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# Scheduling Optimization of IEHS with Uncertainty of Wind Power and Operation Mode of CCP

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**Abstract:** With the gradual depletion of fossil energy sources and the improvement in environmental protection attention, efficient use of energy and reduction in carbon emissions have become urgent issues. The integrated electricity and heating energy system (IEHS) is a significant solution to reduce the proportion of fossil fuel and carbon emissions. In this paper, a stochastic optimization model of the IEHS considering the uncertainty of wind power (WP) output and carbon capture power plants (CCPs) is proposed. The WP output in the IEHS is represented by stochastic scenarios, and the scenarios are reduced by fast scenario reduction to obtain typical scenarios. Then, the conventional thermal power plants are modified with CCPs, and the CCPs are equipped with flue gas bypass systems and solution storage to form the integrated and flexible operation mode of CCPs. Furthermore, based on the different load demand responses (DRs) in the IEHS, the optimization model of the IEHS with a CCP is constructed. Finally, the results show that with the proposed optimization model and shunt-type CCP, the integrated operation approach allows for a better reduction in carbon capture costs and carbon emissions.

**Keywords:** uncertainty; carbon capture power plant; integrated electricity and heating energy system; optimization



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## 1. Introduction

At present, the main source of the world's energy consumption is still traditional fossil energy. However, due to the gradual seriousness of global climate problems, the conflicts and trade-offs between energy and the environment are becoming more and more prominent. The global $CO_2$ emissions produced by the burning of fossil energy are gradually increasing, and are causing global warming, leading to a greater impact on the environment. Thus, determining how to reduce global carbon emissions is a key issue to be considered in the future. On this basis, the Chinese government has taken the lead in adopting measures to reduce energy consumption and carbon emissions, and will make great efforts to achieve the proposed "Double Carbon" goal as scheduled. The proposal of the goal of "Double Carbon" has led China's energy research to examine the climate economy and has started a green change, which has both opportunities and challenges [1].

The integrated electricity and heating energy system (IEHS) can make the best use of electrical and heating energy, and can effectively reduce $CO_2$ emissions. Regarding the uncertainty in optimization in IEHS, the existing literature contains many research works. In [2], the intra-day wind power (WP) generation relationship in IEHS was analyzed, an intra-day WP generation scenario generation model was constructed based on the generation relationship, and a rolling optimal scheduling model for day-ahead internal stochastic scenarios was developed. Ref. [3] proposed a stochastic optimization (SO) dispatching model to represent the uncertainty of WP output and constructed a SO model with electricity and natural gas. The stochastic planning model produces a dispatch scheme with lower cost and higher energy utilization compared to the deterministic model. Considering the uncertainty of WP and photovoltaic (PV) output, a distributed robust optimization (RO) economic dispatch method for multi-microgrids with the aim of minimizing the economic expenses was proposed [4]. Ref. [5] investigated hierarchical SO methods with uncertain variables to deal with the problem of energy utilization and markets for integrated multi-community network systems containing multiple energy couplings. To deal with multiple uncertainties, updateable scenarios were generated using Wasserstein generative adversarial networks with gradient penalties. Based on the analysis of renewable energy output uncertainty, research has also been conducted on the analysis and study of low carbon optimization. The CCP is identified as a critical and promising complement to the carbon emissions in traditional power plants, and its typical operation modes were defined and identified in [6]. Ref. [7] aimed to reduce $CO_2$ emissions while increasing wind power utilization, and constructed the new integrated electricity and gas energy system (IEGS) architecture for a coupled electricity–gas system with the synergistic operation of electricity-to-gas technology (P2G), carbon capture plants (CCPs), and electric vehicles (EVs). This approach is effective in reducing $CO_2$ emissions and significantly improving the penetration of WP. Ref. [8] proposed a time-varying carbon emission allowance allocation method considering a CCP and carbon emission trading mechanisms. In [9], the low-carbon economic operation of an IEHS was investigated. A multi-objective optimization scheme combining a CCP and multi-energy demand response (DR) was proposed. Most of the above studies consider the impact on system optimization after the addition of a CCP. A CCP has multiple modes of operation, and different modes of operation have different effects on the system. However, the uncertainty of WP output and the operation mode of the CCP have not been considered.

On this basis, for the purpose of considering the influence of CCP operating modes on the IEHS, some of the literature has investigated the operation of the CCP. An optimized model for an integrated energy system (IES) considering the impact of energy markets is presented in [10]. The developed model can reduce the systems operation fee and improve the energy efficiency of the systems without causing significant environmental pollution. In [11], ensemble empirical mode decomposition (EEMD) and long short-term memory (LSTM) were used to improve the support vector regression (SVR) to achieve prediction of the uncertainty of WP output of a CCP with high energy consumption. Further, a traditional thermal power plant was converted into a CCP containing a shunt and liquid storage. In [12], an adjustable RO model with a low carbon economy was proposed for the uncertainty of WP output. Ref [13] combined carbon tax and carbon capture technologies to reduce $CO_2$ emissions at an accelerated rate. Considering the existence of various low-carbon technologies, such as thermal and gas-fired unit retrofits and energy storage system utilization, a developed low-carbon economic model of the IEGS was proposed to improve WP utilization. In [8], a distributed power system economic dispatch model was constructed considering a CCP and carbon emission exchange mechanism, which reduces the carbon emission cost. Ref. [14] proposed a low-carbon model for an IEGS considering carbon recovery, carbon emissions trading, DR, and renewable energy generation. Based on opportunity-constrained planning, the low-carbon economic dispatching issue was modeled as a risk-constrained two-stage SO dispatch model. Ref. [15] integrated P2G, carbon capture, and $CO_2$ recycling systems into the system. The carbon capture system can be used to recycle carbon dioxide generated by thermal and gas units in two ways. However, it can be found from the existing literature that although more studies have considered the reduction in carbon emissions, fewer studies have been conducted on the role of CCP and the operation mode of CCP. At the same time, the impact of the integrated flexible operation mode of the CCP in combination with DR on system operation has been little studied.

Table 1 shows the differences between the model and the published references regarding the uncertainty of WP output and the mode of the CCP. According to the summary of the existing literature in Table 1, more studies start from the uncertainty of WP output and then consider the $CO_2$ emissions. Although more scholars have studied this topic from the perspective of carbon emissions, there are few studies on the operation mode of the CCP and the role of DR. In consideration of the above problems, a stochastic optimization model for IEHS considering the integrated flexible operation mode of the CCP and the uncertainty of WP output is proposed in this paper. Firstly, the flue gas bypass system with liquid storage and a CCP are combined to create an integrated and flexible operation. Then, the uncertainty of WP output s represented using the scenario method. Furthermore, the SO model of the IEHS considering the refined DR is constructed. Lastly, the accuracy of the model is demonstrated by numerical simulation. The main work of this paper can be summarized as:

**Table 1.** Summary of the literature review.

| Reference | Uncertainty of WP Output | Carbon Emission | Mode of CCP | DR of Load |
|---|---|---|---|---|
| [2] | ✓ | ✗ | ✗ | ✗ |
| [3] | ✓ | ✗ | ✗ | ✗ |
| [4] | ✓ | ✗ | ✗ | ✗ |
| [7] | ✓ | ✓ | ✗ | ✗ |
| [8] | ✗ | ✓ | ✗ | ✗ |
| [9] | ✓ | ✓ | ✓ | ✗ |
| [11] | ✓ | ✓ | ✓ | ✗ |
| [12] | ✓ | ✓ | ✗ | ✗ |
| [13] | ✓ | ✓ | ✗ | ✗ |
| [14] | ✓ | ✓ | ✗ | ✓ |
| **This paper** | ✓ | ✓ | ✓ | ✓ |

(1) A comprehensive and integrated flexible operation mode for the CCP is proposed.
(2) The IEHS optimization model with the uncertainty of WP output, DR, and the CCP are proposed.
(3) The validity and correctness of the proposed model are verified by comparing the proposed model with the rest of the models.

The contents of this paper are organized as follows. Section 2 focuses on the method of the uncertainty of WP output. The model of the CCP and DR is developed in Section 3. Section 4 develops the IEHS optimization model. Section 5 provides the case simulation and Section 6 is the conclusion.

## 2. Wind Power Output Scenario Representation

WP is defined by the magnitude of the wind speeds in the natural environment. However, the magnitude of wind speed has a stochastic fluctuation and is difficult to determine. Thus, the wind power has a high degree of uncertainty, and it needs to be quantized before the optimization of the IEHS can be performed.

In this paper, a large number of scenarios of WP output are generated using Latin hypercube sampling (LHS), combined with the scenario reduction technique to obtain representative scenarios of wind power output. Latin hypercube sampling is a stratified sampling technique, which classifies samples into different clusters according to a certain characteristic, and then selects these samples from the different clusters separately and stochastically, thus guaranteeing that the construction of the samples is much closer to that of the overall population and increasing the precision of estimation [16].

Assuming that wind power obeys a normal distribution, the probability density function is [17,18]:

$$f_{wind,t} = \frac{1}{\sqrt{2\pi}\sigma_{wind,t}} e^{\frac{(x-\mu_{wind,t})^2}{2\sigma^2_{wind,t}}} \quad (1)$$

where $\mu_{wind,t}$ denotes the WP forecasting output at time $t$. $\sigma^2_{wind,t}$ represents WP forecasting variance.

According to the probability distribution function followed by WP, WP output is assumed to follow the Weibull distribution, and the scenarios are generated by LHS in [18]. Moreover, the scenarios are cut using the fast backward scenario reduction method to obtain the reduced scenarios. The steps of the scenario reduction method are shown in Algorithm 1.

**Algorithm 1** The steps of fast backward scenario reduction method

**Input:** Number of scenario targets; data of wind power output
**Output:** Reduced scenarios of wind power output
***Initialization***: Generate the scenarios by Weibull probability distribution function
***while*** Iteration conditions unsatisfied
    Calculate the scenario distance;
    ***for*** Sampling scale
      Find the most two similar scenarios and reduce old ones;
    Update scenario probabilities;
    ***end for***
Update the number of scenarios;
***end while***
Output reduced scenarios of wind power output
***End***

## 3. The Model of CCP Plants and Demand Response

To comprehensively analyze the integrated and flexible operation mode of the CCP, the structure of the IEHS is analyzed in this section. The carbon capture system is introduced on the basis of the original power generation equipment of traditional thermal power plants, thus forming carbon capture power plants. The CCPs are used to separate and treat $CO_2$ from the flue gases emitted from thermal power plants, thus avoiding the climate change caused by its emission into the atmosphere and achieving the sustainable use of fossil fuels. Carbon capture technology can be divided into three types: post-combustion capture, pre-combustion capture, and oxygen-enriched combustion capture. There are two main types of flexible operation methods for carbon capture power plants: split-flow flexible operation and solution storage flexible operation. The IEHS is a comprehensive energy system, which includes a variety of energy forms and conversion between these energy forms. Moreover, the electricity, heating, and gas energy are mainly considered in this paper.

Figure 1 is the structure diagram of the IEHS. The IEHS studied in this paper mainly includes conventional thermal power units, CCPs, wind power, gas turbines (GTs), electric boilers (EBs), and waste heat recovery devices. The GT can supply the required power to the power system. Moreover, the high-temperature waste heat generated by the GT can be recovered by the waste heat recovery device to provide a heating load (assuming that the utilization rate of the waste heat recovery device is 100%). If this part of the energy cannot meet the heat load, the EB will produce heating to meet the heating demand. In the electric network, the traditional thermal power units are combined with carbon capture technology to improve the $CO_2$ emissions. The $CO_2$ generated by thermal power units is transmitted to the CCP for recycling. In this way, effective carbon use can be better achieved. As well as the goal of "Double Carbon".

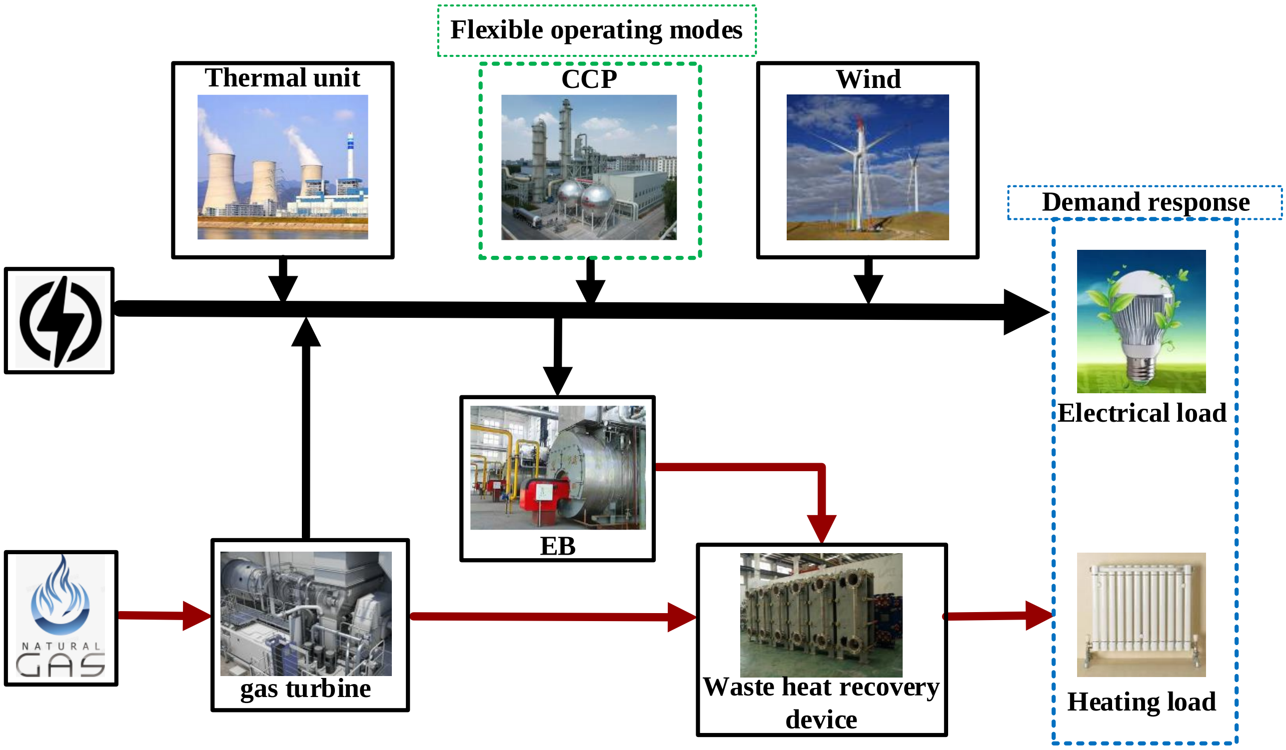


**Figure 1.** Structure diagram of IEHS.

### 3.1. The Flexible Operating Modes of CCP

There are many operating modes of CCPs, and the flexible operating modes of CCPs are mainly considered in this paper. In this operation mode, a flue gas bypass system and a liquid storage reservoir are introduced. During the peak load period, the CCP can fully absorb $CO_2$ and store it in the liquid storage reservoir, but without capturing it, thus reducing the energy consumption of carbon capture and increasing the net output power of the CCP. During low load periods, the $CO_2$ compounds stored in the storage tank during peak load are sent to the desorption tower for desorption, and the $CO_2$ is released for capture treatment, thus increasing the carbon capture energy consumption of the unit and providing more capacity for WP generation. Therefore, the contraction between carbon capture demand and the net output of CCP can be alleviated [19,20]. Carbon capture consists of $CO_2$ absorption, resolution, and compression, and includes a $CO_2$ absorption device, solution storage, resolution tower, and compressor. The $CO_2$ absorption tower is used as an input to the processing unit for $CO_2$ generated by conventional thermal power plants to achieve $CO_2$ absorption and utilization. The absorbed $CO_2$ is then passed through a storage tank to regulate the amount of $CO_2$ being processed by the desorption tower and the compressor, allowing the energy consumption of the CCP to be regulated [12].

The net output power of the integrated flexible CCP can be flexibly adjusted by increasing or decreasing the carbon capture energy consumption. If the energy consumption of operation of carbon capture equipment is used to regulate the net output of the CCP, it can not only reduce the number of startups and shutdowns of thermal power units, but also improve the speed of power output regulation of thermal power plants. At the same time, the output of high carbon units will be replaced by that of low carbon units, leading to the $CO_2$ emissions of the IEHS reducing to a certain extent.

The total output of CCPs can be divided into two parts, which are net output and energy consumption of carbon capture [21]. Moreover, the energy consumption of carbon capture is composed of fixed energy consumption (FE) and operation energy consumption

(OE), and the OE should include the energy consumption of compression and desorption. A mathematical model for the output of CCP plants can be developed as:

$$\begin{cases} E_{Gi,t} = e_{gi} P_{Gi,t} \\ 0 \leq \delta_i \leq 1 \\ E_{total CO_2 i,t} = E_{CGi,t} + \beta \delta_i E_{Gi,t} \\ 0 \leq E_{total CO_2 i,t} \leq \eta \beta e_{gi} P_{Gi,\max} \\ P_{Bi,t} = \lambda E_{total CO_2 i,t} \\ P_{Gi,t} = P_{Ji,t} + P_{Di} + P_{Bi,t} \end{cases} \quad (2)$$

where $P_{Gi,t}$ and $E_{Gi,t}$ represent the total output and total $CO_2$ production of CCP unit $i$ at time $t$, respectively. $e_{gi}$ is the carbon emission intensity of unit $i$. $\delta_i$ denotes the flue gas split ratio of unit $i$. $E_{totalCO_2 i,t}$ is the total amount of $CO_2$ captured by unit $i$. $E_{CGi,t}$ is the amount of $CO_2$ to be captured by the liquid storage reservoir of unit $i$. $\beta$ is the carbon capture efficiency. $\eta$ is the max operating condition factor of the desorption tower and compressor. $P_{Gi,max}$ is the max technical output of thermal power unit $i$ when it is on. $P_{Bi,t}$ represents the OE of unit $i$ at time $t$. λ denotes the energy consumption per unit of $CO_2$ capture. $P_{Ji,t}$ and $P_{Di,t}$ indicate the net output power and FE of unit $i$ [22].

According to Equation (1), it can be seen that the range of FE and OE for the integrated flexible operation mode is:

$$P_{Di} \leq P_{BYi,t} + P_{Di} \leq \lambda \eta \beta \delta_{i\max} e_{gi} P_{Gi,\max} + P_{Di} \quad (3)$$

The expression for the net output range can be derived as follows:

$$P_{Di,\min} - \lambda \eta \beta \delta_{i\max} e_{gi} P_{Gi,\max} - P_{Di} \leq P_{Ji,t} \leq P_{Gi,\max} - P_{Di} \quad (4)$$

The split-flow operation does not have a liquid memory and cannot be energy time-shifted for carbon capture energy consumption; thus, a net output range can be deduced as:

$$P_{Di,\min} - \lambda \beta \delta_{i\max} e_{gi} P_{Gi,\min} - P_{Di} \leq P_{Ji,t} \leq P_{Gi,\max} - P_{Di} \quad (5)$$

At present, most of the power generation units are traditional coal-fired thermal power plants. Because these do not have the "energy time shift" characteristics [19], they cannot achieve a reasonable transfer of carbon capture energy consumption, and thus cannot alleviate the contradiction between load demand during the load peak period and low-carbon emission goals. High-carbon-emission units must increase the output with high operating costs, which violates IEGS's low-carbon economic operation goal. However, for CCP plants with the same installed capacity as traditional plants, due to the existence of carbon capture energy, the lower limit of the net output of a diverted CCP is lower than that of a conventional thermal plant. Due to the energy time-shifting effect of the liquid memory on the FE and OE, the integrated flexible operation mode of the CCP has a lower net output limit, and the latter has a lower net output under the same rotation standby requirements, which is conducive to the consumption of WP output and reduction in $CO_2$ emissions [23]. The "energy time-shifting phenomenon" of the carbon capture plant under the integrated flexible operation mode is achieved by adjusting the liquid storage volume. At peak load, the energy consumption of carbon capture can be reduced by increasing the storage volume of the rich tank and decreasing the storage volume of the lean tank, thus realizing peak shaving; at trough load, the energy consumption of carbon capture can be increased by decreasing the storage volume of the rich tank and increasing the storage volume of the lean tank, thus realizing valley filling [22].

The max and min output constraints, climbing constraints, and start–stop constraints of the CCP are similar to those of the conventional thermal power plants. In addition, considering that the $CO_2$ in the liquid storage reservoir exists in the form of alcohol-amine mixed solution, the constraints of liquid storage reservoirs mainly include the volume constraint and volume change constraint.

$$V_{CAi,t} = \frac{E_{CGi,t} M_{MEA}}{M_{CO_2} \theta C_R \rho_R} \tag{6}$$

where $V_{CAi,t}$ denotes the volume of solution required to release $CO_2$ from the solution memory installed in carbon capture unit $i$. $M_{MEA}$ and $M_{CO_2}$ represent the molar masses of MEA and $CO_2$, respectively. θ denotes the regeneration tower resolution. $C_R$ and $\rho_R$ denote the concentration and density of alcohol-amine mixed solution, respectively.

$$\begin{cases} V_{FYi,t} = V_{FYi,t-1} - V_{CAi,t} \\ V_{PYi,t} = V_{PYi,t-1} + V_{CAi,t} \\ 0 \le V_{FYi,t} \le V_{CRi} \\ 0 \le V_{PYi,t} \le V_{CRi} \\ V_{FYi,0} = V_{FYi,24} \\ V_{PYi,0} = V_{PYi,24} \end{cases} \tag{7}$$

where $V_{FYi,t}$, $V_{PYi,t}$ are the solution volumes of liquid-rich memory and liquid-poor memory, respectively. $V_{CRi}$ is the capacity of unit i's solution memory. $V_{FYi,0}$ and $V_{PYi,0}$ are the initial solution volumes of unit $i$'s liquid-rich memory and liquid-poor memory, respectively. $V_{FYi,24}$ and $V_{PYi,24}$ are the solution volumes of liquid-rich memory and liquid-poor memory at the end of unit $i$'s dispatch cycle, respectively.

### 3.2. Electrical and Heating Load Demand Response

The incentive-based DR is considered for different types of loads, which is taken into account along with the DR of the heating load. The different types of loads are classified as fixed, transferable, and interruptible loads [24]. Then, the following relationship can be obtained:

$$P_{dl,t} = P_{Fl,t} + P_{Sl,t} + P_{Il,t} \tag{8}$$

$$P_{dh,t} = P_{Fh,t} + P_{Sh,t} + P_{Ih,t} \tag{9}$$

where $P_{dl,t}, P_{Fl,t}, P_{Sl,t}, P_{Il,t}$ indicate electrical load, fixed electrical load, transferable electrical load, and interruptible electrical load, respectively. $P_{dh,t}, P_{Fh,t}, P_{Sh,t}, P_{Ih,t}$ denote heating load, fixed heating load, transferable heating load, and interruptible heating load, respectively.

Incentive-based DR regulation receives restrictions on responsiveness and speed of response, and the following constraints can be deduced:

$$\begin{cases} P_{Sl,\min} \le P_{Sl,t} \le P_{Sl,\max} \\ -R_{Sl} \le P_{Sl,t} - P_{Sl,t-1} \le R_{Sl} \\ \sum\limits_{t=1}^{T} P_{Sl,t} = 0 \\ P_{Il,\min} \le P_{Il,t} \le P_{Il,\max} \end{cases} \tag{10}$$

$$\begin{cases} P_{Sh,\min} \le P_{Sh,t} \le P_{Sh,\max} \\ -R_{Sh} \le P_{Sh,t} - P_{Sh,t-1} \le R_{Sh} \\ \sum\limits_{t=1}^{T} P_{Sh,t} = 0 \\ P_{Ih,\min} \le P_{Ih,t} \le P_{Ih,\max} \end{cases} \tag{11}$$

where $P_{Sl,\min}, P_{Sl,\max}$ indicate the min and max values of transferable electrical load, respectively. $R_{Sl}$ represents the transferable electrical load response rate. $P_{Il,\min}, P_{Il,\max}$ denote the min and max values of the interruptible electrical load, respectively. $R_{Sh}$ indicates the transferable heating load response rate. $P_{Ih,\min}, P_{Ih,\max}$ are the min and max values of interruptible heating load, respectively.

## 4. The IEHS Model Considering CCP and DR

### 4.1. Objective Function

In the existing studies, the economic operating cost is mainly solved as the objective, and the abandoned wind cost and CCP cost are less often taken into account. The objective functions in this paper are cost of DR ($f_{DR}$), thermal unit operating cost ($F_g$), net cost of the CCP ($f_C$), solvent loss cost in the carbon capture process ($f_R$), gas turbine cost ($f_{gas}$), gas boiler operating cost ($f_{eb}$), and wind abandonment cost ($f_{wind}$). The above objective functions can be described as Equation (12):

$$minF = min\left(f_{DR} + f_G + f_C + f_R + f_{gas} + f_{eb} + f_{wind}\right) \tag{12}$$

$$f_{DR} = \sum_{t=1}^{T}(K_{DRl,S}P_{Sl,t} + K_{DRl,I}P_{Il,t} + K_{DRh,S}P_{Sh,t} + K_{DRh,I}P_{Ih,t}) \tag{13}$$

$$f_G = \sum_{t=1}^{T}\sum_{i=1}^{N_g}\left(a_iP_{Gi,t}^2 + b_iP_{Gi,t} + c_i\right) \tag{14}$$

$$f_C = \sum_{t=1}^{T}\sum_{i=1}^{N_g}(K_C\beta P_{Ji,t}) \tag{15}$$

$$f_R = \sum_{t=1}^{T}\sum_{i=1}^{N_g}K_R\varphi E_{totalCO_2i,t} \tag{16}$$

$$f_{GT} = \sum_{t=1}^{T}\sum_{j=1}^{N_{GT}}K_{GT}P_{GTj,t} \tag{17}$$

$$f_{eb} = \sum_{t=1}^{T}\sum_{z=1}^{N_{eb}}K_{eb}P_{ebz,t} \tag{18}$$

$$f_{wind} = \sum_{t=1}^{T}K_{wind}\left(P_{wind,t}^{pre} - P_{wind,t}\right) \tag{19}$$

where $K_{DRl,S}, K_{DRl,I}, K_{DRh,S}, K_{DRh,I}$ denote transferable electric load, interruptible electric load, transferable heating load, interruptible heating load dispatch cost factor, respectively [25]. $a_i$, $b_i$, $c_i$ denote the operating cost coefficients of the $i$-th thermal power unit. $K_C$ denotes the carbon capture plant operating cost factor, and $K_R$ is the ethanolamine solvent cost factor; $\varphi$ is the solvent operating loss factor. $E_{totalCO_2i,t}$ is the mass of $CO_2$ captured by unit $i$. $K_{GT}$, $K_{eb}$ are the GT and EB cost factors, respectively. $K_q$ is the penalty cost per unit of wind abandonment. $P_{wind,t}^{pre}$ is the day-ahead predicted WP output. $P_{wind,t}$ is the WP output in time period $t$.

### 4.2. Constraints

(1) The power balance constraint is composed of electrical and heating power balance, which can be expressed as (20) and (21) [26]:

$$P_{wind,t} + \sum_{j=1}^{N_{GT}}P_{GTj,t} + \sum_{i=1}^{N_g}P_{Gi,t} + \sum_{i=1}^{N_g}P_{Ji,t} = P_{dl,t} + P_{EB,t} \tag{20}$$

$$P_{hEB,t} + P_{hGT,t} = P_{dh,t} \tag{21}$$

where $P_{hEB,t}$ denotes the heating power of EB. $P_{hGT,t}$ represents the heating power of GT. $P_{EB,t}$ is the power of EB.

(2) The output constraint is shown as:

$$P_{Gi,\min} \le P_{Gi,t} \le P_{Gi,\max} \tag{22}$$

where $P_{Gi,\min}$, $P_{Gi,\max}$ indicate the min and max values of the output of thermal power unit $i$.

(3) The climbing constraint is represented as below:

$$\begin{cases} P_{Gi,t} - P_{Gi,t-1} \leq R_{up,i} \\ P_{Gi,t-1} - P_{Gi,t} \leq R_{down,i} \end{cases} \tag{23}$$

where $R_{up,i}$, $R_{down,i}$ denote the up and down climbing rate of unit $i$.

(4) The WP output range constraint can be obtained as:

$$0 \leq P_{wind,t} \leq P_{wind,t}^{pre} \tag{24}$$

(5) The gas boiler output constraint is

$$P_{GT,\min} \leq P_{GTj,t} \leq P_{GT,\max} \tag{25}$$

where $P_{GT,\min}$, $P_{GT,\max}$ are the min and max value of GT output.

(6) The EB output constraint is shown as

$$P_{hEB,\min} \leq P_{hEB,t} \leq P_{hEB,\max} \tag{26}$$

$$P_{hEB,t} = \eta_{EB} P_{EB,t} \tag{27}$$

where $P_{hEB,\min}$, $P_{hEB,\max}$ indicate the min and max value of thermal power of EB. $\eta_{EB}$ is the conversion efficiency of EB.

The model in this paper is solved using CPLEX in combination with the aforementioned constraints on the integrated flexible operation mode of the proposed CCP [27]. The computer configuration for solving the model of this paper using the solver is AMD, 3.20 GHz and 16 GB.

## 5. Case Simulation

### *5.1. Simulation Settings*

To verify the correctness of the developed model, a typical IEHS is analyzed as an example. This IEHS contains three conventional thermal power units with the unit parameters shown in Table 2, the energy consumption per unit of carbon capture is set at 0.269, and the parameters of the remaining CCP are shown in Table 3. The day-ahead forecasting data and time-of-day tariffs for different load types are shown in Figure 2 and Figure 3, respectively. The scenarios of WP output after reduction are shown in Figure 4 (S means the scenario in Figure 4). Based on the wind power and load day-ahead forecasting data and the constructed optimization model, CPLEX is used to solve the model to obtain the scheduling results.

To verify the effectiveness of the proposed model, five typical cases are set up for comparative validation. Their descriptions are listed as follows:

Case 1: Deterministic case, considering integrated flexible operation of the CCP, and DR is not considered.
Case 2: Deterministic case, considering integrated flexible operation of CCP and considering DR.
Case 3: Uncertainty case, considering integrated flexible operation of CCP, DR, and uncertainty of WP output.
Case 4: Uncertainty case, considering DR and uncertainty of WP output.
Case 5: Uncertainty case, considering split-flow CCP, DR, and uncertainty of WP output.

Cases 1 and 2 are the deterministic cases, and the main difference is whether DR is considered or not. Cases 3 to 5 are the uncertainty cases, where Cases 3 and 5 consider different modes of operation of the CCP, whereas Case 4 does not consider the CCP.

**Table 2.** Unit parameters.

| Unit | a | b | c | $P_{max}$ (kW) | $P_{min}$ (kW) | Up/Down Climbing |
|---|---|---|---|---|---|---|
| 1 | 0.00048 | 16.2 | 1000 | 400 | 200 | 50 |
| 2 | 0.00031 | 17.3 | 970 | 455 | 120 | 50 |
| 3 | 0.0002 | 16.6 | 700 | 200 | 100 | 25 |

**Table 3.** Carbon capture plant parameters.

| Parameters | Value | Parameters | Value |
|---|---|---|---|
| Carbon Capture Efficiency β | 0.81 | Fluid running loss factor/(kg/t) | 1.5 |
| Maximum work efficiency η | 1.05 | MMEA (MEA Molar mass)/(g/mol) | 61.08 |
| Carbon capture power plant fixed energy consumption | 10/10/7.5 | $MCO_2$ ($CO_2$ Molar mass)/(g/mol) | 44 |
| Carbon emission factor | 0.91/0.95/0.98 | Θ (Regeneration tower analysis volume)/(mol/mol) | 0.4 |
| Ethanolamine solvent cost factor/($/kg) | 1.17 | $\rho_R$ (Density of alcoholic amine solution)/(g/mL) | 1.01 |

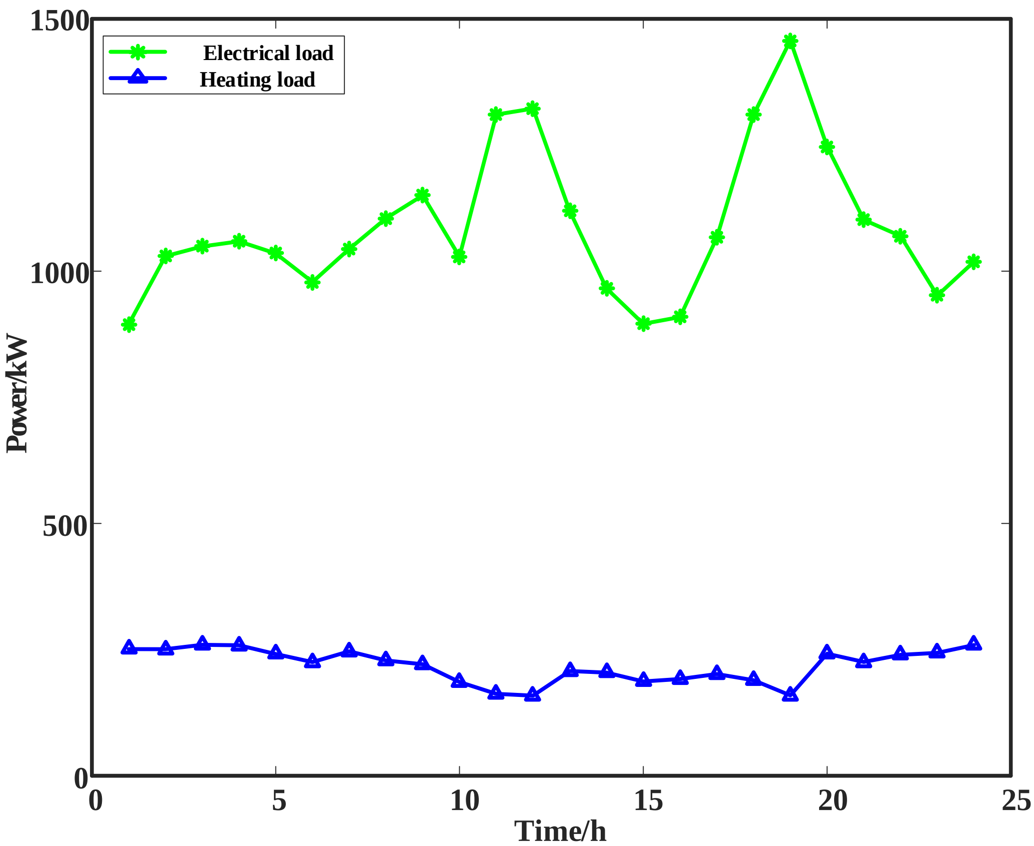


**Figure 2.** Different load curves.

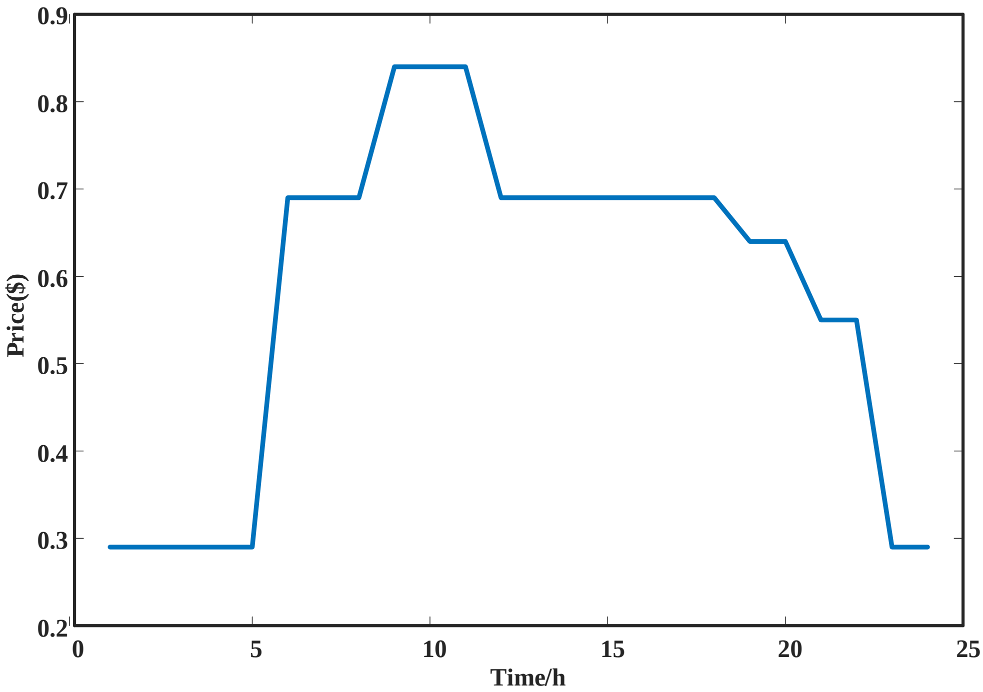


**Figure 3.** Time-of-day tariffs.

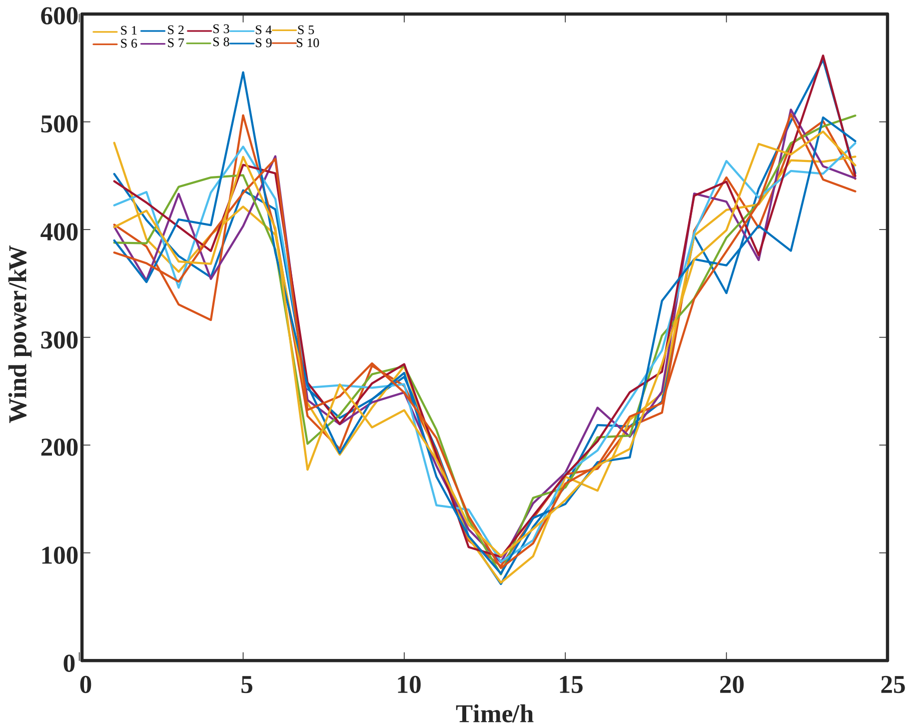


**Figure 4.** WP scenario after reduction.

## *5.2. Results Analysis*

(1) Scheduling results analysis

The simulation solution is performed for the five different cases set up and the results obtained are shown in Table 4. The second column in Table 4 shows the results of the objective function of the optimization model, the third column shows the thermal unit operating cost, gas turbine cost, and gas boiler operating cost (operating cost), and the fourth column shows the CCP costs.

**Table 4.** Comparison of optimization results (USD).

| Case | Objective Function | Operating Costs | CCP Costs |
|---|---|---|---|
| 1 | 459,809.3724 | 412,880.3978 | 18,755.5013 |
| 2 | 459,579.0022 | 416,803.3981 | 19,133.5046 |
| 3 | 458,327.6826 | 413,168.8400 | 18,812.5514 |
| 4 | 462,925.7895 | 415,894.6592 | / |
| 5 | 459,683.1569 | 414,529.2958 | 19,187.5963 |

Table 4 shows the simulation analysis and comparison of optimization results of the five cases analyzed. Due to the DR and uncertainty of WP output, the optimization results in each case vary considerably. The largest value of the total objective function in Case 4 indicates that it is the most expensive and not conducive to reducing carbon emissions without considering the CCP. The total objective function is the smallest in Case 3, which is only USD 458,327.6826. The results indicate that the system cost can be effectively reduced, and its economics can be improved with the consideration of the uncertainty of WP output and DR.

Comparing the optimization results of Cases 3 and 4, it can be found that the system operation cost can be effectively reduced after the addition of the CCP. In Case 3, which incorporates the integrated flexible operation of the CCP, the objective function is reduced by USD 4598.1069.

From Cases 1 and 2, with the addition of DR, there is a certain increase in operating costs and CCP costs in Case 2, but the overall objective function in Case 2 is reduced by USD 230.3702, reflecting its economics. Comparing Cases 2 and 3, the objective function of Case 3 is reduced by USD 1251.3196 after considering the uncertainty of WP output. This shows that the uncertainty of WP output and DR can effectively reduce the economic cost of the system and improve the economics. The operating costs are the smallest in Case 3 and the largest in Case 2. The CCP cost of Case 1 is the smallest; the main reason for this is that the remaining costs in the objective function are reduced in Case 2, making the total objective function of Case 2 smaller than the objective function of Case 1. However, according to the different objective function costs, a critical inclusion can be derived, where the CCP has a positive effect on reducing the carbon emissions and the economics of the system by considering DR and the uncertainty of WP output.

In addition, the results are compared between Cases 3 and 5 for different operation modes of the CCP. The total objective function for Case 3 is USD 1355.4743 lower than that of Case 5, and the operating cost of Case 3 is lower than that of Case 5 by USD 375.0449. This result verifies the scheduling advantages of the integrated flexible operation of the CCP. The use of the CCP integrated flexible operation approach can realize the energy time-shift of carbon capture energy consumption and reduce the operating cost and total economics of the system.

(2) Equipment output analysis

The scenario with the highest probability in stochastic optimization is used as an example for the equipment output analysis of Case 3. The three thermal units in Figure 5 are all integrated with carbon capture systems. The obtained results are shown in Figure 5. It can be seen from Figure 5 that among the three traditional thermal power units, unit 3 has the smallest $CO_2$ capture, and the second and third smallest are units 1 and 2, respectively. This is because unit 3 has less output, which limits its $CO_2$ capture ability. On the other hand, units 1 and 2 produce more power during the dispatch cycle and capture more carbon. The more the thermal units produce, the more carbon is captured. However, the higher the unit output, the lower the carbon capture capacity.

As shown in Figures 6 and 7, since the load of each case is supplied by the thermal power and the WP output, the system's wind abandonment can be analyzed by simply comparing its thermal power output. The net output of thermal power units is closely related to the FE and OE of each scenario. According to the comparison, it can be found that the energy consumption of the CCP is instead the lowest in the case of higher net thermal power output. The use of the CCP integrated flexible operation method can realize the energy time-shift of FE and OE, so the energy consumption of the valley load is higher.

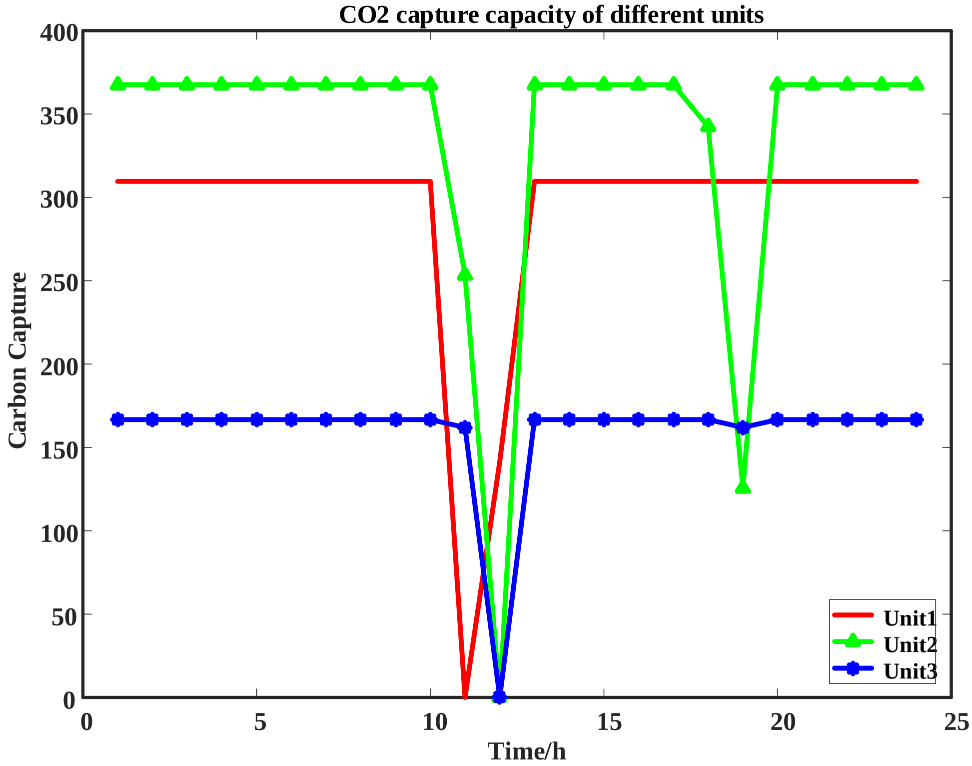


**Figure 5.** $CO_2$ capture capacity of different units.

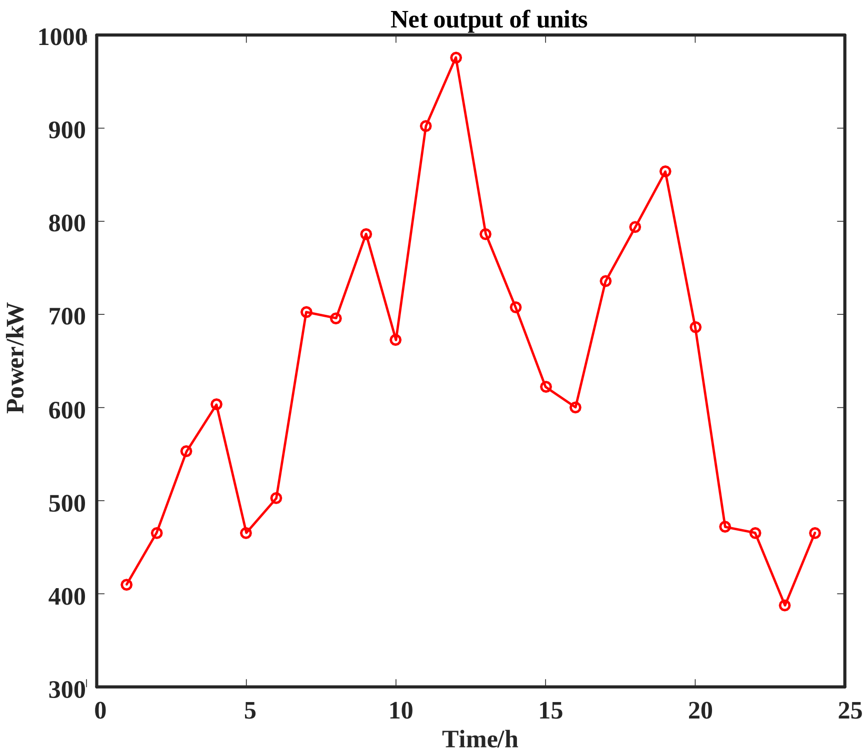


**Figure 6.** Net output of thermal power units.

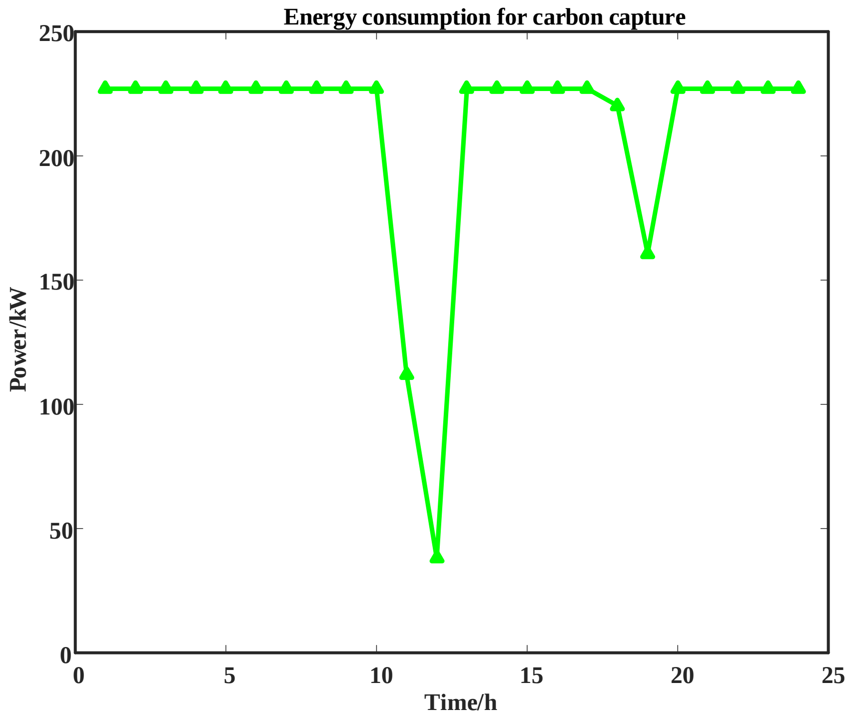


**Figure 7.** CCP energy consumption.

In the heating network, the heating load is mainly satisfied by using GT in Figure 8. After using DR, it can effectively achieve peak and valley reduction and improve the energy utilization rate. The valley of the heating load is in the period of 10:00–12:00, and it can be found that the load trough has a significant improvement with DR. During 20:00–24:00, which is the peak time of the heating load, DR is introduced to reduce the heating load in order to reduce the peak-to-valley difference.

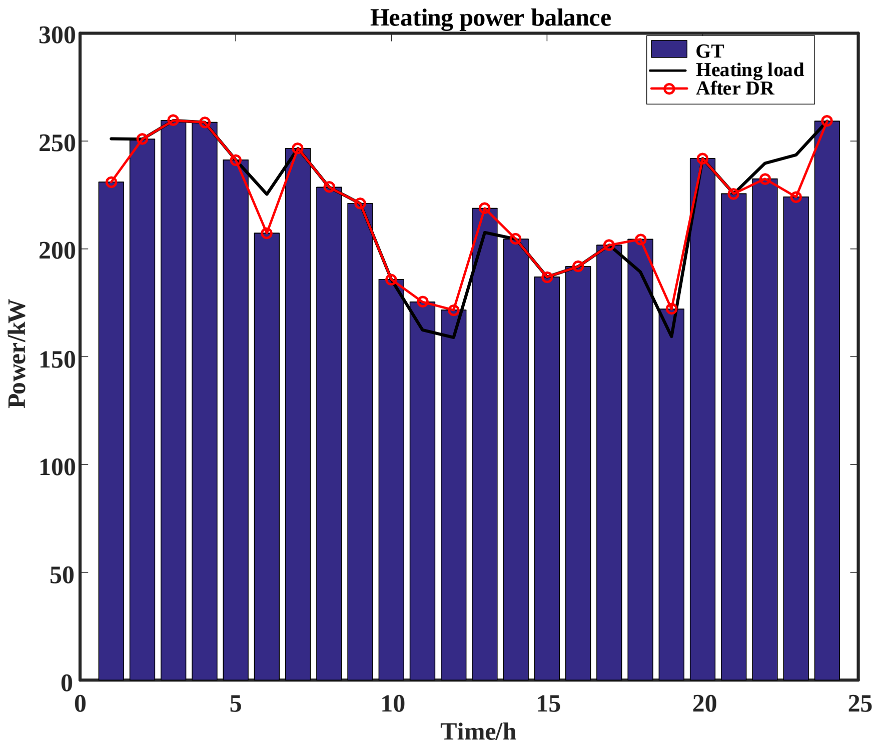


**Figure 8.** Heating power balance.

Figure 9 depicts the electric power balance results, from which it can be found that at night, when the load is low, the load value is boosted by DR to consume WP to a greater extent. In this period, the load demand is mainly met by unit 1 output, and more priority is given to using WP to meet the load, which can reduce carbon emissions. During the load afternoon peak and evening peak hours, the peak load is significantly reduced after DR. As the load demand decreases during the peak hours, the CCP can appropriately increase the carbon capture power, reduce the net output to provide up-rotation backup, share the backup capacity borne by the high carbon thermal units, and thus reduce the high carbon thermal output.

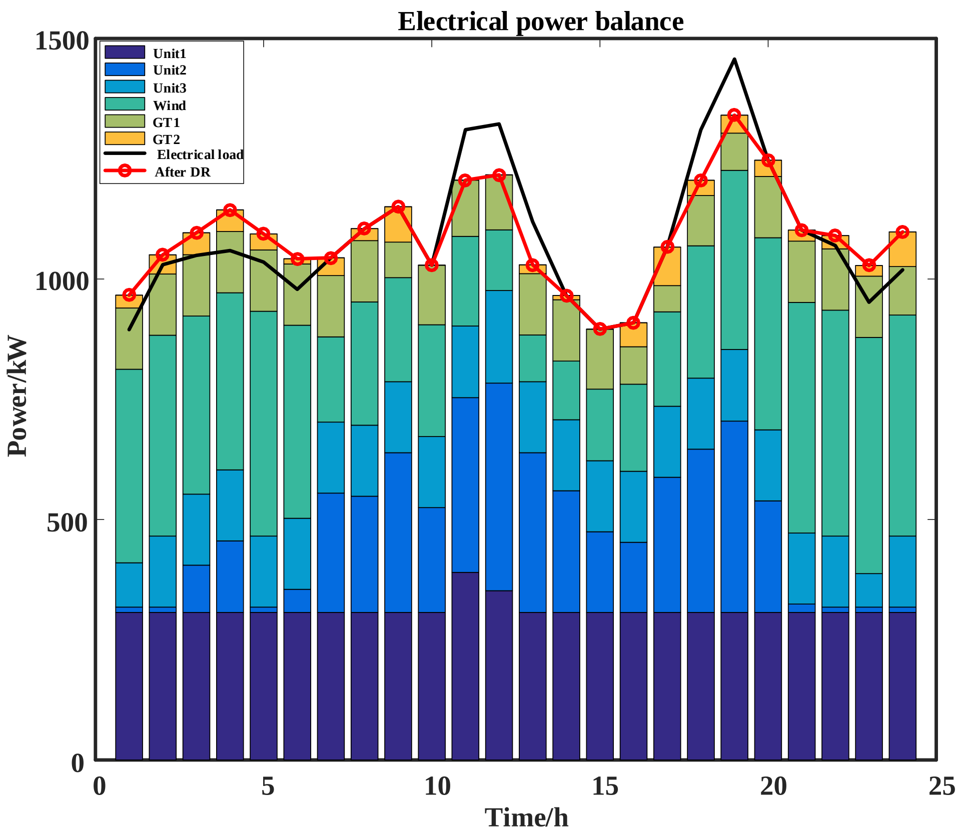


**Figure 9.** Electrical power balance.

During the peak load hours, the output of units 2 and 3 increases. It can be found that the output of high carbon units is less during the peak load. At the same time, the output of unit 2 is high, but the $CO_2$ capture volume decreases. Both units 1 and 3 are close to the maximum output of the unit at the afternoon and evening peaks of the load, the output fluctuates little, and the $CO_2$ capture of the two units is relatively stable without large fluctuations. The main reason for this phenomenon is that the solution storage shifts the carbon capture energy from the peak load to the valley, which is equivalent to using the abandoned wind and carbon capture output to replace the high carbon thermal power output, thus reducing the carbon emission.

There is still space for optimization of the system in this scenario. On the one hand, the low demand in the load valley and the pressure on the lower rotating standby cause the system to still have wind abandonment problems. On the other hand, due to the low FE and OE at the load peak, the net unit output is close to the upper operating limit, and the upper rotating standby of the system is mostly provided by high carbon thermal power.

## 6. Conclusions

This paper focuses on the impact of uncertainty of WP output and the CCP on the IEHS, and the coordinated optimization of DR. Based on the full consideration of resources and the uncertainty of the source and DR of the load, the system economics and carbon emissions are reduced by introducing an integrated and flexible operation of a CCP. The main conclusions of this paper are as follows.

(1) By considering the uncertainty of WP output based on the introduction of the integrated flexible operation mode of the CCP and DR, the proposed model can effectively reduce the IEHS economics and carbon emission level. The cost is reduced compared to when the uncertainty is not considered. The carbon emissions are significantly reduced when compared with the case without considering the CCP.
(2) The liquid storage can realize the energy time-shift of FE and OE, so that the integrated flexible operation mode of the CCP has a broader net output range. The use of DR and the CCP can fully reduce the $CO_2$ emissions of the IEHS and can increase the economic benefits of the IEHS.

The impact on the IEHS is analyzed through the study of the uncertainty of WP output and the operation mode of the CCP in this paper. In the subsequent study, we will focus on the impact of the IEHS with the CCP with multi-time scale rolling optimization, and on the operation mode of the CCP under the market environment.

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