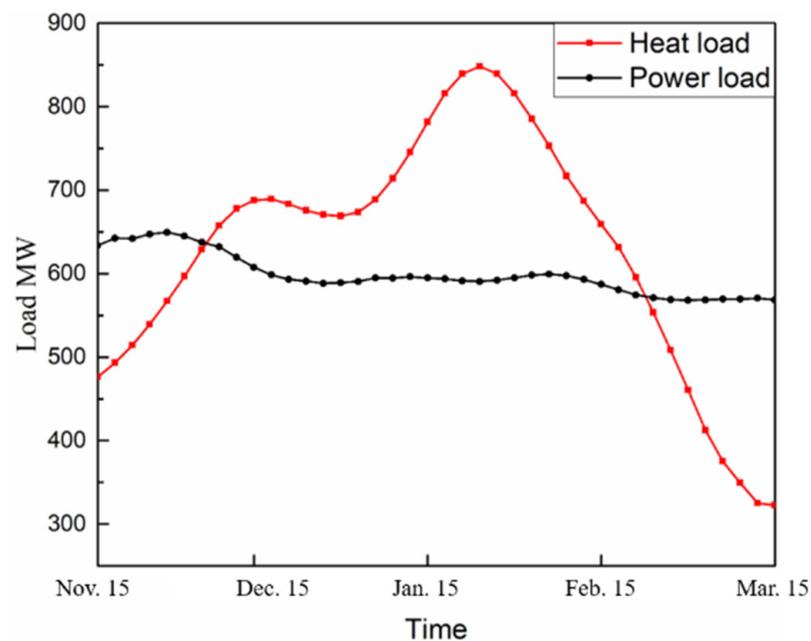


Figure 9. Loads of the case CHP system during a heating season.

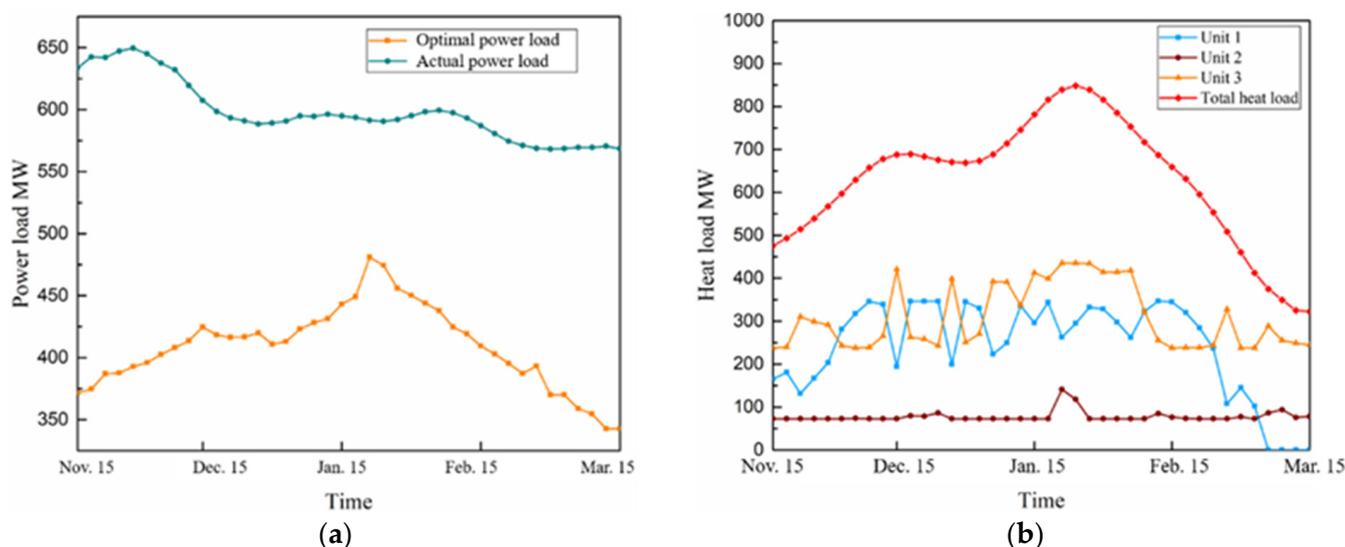


Figure 10. Optimization results. (a) Optimal power load, (b) optimal heat load.

As shown in Figure 10a, compared with the actual power load, the power load can be reduced by 18.7% to 41.7% after optimal dispatch. It can be seen that the minimum power load of the case CHP system is reduced considerably, which means more space for intermittent renewable energy consumption. The corresponding heat load dispatch of each unit before and after the optimized dispatch is shown in Figure 10b.

The distribution results show that the unit with HBP renovation undertakes a steady lower heat load, while both the LZPO renovation and EC unit undertake the higher heat load. This result is determined by the heat–power coupling mechanism of each unit itself. The increase of the HBP unit’s heat load has a more obvious impact on the increase of the power load. The heat load undertaken by the HBP unit should be kept as low as possible under the condition of meeting the total heat load. Due to the presence of the critical heat load of 145.8 MW for the EC unit, the heat load of the EC unit should be as close to its critical heat load as possible to reduce the power load. So, the LZPO unit usually undertakes the higher heat load.

4.3. Impact of Unit Renovations on Load Dispatch

Four cases were selected to evaluate the impact of unit renovations and different types of units on optimal load dispatch. The combinations of units are listed in Table 4.

Table 4. Combinations of CHP units.

Items	#1 Unit	#2 Unit	#3 Units
Case 1	EC	HBP renovation	LZPO renovation
Case 2	EC	HBP renovation	EC
Case 3	EC	EC	LZPO renovation
Case 4	EC	EC	EC

With the change in heat load, the optimized minimum lower limit of the power load is calculated in different cases, shown in Figure 11.

Compared with the units without any renovations (case 4), the HBP renovation (case 2) improves the overall heating supply capacity, but the lower limit of the power load for the CHP system is increased in case of large demand for heat load. The LZPO renovation (case 3) not only improves the overall heating supply capacity, but also further reduces the lower limit of the power load. The LZPO renovation (case 3) is more effective than the HBP renovation (case 2) in reducing the lower limit of the power load for the CHP system.

On the contrary, the HBP renovation (case 2) is more effective than the LZPO renovation (case 3) in improving the heating supply capacity. Case 1, with the HBP renovation and the LZPO renovation, is relatively balanced, which improves the overall heating supply capacity and reduces the lower limit of the power load for the CHP system.

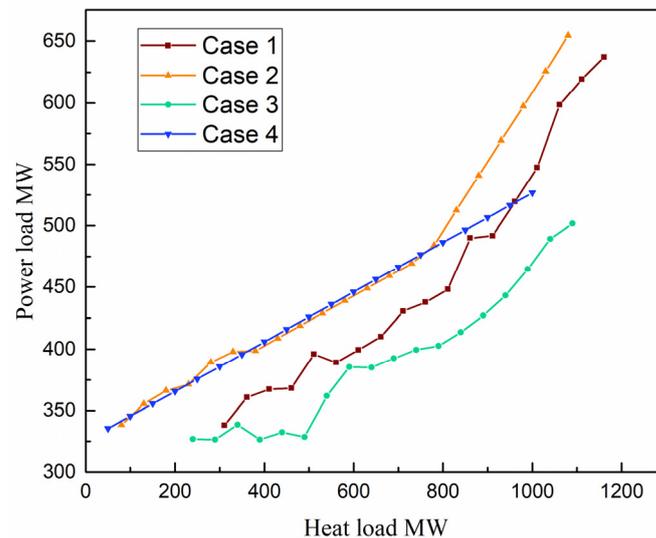


Figure 11. The optimized minimum lower limit of power load in different cases.

5. Conclusions

In this paper, the data-mining-based method is proposed for revealing and utilizing the heat–power coupling mechanism of CHP units. Next, the dispatch model for multi-CHP units is established to obtain the minimum feasible output power. The GA is then introduced to solve the above dispatch model, and some helpful conclusions are as follows:

- (1) The heat–power coupling mechanism of the EC, HBP renovation and LZPO renovation units in the CHP system are analyzed through the data-mining-based analysis method. The LZPO and HBP renovations have the similar impact on the heating supply capacity and reducing the power load. Specifically, the LZPO renovation is more effective than the HBP renovation in reducing the lowest limit of the power load for the CHP system, and then the HBP renovation is more effective than the LZPO renovation in improving the heating supply capacity.
- (2) The EC unit has a critical heat load due to the exhaust steam limit of the LPT. With the critical heat load as the dividing point, the trend in the lower limit of the power load for EC units is when the heat load decreases and then increases. The exhaust steam limit of the LPT has the important influence on the heat load dispatch for EC units.
- (3) After the optimal load dispatch, the power load of the CHP system can be reduced by 18.7% to 41.7% in the heating season, compared with the actual power load. Because of the different heat–power coupling mechanisms of units, the HBP renovation unit undertakes a steady lower heat load, while both the LZPO renovation unit and EC unit undertake the higher heat load. For reducing the power load of the EC unit, its heat load should be dispatched so that the heat load is as close to its critical heat load as possible.

This study is conducted based on coal-fired CHP units. The proposed mining-based modeling method and the dispatch models are also available for nuclear CHP units with similar turbines, regenerative system and condensers, which provide a reference for a CHP system including nuclear power units. The applications of flexibility renovations on nuclear CHP units will be studied in the future. In addition, focusing on the accommodation of increasing renewables, this paper proposed dispatching models with the objective function of minimizing CHPs' power output. However, the intermittency and uncertainty

of renewables are worth being introduced into the proposed models as boundary conditions for optimization as well. Therefore, research with the objective function of minimizing the power imbalance between supply and demand will be carried out in the future. The integrated energy systems will replace the current CHP system as new research objects, while real-time data of renewables will be introduced.

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References

1. Takeshita, T.; Aki, H.; Kawajiri, K.; Ishida, M. Assessment of utilization of combined heat and power systems to provide grid flexibility alongside variable renewable energy systems. *Energy* **2020**, *214*, 118951. [[CrossRef](#)]
2. Tang, H.; Hua, Z.; Wang, Y.; Han, Y.; Zhang, D.; Liu, J. Summary of research progress on enhancement methods of depth peak load shaving capacity of heating units. *Sci. Technol. Innov. Her.* **2015**, *12*, 15–16. (In Chinese)
3. Thomas, N.; Bert, C.; Kristof, P.; Van Bael, J.; Six, D. Flexibility of a combined heat and power system with thermal energy storage for district heating. *Appl. Energy* **2013**, *104*, 583–591.
4. Diana, B.; Mario, G.; Nelly, L.; Kondziella, H.; Bruckner, T. Potential of the Power-to-Heat Technology in District Heating Grids in Germany. *Energy Procedia* **2014**, *46*, 253–264.
5. Xin, Y.; Zhao, T.; Chen, X.; He, K.; Ma, H.; Chen, Q. Heat current method-based real-time coordination of power and heat generation of multi-CHP units with flexibility retrofits. *Energy* **2022**, *252*, 124018. [[CrossRef](#)]
6. Zhang, H.; Li, Z.; Zhao, H. Thermodynamic performance analysis of a novel electricity-heating cogeneration system (EHCS) based on absorption heat pump applied in the coal-fired power plant. *Energy Convers. Manag.* **2015**, *105*, 1125–1137. [[CrossRef](#)]
7. Dunn, B.; Kamath, H.; Tarascon, J.-M. Electrical Energy Storage for the Grid: A Battery of Choices. *Science* **2011**, *334*, 928–935. [[CrossRef](#)]
8. Jason, L.; Lukas, G. Selection of battery technology to support grid-integrated renewable electricity. *J. Power Sources* **2012**, *216*, 376–386.
9. Moncho-Esteve, I.J.; Gasque, M.; González-Altozano, P.; Salvador, G.P. Simple inlet devices and their influence on thermal stratification in a hot water storage tank. *Energy Build.* **2017**, *150*, 625–638. [[CrossRef](#)]
10. Abdoly, M.; Rapp, D. Theoretical and experimental studies of stratified thermocline storage of hot water. *Energy Convers. Manag.* **1982**, *22*, 275–285. [[CrossRef](#)]
11. Xue, T.; Deng, S.; Kang, L.; Zhao, J.; An, Q. Study on heat and power decoupling for CCHP system: Methodology and case study. *Appl. Therm. Eng.* **2018**, *142*, 597–609.
12. Blarke, M.B. Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration. *Appl. Energy* **2012**, *91*, 349–365.
13. Fabian, L. CHP and heat pumps to balance renewable power production: Lessons from the district heating network in Stockholm. *Energy* **2017**, *137*, 670–678.
14. Wang, C.; Song, J. Optimal dispatch of the cascade heating CHP plants integrating with the high back-pressure technology. *Case Stud. Therm. Eng.* **2022**, *38*, 102330.
15. Liu, M.; Wang, S.; Zhao, Y.; Tang, H.; Yan, J. Heat–power decoupling technologies for coal-fired CHP plants: Operation flexibility and thermodynamic performance. *Energy* **2019**, *188*, 116074. [[CrossRef](#)]
16. Wang, X.; Wei, D.; Sun, S.; Gong, G.; Zhang, S.; Lv, B. Optimizing Distribution of Heat-power Load and Peak Regulation Ability of Heat Supply Units with Different Types. *Turbine Technol.* **2010**, *52*, 387–390. (In Chinese)
17. Yuan, G.; Yang, W. Study on optimization of economic dispatching of electric power system based on Hybrid Intelligent Algorithms (PSO and AFSA). *Energy* **2019**, *183*, 926–935.
18. Wang, C.; Song, J.; Zhu, L.; Zheng, W.; Liu, Z.; Lin, C. Peak shaving and heat supply flexibility of thermal power plants. *Appl. Therm. Eng.* **2021**, *193*, 117030.
19. Lu, X.; Liu, Z.; Ma, L.; Wang, L.; Zhou, K.; Feng, N. A robust optimization approach for optimal load dispatch of community energy hub. *Appl. Energy* **2020**, *259*, 114195.
20. Yao, L.; Guo, J.; Wang, S. The Analysis of Load Characteristics About Regulated Extraction Turbine’s Peak Regulation in Electric Network. *Turbine Technol.* **2009**, *51*, 61–63. (In Chinese)
21. Wang, X.; Zheng, W.; Song, A. Analysis and Evaluating on Performance Characteristics of Heating Supply Unit with High Back-pressure. *Power Syst. Eng.* **2014**, *30*, 49–51. (In Chinese)

22. Wang, C.; Song, J.; You, D. Combined heat and power plants integrated with steam turbine renovations: Optimal dispatch for maximizing the consumption of renewable energy. *Energy Convers. Manag.* **2022**, *258*, 115561. [[CrossRef](#)]
23. Liu, B. *Research on Energy Saving Optimization of Power Station Units Based on Big Data Technology*; North China Electric Power University: Beijing, China, 2019. (In Chinese)
24. Yeh, W.-C.; He, M.-F.; Huang, C.-L.; Tan, S.-Y.; Zhang, X.; Huang, Y.; Li, L. New genetic algorithm for economic dispatch of stand-alone three-modular microgrid in DongAo Island. *Appl. Energy* **2020**, *263*, 114508. [[CrossRef](#)]
25. Haghrah, A.; Nazari-Heris, M.; Mohammadi-Ivatloo, B. Solving combined heat and power economic dispatch problem using real coded genetic algorithm with improved Mühlenbein mutation. *Appl. Therm. Eng.* **2016**, *99*, 465–475. [[CrossRef](#)]
26. Yao, J. *Research on Thermal Power Units Load Optimal Distribution Based on Genetic Algorithm*; Wuhan University: Wuhan, China, 2013. (In Chinese)