Abstract: The anti-peaking characteristics of a high proportion of new energy sources intensify the peak shaving pressure on systems. Carbon capture power plants, as low-carbon and flexible resources, could be beneficial in peak shaving applications. This paper explores the role of carbon capture devices in terms of peak shaving, valley filling, and adjustment flexibility and constructs a virtual energy storage model utilizing various flexible loads on the demand side. Also, it proposes a joint peak shaving strategy involving carbon capture devices and virtual energy storage. Considering the predictive error characteristics of wind power and load across different time scales, this study establishes a day-ahead and intraday two-stage rolling regulation peaking model based on carbon capture power plants and virtual energy storage to fully leverage the diverse response speeds and peak shaving capabilities of various types of flexible loads. Initially, the model calculates the net load curve after implementing a demand response system, aiming to minimize the load peak–valley difference. Subsequently, within the intraday period, it seeks to minimize system operating costs by precisely allocating peak shaving resources as per demand, thus aiming for economic efficiency while ensuring the system’s peak shaving capability.

Keywords: carbon capture power plant; virtual energy storage; joint peak shaving; two-stage optimized scheduling; low carbon

1. Introduction

With the proposal of ‘dual carbon goals’, China’s new energy installed capacity continues to rise. In the first half of 2023, China’s newly installed renewable energy power generation capacity reached 109 million kilowatts, and its renewable energy power generation reached 1.34 trillion kilowatt hours [1]; however, the fluctuation and anti-peaking characteristics of new energy sources intensify the peaking pressure on systems, requiring faster and more accurate peaking responses to ensure their stability and reliability.

Thermal power serves as China’s primary peaking resource. In the deep peaking stage, the low efficiency and high cost of thermal power diminish its appeal for use within peaking and hinder the clean and efficient utilization of coal. Transforming thermal power into a low-carbon and flexible resource is crucial for mitigating system peak pressure and enhancing the consumption of new energy. Carbon capture power plants (CCPPs) [2] capture and store emissions from coal-fired plants, reducing carbon emissions and enhancing the flexibility of thermal power units for peak regulation. Reference [3] investigated the operational mechanisms of CCPP units, affirming their superiority in delivering peak shaving auxiliary services by evaluating their capacity and rate of peak shaving.

References [4,5] examined CCPP units’ capability to mitigate new energy and load uncertainty. However, the coupling between carbon capture and storage constrains the
CCPP units' adjustment flexibility. Reference [6] developed a low-carbon dispatch model featuring CCPP and pumped storage units, noting that their combined dispatch enhances the system’s economy and lowers its carbon emissions, although the CCPP’s peak output capacity remains limited. Reference [7] explores carbon capture equipment’s role in augmenting energy utilization within electrical integrated systems, yet overlooks the optimization of the balance between unit output and carbon emissions.

The aforementioned demonstrate that the superior peak shaving capabilities of carbon capture power plants significantly enhance their ability to manage uncertainties in new power systems, while also improving their reliability margins and dispatch flexibility [3,8]. However, in the context of peak regulation, CCPP units face several challenges: (1) Operational energy consumption persists during the peak load stages for CCPP units. Although CCPP units with liquid storage and flexible operation have achieved partial decoupling between carbon capture and storage, they incur fixed energy consumption costs. This consumption is in contrast to conventional thermal power, in which the peak output capacity is found to be insufficient. (2) During low load stages, the limited carbon capture capacity of CCPP units hinders the promotion of new energy consumption, exacerbating issues such as wind and solar energy curtailment. (3) Current peak shaving strategies for CCPP units are limited to a single time scale, primarily targeting the day-ahead stage. However, since the prediction accuracy of new energy and load models significantly depends on the time scale [9], maximizing the benefits of precise peak shaving in CCPP units is challenging.

Energy storage devices, characterized by rapid response, can smooth the load curve, and their combined peak shaving efforts alongside CCPP units significantly enhance the system’s peak shaving capabilities. However, the peak shaving capacity of existing energy storage devices is limited by geographical location, energy utilization, and other factors. Leveraging methods from references [10,11], this paper extends the concept of flexible loads and actual energy storage devices with peak shaving potential to virtual energy storage, thereby establishing a joint peak shaving model for carbon capture power plants and virtual energy storage. Based on the operational mechanisms of peak shaving, flexible loads can be categorized into peak shifting loads and peak avoidance loads. Peak shifting loads encompass transferable and shiftable loads, while peak avoidance loads are characterized as reducible loads [12]. Research has explored the adjustment capabilities of flexible loads and energy storage devices across various time scales [13,14]. Reference [15] developed a grid-connected microgrid day-ahead optimization model, incorporating a lithium battery energy storage system, and applied a \( \theta \)-modified krill herd algorithm for its solution. Reference [16] employs a hybrid crow and pattern search algorithm to address the microgrid day-ahead scheduling challenge. Reference [17] examines the flexibility afforded by the joint dispatch of diverse flexible loads and energy storage devices. The scheduling flexibility of flexible loads and energy storage devices across multiple time scales can fully leverage the demand side’s regulation capacity, facilitating precise peak shaving by CCPP units.

Based on these, this paper establishes a day-ahead and intraday two-stage dispatch model for the joint peak shaving of virtual energy storage and carbon capture power plants. Initially, it examines the working principles of carbon capture devices and their potential advantages in peak shaving. Subsequently, it analyzes the rapid response capabilities of flexible loads and their role in peak shaving, constructing a virtual energy storage model focused on flexible loads. Finally, it proposes a joint peak shaving strategy for CCPP units and virtual energy storage. The core idea is to assist CCPP units in peak shaving by integrating user-side resources, using virtual energy storage devices to achieve bidirectional interaction with the power system, and rationally allocating different peak shaving resources according to demand to achieve peak reductions and valley filling, thereby enhancing the system’s emergency peak shaving capabilities. Through a simulation based on the improved IEEE 39-node model and using four distinct scenarios, this paper validates the effectiveness of the proposed joint peak shaving strategy in reducing system peak–valley differences, decreasing system operating costs, and lowering carbon emissions.
Our contribution is twofold: on one hand, the model fully exploits the peak shaving flexibility of carbon capture plants and virtual energy storage, integrating them into the system’s peak shaving scheduling. On the other hand, the day-ahead and intraday two-stage peak shaving model maximizes the multi-temporal scale advantages of virtual energy storage in peak shaving, working in conjunction with carbon capture plants to address system uncertainties.

2. CCPP and Virtual Energy Storage Joint Peak Shaving

The scenario constructed in this paper, encompassing a carbon capture system, energy storage devices, and integrated demand response, is illustrated in Figure 1.

![Figure 1. An integrated system featuring carbon capture devices and virtual energy storage.](image)

2.1. Basic Model of a Carbon Capture Power Plant

2.1.1. Basic Principles of Carbon Capture Power Plants

Carbon capture devices can generally be divided into three types: post-combustion, pre-combustion, and oxy-combustion. Among these, post-combustion carbon capture technology is the most mature. It is capable of separating and capturing CO₂ from the flue gas directly emitted at the end of boilers, making it suitable for retrofitting existing thermal power units. The main structure of the post-combustion carbon capture power plant is detailed in reference [18]. The net output of the CCPP unit is as follows:

\[ P_{C,i,t}^N = P_{C,i,t}^G - P_{C,i,t}^M - P_{C,i,t}^R \]  

Fixed energy consumption is caused by changes in the structure and working conditions of the original thermal power unit. For example, after the introduction of a carbon capture device, valves need to be added to the steam turbine to extract hot steam, resulting in changes in the working conditions of the steam cycle. Generally speaking, the basic energy consumption has little relationship with the operation of the CCPP and can be regarded as a fixed value. The operational energy consumption is directly influenced by the operational conditions of the CCPP, including the thermal energy required to separate carbon dioxide from the rich liquid, the electrical energy needed for compressing carbon dioxide, and the operation of liquid pumps. The operational energy consumption is approximately linearly related to the volume of carbon dioxide captured as follows:

\[ P_{C,i,t}^R = \lambda_{GE} Q_{dc,i,t} \]  

The flexible operation mode of the CCPP relies on two parts of the structure: the flue gas bypass system and the liquid storage tank. Through the flue gas bypass system and liquid storage tank, the CCPP can flexibly adjust the operating energy consumption of the unit, thereby changing the net output of the unit and providing the system with a greater peak shaving capacity and faster response speed.
(1) Flue gas bypass system

The flue gas bypass system separates the flue gas output from the power plant into two parts. One part is emitted directly into the atmosphere, and the other part is emitted into the carbon capture device so that the power plant can control the rate entering the absorption tower and adjust the operational energy consumption of the CCPP.

\[ Q_t = Q_{B,t} + Q_{-t} \]  \hspace{1cm} (3)

\[ Q_{B,t} = \eta_C Q_t = \eta_C \zeta_C P_{C,t} \]  \hspace{1cm} (4)

(2) Liquid storage tank

In conventional carbon capture power plants, the absorption and regeneration of carbon dioxide occur concurrently, limiting the adjustment flexibility of operational energy consumption. The rich liquid and lean liquid storage of the liquid carbon capture device can flexibly adjust the inflow and outflow of the absorption tower, so that the absorption tower and desorption tower can handle different amounts at the same time, achieving a certain degree of decoupling of carbon capture and absorption. The inflow and outflow of the absorption tower and regeneration tower meet as shown below:

\[ Q_{ab,t} = Q_{B,t} \]  \hspace{1cm} (5)

\[ Q_{R-in,t} = \mu_C Q_{ab,t} \]  \hspace{1cm} (6)

\[ Q_{R-out,t} = \lambda_C Q_{R-in,t} \]  \hspace{1cm} (7)

\[ Q_{de,t} = Q_{R-out,CO_2} \]  \hspace{1cm} (8)

2.1.2. Analysis of Peak Shaving Capacity of Carbon Capture Power Plants

Combining Equations (1) and (2), the net output of the CCPP unit can be obtained as follows:

\[ P_{N,t}^C = P_{G,t}^C - P_{M,t}^C - \lambda_G Q_{R-out,t} \]  \hspace{1cm} (9)

During low-load periods, the total power generation output of the unit is \( P_{min} \), and the CCPP reduces the net output by capturing CO\(_2\). In addition to the CO\(_2\) generated during the same period, the CCPP can capture the CO\(_2\) in the rich liquid storage. At this time, both \( \eta_C \) and \( Q_{R-out,t} \) take the maximum value, so that we can maximize the amount of carbon capture to transfer surplus electric energy during the valley load period and promote the consumption of wind and solar energy.

\[ P_{N,t}^{C,\text{min}} = P_{G,t}^C - P_{M,t}^C - \lambda_G Q_{R-out,CO_2} \]  \hspace{1cm} (10)

During peak load periods, the total power generation output of the unit is \( P_{max} \). Within the allowed range, the operational energy consumption of the CCPP is reduced by compressing \( \eta_C \) and \( Q_{R-out,CO_2} \), and the net output of the unit is increased to ensure the power supply and compensate for the load deficit. When \( Q_{R-out,t} = 0 \), carbon dioxide is captured without compression, and the energy consumed by the parser and compressor is 0.

\[ P_{N,t}^{C,\text{max}} = P_{G,t}^C - P_{M,t}^C - \lambda_G Q_{R-out,CO_2} \]  \hspace{1cm} (11)

From the above analysis, it can be seen that by adjusting the ratio of \( Q_{R-in,t} \) and \( Q_{R-out,t} \), the operational energy consumption and the carbon capture volume of the CCPP are no longer one to one. Through the flue gas bypass system and rich liquid storage, the CCPP can flexibly adjust the unit’s operational energy consumption, providing a larger peak shaving capacity. This not only aids in peak shaving and valley filling but also further promotes the consumption of renewable energy. Additionally, conventional thermal power units require a change in boiler status for peak shaving, resulting in slower response times; in contrast, the carbon capture energy consumption of CCPP units, mainly consisting of the
electricity used within the plant, allows for the rapid adjustment of the unit’s net output within a certain range, offering a faster peak shaving response speed.

2.2. Virtual Energy Storage

2.2.1. Transferable Loads

The total power consumption of the transferable loads during the dispatch period remains unchanged, and the load demand power at different times can be adjusted within a certain range. Users spontaneously respond to time-of-use electricity prices (TOU), reducing their electricity consumption during peak load periods and increasing their electricity consumption during low-load periods.

The transferable loads response model based on incentive pricing is as follows:

\[
P_{\text{PDR},t} = P_{L,t} + \Delta P_{\text{u}L,t} - \Delta P_{\text{d}L,t}
\]

(12)

where \(P_{\text{PDR},t}\) denotes the total load demand following the implementation of transferable loads during period \(t\); \(P_{L,t}\) represents the total load demand prior to the implementation of PDR; \(\Delta P_{\text{u}L,t}\) represents the increase in load due to transferable loads; and \(\Delta P_{\text{d}L,t}\) represents the reduction in load due to transferable loads during the period.

A detailed model of the transferable load can be found in [19].

2.2.2. Shiftable Loads

Shiftable loads are a peak-shifting load, whose electricity usage periods can be adjusted based on actual conditions. However, the load curve must be adjusted continuously and holistically. It is strictly restricted by the industrial production process.

2.2.3. IDR Loads

IDR (interruptible demand response) loads can reduce part or all of the power consumption during peak load periods, ensuring the reliability of the power grid supply. Customers sign contracts with power supply companies or independent system operators to reduce demand when necessary, guaranteeing the reliability of power supply during peak grid loads and saving on expensive energy storage facilities. The benefits for users include reduced energy costs and incentives provided by the contract. IDR loads can be controlled through time-of-use electricity pricing or compensation policies specified in contracts. IDR loads adopting contractual incentive strategies are divided into two categories: Type A loads respond to load adjustment instructions from a control center based on the operating conditions of the grid, which is a form of indirect control; and Type B loads are directly controlled by the grid based on contracts, such as the central air-conditioning in commercial loads.

2.2.4. Actual Energy Storage Device

The energy storage device reduces the peak–valley difference of the system by charging during low loads and discharging during peak loads, which can effectively alleviate the imbalance between electricity supply and demand. From the perspective of the power system, energy storage devices have the same role as transferable loads, with added flexibility and reliability. Energy storage is capable of rapid responses and has a flexible layout. It is an important technical means to enhance the peak shaving capacity of the power grid and promote new energy consumption. The operational cost of the energy storage device is as follows:

\[
C_{\text{ESS}} = \sum_{t=1}^{T} \left( c_{\text{cha}E_{\text{ESS},t}} - c_{\text{de}E_{\text{ESS},t}} \right)
\]

(13)
2.3. Joint Peak Shaving Strategy between CCPP and Virtual Energy Storage

The joint peak shaving mechanism of virtual energy storage and CCPP is shown in Figure 2, which fully considers the adjustable characteristics of virtual energy storage to achieve elastic adjustments of the demand-side response, as well as the complementary characteristics of carbon capture power plants.

Figure 2. Joint peak shaving strategy.

Peak load stage: During peak load phases, within the permissible range, compressing $\eta_C$ and $Q_{R,\text{out},CO_2}$ reduces the operational energy consumption of the CCPP, thereby increasing the net output of the unit to ensure the power supply and address the load shortfall. However, relying solely on the output of CCPP units cannot typically meet the system’s electricity demand. During peak load periods, both peak avoidance and load shifting can reduce electricity demand, alleviating the pressure on peak shaving. Energy storage devices can also smooth out load fluctuations by releasing electrical energy.

Valley load stage: During low-load phases, due to the uncontrollability of the new energy output, the deep peak shaving pressure of traditional thermal power units increases, exacerbating the phenomena of wind and solar power curtailment. The CCPP reduces the net output by capturing as much CO$_2$ as possible. In addition to the CO$_2$ generated in the same period, the CCPP can capture the CO$_2$ in the rich liquid storage, with both $\eta_C$ and $Q_{R,\text{out},CO_2}$ taking their maximum values. Moreover, load shifting can quickly adjust the demand for loads, consume surplus energy, and alleviate the pressure of deep peak shaving.

3. Day-Ahead and Intraday Scheduling Model

As the penetration rate of new energy sources such as wind power increases, their uncertainty and anti-peaking characteristics increase the peak–valley difference of the system. As the time scale approaches, the prediction accuracy of the new energy output increases step by step, which is beneficial to the formulation of peak shaving plans for power units. At the same time, taking into account the multi-time scale characteristics of different peak shaving resources in the system, especially the response characteristics of multiple types of flexible loads, it is urgent to further improve the peak shaving plan under refined time scales.

As shown in Figure 3, this paper establishes a day-ahead and intraday two-stage rolling optimization model for peak shaving, aiming to fully exploit the peak shaving capabilities of various resources, reduce the peak-to-valley difference, and ensure the system’s reliable and economical operation. The joint scheduling architecture of this model is shown in Table 1 as follows.
As the penetration rate of new energy sources such as wind power increases, their uncertainty and anti-peaking characteristics increase the peak–valley difference of the system. As the time scale approaches, the prediction accuracy of the new energy output increases step by step, which is beneficial to the formulation of peak shaving plans for power units. At the same time, taking into account the multi-time scale characteristics of different peak shaving resources in the system, especially the response characteristics of multiple types of flexible loads, it is urgent to further improve the peak shaving plan under refined time scales.

As shown in Figure 3, this paper establishes a day-ahead and intraday two-stage rolling optimization model for peak shaving, aiming to fully exploit the peak shaving capabilities of various resources, reduce the peak-to-valley difference, and ensure the system’s reliable and economical operation. The joint scheduling architecture of this model is shown in Table 1 as follows.

**Table 1. Day-ahead and intraday peak shaving framework.**

<table>
<thead>
<tr>
<th>Source/Load Type</th>
<th>Day-ahead and intraday joint scheduling architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day-ahead (1 h)</td>
</tr>
<tr>
<td>Conventional thermal power units</td>
<td>Start/stop plan</td>
</tr>
<tr>
<td>Carbon capture power plant</td>
<td>Start/stop plan</td>
</tr>
<tr>
<td>Wind power</td>
<td>Consumption</td>
</tr>
<tr>
<td>Shiftable load</td>
<td>Adjustment amount</td>
</tr>
<tr>
<td>PDR</td>
<td>Adjustment amount</td>
</tr>
<tr>
<td>IDR load</td>
<td>Category A</td>
</tr>
<tr>
<td>Energy storage device</td>
<td>-</td>
</tr>
</tbody>
</table>

**Figure 3. Day-ahead and intraday joint peak shaving model.**

1. Day-ahead scheduling: Executed every 24 h with a time scale of 1 h, the upper-layer model aims to minimize the net load variance to determine the total load demand after the PDR project. The lower level, with the objective function of minimizing costs, establishes the start/stop plans for conventional thermal and carbon capture units, as well as the dispatch plans for shiftable loads.

2. Intraday scheduling: For a time scale of 15 min, we determine the output of conventional units and carbon capture power plants; the charge and discharge power of the energy storage; and the dispatch amount of Class A and B IDR loads.

The prediction accuracy of wind power in different stages is different, and different output plans should be formulated for the wind power prediction values in the two stages of the day-ahead and intra-day models.

3.1. Day-Ahead Scheduling Model

3.1.1. Objective Function
1. Minimize net load fluctuations:

Net load is defined as the residual load borne by the unit after the PDR. Excessive net load fluctuations can easily lead to frequent starts and stops of thermal power units,
shortening the lifetime of equipment and increasing operation and maintenance costs. In
order to ensure the peak shaving capabilities of the units, the net load fluctuations after
the PDR should be suppressed as much as possible, as shown below:

$$\min F_1 = \frac{1}{N_t} \sum_{t=1}^{N_t} |P_{PDR,t} - P_{PDR,av}|$$  \hspace{1cm} (14)$$

$$P_{PDR,av} = \frac{1}{N_t} \sum_{t=1}^{N_t} P_{PDR,t}$$  \hspace{1cm} (15)$$

where $P_{PDR,av}$ is the load average after the PDR is implemented in a scheduling period.

2. The day-ahead peak shaving cost is minimal, as shown below:

$$F_1 = \min (C_G + C_H + C_W + C_Z + C_{ESS} + C_{FL} + C_T)$$  \hspace{1cm} (16)$$

The start and stop costs of the thermal power units are as follows:

$$C_G = \sum_{t=1}^{T} \sum_{i=1}^{N_{G1}+N_{G2}} G_i [u_{i,t}(1 - u_{i,t-\delta}) + u_{i,t-\delta}(1 - u_{i,t})]$$  \hspace{1cm} (17)$$

where $N_{G1}$ and $N_{G2}$ are the number of conventional thermal power units and CCPP units
respectively; $G_i$ is the start-up and shutdown costs of the $i$th unit; and $u_{i,t}$ is the 0/1 variable,
indicating the operating status of the unit.

The coal consumption cost of thermal power units is as follows:

$$C_H = \sigma_g \sum_{t=1}^{T} \sum_{i=1}^{N_{G1}+N_{G2}} u_{i,t} \left( a_i P_{Gi,t}^2 + b_i P_{Gi,t} + c_i \right)$$  \hspace{1cm} (18)$$

where $\sigma_g$ is the unit coal consumption cost; $a_i$, $b_i$, and $c_i$ are the coal combustion coefficients
of the unit; and $P_{Gi,t}$ is the equivalent output of the $i$th unit in period $t$.

The wind abandonment cost is as follows:

$$C_W = \sum_{t=1}^{T} f_{cut}(P_{wpre,t} - P_{wss,t})$$  \hspace{1cm} (19)$$

The scheduling cost of load shifting is as follows:

$$C_{FL} = \sum_{j=1}^{n-t_0} \sum_{k=m}^{n} u_k \left( \sum_{i=j}^{n} C_{s,t} P_{s,i} \right)$$  \hspace{1cm} (20)$$

where $j$ is the original starting time set of the shiftable load; $[m,n]$ is the time interval
for which the load is adjustable; $C_{s,t}$ is the unit compensation cost for shifting the load
at moment $t$; $P_{s,i}$ is the active power of the shiftable load during the $t$ interval before
adjustments; and $u_k$ is the state of load shifting, where $u_k = 1$ means that the load shifts
and $u_k = 0$ means that the load does not shift.

The depreciation costs of carbon capture power plants are as follows:

$$C_Z = \frac{C_{cc}^{cc}(1 + r)^{N_{cc}r}}{365 \left( (1 + r)^{N_{cc}r} - 1 \right)} + \frac{C_{ess}^{ess} V_{ess}(1 + r)^{N_{ess}r}}{365 \left( (1 + r)^{N_{ess}r} - 1 \right)}$$  \hspace{1cm} (21)$$

Carbon emission cost:

The baseline method [20] is used to approximately calculate the carbon emission costs
as follows:

$$C_T = K_M \left( E_c - \sum_{i=1}^{N} \sum_{t=1}^{24} (\delta_{h} P_{Gi,t}) \right)$$  \hspace{1cm} (22)$$
3.1.2. Restrictions

1. Power Balance Constraints

\[
\sum_{i=1}^{N_G} p_{G,i,t} + \sum_{j=1}^{N_c} p_{c,j,t} + \sum_{i=1}^{N_w} p_{wi,t} = p_{PDR,t} + p_{ESS} + p_{S,t} - \sum_{i=1}^{N_A} \Delta p_{A,i, IDR,t} - \Delta p_{B,IDR,t} \tag{23}
\]

2. Carbon Capture Power Plant Constraints

The reserve of the solution storage in period \( t \) is related to the reserve in time \( t-1 \) and the inflow and outflow in period \( t \). The storage level of the solution reservoir at the moment \( t \) is related to the storage level at the moment \( t-1 \) and the inflow and outflow amounts during the interval \( t \) as shown below:

\[
\begin{align*}
Q_{j,R,t} &= Q_{j,R,t-1} + Q_{j,R-in,t} - Q_{j,R-out,t} \\
Q_{j,L,t} &= Q_{j,L,t-1} + Q_{j,L-in,t} - Q_{j,L-out,t}
\end{align*}
\tag{24}
\]

where \( Q_{j,R,t} \) and \( Q_{j,L,t} \) represent the storage volumes of rich and lean solutions in their storage units at time \( t \), respectively; \( Q_{j,R-in,t} \) and \( Q_{j,R-out,t} \) are the inflow and outflow volumes of rich liquid storage, respectively; and \( Q_{j,L-in,t} \) and \( Q_{j,L-out,t} \) are the inflow and outflow volumes of lean liquid storage, respectively.

The solution storage capacity is limited to the following:

\[
\begin{align*}
0 &\leq Q_{j,R,t} \leq Q_{j,R,\text{max}} \\
0 &\leq Q_{j,L,t} \leq Q_{j,L,\text{max}}
\end{align*}
\tag{25}
\]

In order to ensure the stable adjustment capability of the CCPP unit during the dispatch cycle, it is necessary to ensure that the liquid storage volume of the liquid storage tank is equal at the beginning and end of each day as follows:

\[
\begin{align*}
\sum_{i=1}^{T} (Q_{j,R-in,t} - Q_{j,R-out,t}) &= 0 \\
\sum_{i=1}^{T} (Q_{j,L-in,t} - Q_{j,L-out,t}) &= 0
\end{align*}
\tag{26}
\]

3. Transferable Load Constraints:

Restricted by user needs, transferable loads can only be transferred in and out at specific times. At the transferable time \( t \), the load transfer capacity is limited to the following:

\[
\Delta P_{PDR,t} \leq \lambda_{PDR,t} p_{PDR,t}^{L} \tag{27}
\]

The load transfer of the transferable load at time \( t \) satisfies the power balance as follows:

\[
P_{PDR,t} = P_{L,t} + \Delta P_{PDR,t} \tag{28}
\]

The user satisfaction constraint is as follows:

\[
1 - \frac{\sum_{t=1}^{T} \Delta P_{PDR,t}}{\sum_{t=1}^{T} p_{L,t}} \geq R_{\text{min}} \tag{29}
\]

where \( R_{\text{min}} \) is the minimum value of user satisfaction.

Through day-ahead decision making, the start/stop status of thermal power units and the adjustment amount of the shiftable load are determined, and they are substituted into the intra-day dispatch model as fixed quantities.
4. Line Power Flow Constraints:

This paper adopts branch power flow constraints, which are described by the following generator output power transfer distribution factors:

\[ P_{x,\text{min}} \leq \sum_{i=1}^{N} G_{x-i} P_{i,t} - \sum_{j=1}^{N} G_{x-j} P_{d,t} \leq P_{x,\text{max}} \]  

(30)

where \( G_{x-i} \) represents the impact of the injected power of node \( i \) on line \( x \); \( G_{x-j} \) represents the impact of the injected power of node \( j \) on line \( x \); \( P_{x,\text{max}} \) and \( P_{x,\text{min}} \) are the maximum and minimum transmission capacities of line \( x \), respectively; \( P_{i,t} \) is the output of the unit located at node \( i \) at time \( t \); and \( P_{d,t} \) is the load demand of node \( d \) at time \( t \).

5. Other Constraints

Wind power meets the output upper-limit constraint, and conventional thermal power units should meet ramp constraints, unit output constraints, etc.

3.2. Intraday Scheduling Model

3.2.1. Objective Function

The intraday dispatch model no longer considers the start and stop costs of thermal power units or the dispatching costs of shiftable loads and TOU flexible loads. The objective function of the intraday dispatch model is as follows:

\[ F_1 = \min(C_H + C_W + C_{FL} + C_{ESS}) \]  

(31)

where the physical meanings of \( C_H \) and \( C_W \) are the same as those in Formula (16).

The scheduling cost \( C_{FL} \) of the flexible load is the cost of the IDR load as follows:

\[ C_{FL} = \sum_{t=1}^{T} \sum_{i=1}^{N} \sum_{m=1}^{M_A} \gamma_{i,m} C_{i,m,t}^{A,IDR} P_{i,IDR,t}^{A} + \sum_{t=1}^{T} C_{i,t}^{B,IDR} P_{i,t}^{B,IDR} \]  

(32)

where \( N_A = \) the number of users of the Class A load; \( M_A = \) the number of gears of the A load; \( \gamma_{i,m} = \) the adjustment state of the \( i \)th Class A IDR in the \( m \) gear; \( C_{i,m,t}^{A,IDR} \) and \( C_{i,t}^{B,IDR} \) are the unit compensation standards of the corresponding gear load adjustment amounts, respectively; \( P_{i,IDR,t}^{A} \) is the response quantity of the \( i \)th type A load at time \( t \); and \( P_{i,t}^{B,IDR} \) is the response quantity of the type B load at time \( t \).

3.2.2. Restrictions

1. Network Operating Constraints:

The limit of system spinning reserve is generally ensured by the final scheduling level of the system [21]. Therefore, the total amount of spinning reserve acquisition required by the system should be determined based on the wind power and load forecast values at the final dispatch level, as well as the characteristics of the forecast error. Day-ahead scheduling is not the final schedule of the system, and it is difficult to determine the appropriate total amount of spinning reserve acquisition without considering spinning reserve constraints. In the intraday peaking model, it is necessary to ensure a certain amount of reserve capacity to address the uncertainty of the load and wind power response. The constraints for the system’s spinning reserve are as follows:

\[ \sum_{i=1}^{N_{G1}} U_i P_{G,i,t}^{up} + \sum_{i=1}^{N_{G2}} U_i P_{G,i,t}^{up} + P_{ESS,t}^{up} \geq \xi_1 P_{L,t} + \xi_2 P_{W,t} \]  

(33)

\[ \begin{align*}
0 \leq P_{G,i,t}^{up} & \leq \min(P_{G,i,t}^{max} - P_{G,i,t}^{min}) \\
0 \leq P_{G,i,t}^{up} & \leq \min(P_{L,i,t}^{max} - P_{L,i,t}^{min})
\end{align*} \]

(34)
2. Flexible Load Constraints

In the intraday dispatch model, the constraints for flexible loads primarily consist of Type A and Type B IDR constraints, without considering the role of shiftable loads. To ensure the reliability of adjustments, Type A IDR participants can only choose one adjustment level, which is as follows:

\[
0 \leq p_{\text{up},t}^{\text{ESS},t} \leq \min \left( e_{\text{ESS},t}^{\text{de}}(P_{\text{ESS},t}^{\text{max}} - P_{\text{de},t}^{\text{ESS},t}), e_{\text{ESS},t}^{\text{de}}(S_{\text{ESS},t-1} - P_{\text{de},t}^{\text{ESS},t}) \right)
\] (35)

2. Flexible Load Constraints

In the intraday dispatch model, the constraints for flexible loads primarily consist of Type A and Type B IDR constraints, without considering the role of shiftable loads. To ensure the reliability of adjustments, Type A IDR participants can only choose one adjustment level, which is as follows:

\[
\sum_{m=0}^{M_i} \gamma_{i,m} = 1
\] (36)

where \( \gamma_{i,m} \) is the calling status of the \( i \)th Class A IDR in the \( m \) position.

The constraints of the Class B IDR load include the upper and lower limits of the adjustable power, the limit of adjustable times, the minimum adjustment time limit, and the maximum interruption time limit as follows:

\[
p_{\text{IDR},t}^{\text{B},\text{min}} \leq P_{\text{IDR},t}^{\text{B}} \leq P_{\text{IDR},t}^{\text{B},\text{max}}
\] (37)

\[
\sum_{t=1}^{T} r_t \leq N_{\text{max}}
\] (38)

Minimum call interval constraint:

\[
(x_t - x_{t-1}) + (x_{t+\alpha} - x_{t+\alpha}) \leq 1 \quad \alpha \in \{1, 2, \cdots, t_{\text{on}} - 1\}
\] (39)

Minimum continuous call time constraint:

\[
(x_{t-1} - x_t) + (x_{t+\beta} - x_{t+\beta}) \leq 1 \quad \beta \in \{1, 2, \cdots, t_{\text{off}} - 1\}
\] (40)

where \( t_{\text{on}} \) and \( t_{\text{off}} \) are the minimum continuous calling time and the minimum calling time interval constraints, respectively.

Adjusted rate constraints:

\[
\left| P_{\text{IDR},t}^{\text{B}} - P_{\text{IDR},t-1}^{\text{B}} \right| \leq R
\] (41)

3. Energy storage device constraints:

\[
P_{\text{ESS},t} = e_{\text{ESS},t}^{\text{de}}P_{\text{ESS},t} - (1 - e_{\text{ESS},t}^{\text{de}})P_{\text{ESS},t}^{\text{cha}}
\] (42)

Constraints such as the charging and discharging power and the state of charge of energy storage devices can be found in reference [21].

4. Other constraints

The constraints of carbon capture plants, conventional thermal power units, wind power output, and line flow are consistent with those described in Section 2.1.

3.3. Model Solving

CPLEX 12.6.3 is one of the most commonly used solvers. It has been widely used in the optimal dispatch of power systems and is suitable for day-ahead, intraday, and real-time dispatch. Therefore, we chose the CPLEX solver to solve our model.

4. Case Analysis

4.1. Calculation Conditions

This article employs an improved IEEE39 node system for our simulation, designating G1 and G2 as the CCPP units. An 800 MW wind farm replaces the No. 5 thermal power unit,
while the parameters for the remaining thermal units are based on those of reference [5]. The callable capacity of the IDR load is set at 5%, with the compensation costs based on those of [15,22]. The elastic coefficient of the PDR load and the upper and lower limits of the electricity price change are all based on those of reference [19].

In order to verify the effectiveness of the joint peak shaving strategy of CCPPs and virtual energy storage, the following four scenarios were selected for our comparative analysis:

1. Scenario 1: Excluding virtual energy storage and CCPPs, only conventional thermal power units are used for peak shaving;
2. Scenario 2: Joint peak shaving between CCPPs and conventional thermal power units;
3. Scenario 3: Joint peak shaving involving both CCPPs and conventional thermal power units;
4. Scenario 4: CCPP and virtual energy storage devices participate in joint peak shaving.

4.2. Analysis of Calculation Results

In order to comprehensively study the joint peak shaving effect of various resources, the day-ahead and intraday joint peak shaving results of different models under four scenarios are used as examples in our analysis. The typical daily load curve and wind power prediction curve are shown in Figure 4. The maximum and minimum loads are approximately 1500 MW and 900 MW.

![Figure 4. Forecast curve of wind power and load.](image)

4.2.1. Analysis of Day-Ahead Results

The detailed scheduling results of various types of resources in the above four scenarios in the day-ahead stage are shown in Table 2.

<table>
<thead>
<tr>
<th>Scheduling Results</th>
<th>Scene 1</th>
<th>Scene 2</th>
<th>Scene 3</th>
<th>Scene 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating costs / CNY</td>
<td>2,453,267</td>
<td>2,618,741</td>
<td>2,417,835</td>
<td>2,427,188</td>
</tr>
<tr>
<td>Start and stop costs / CNY</td>
<td>57,231</td>
<td>56,784</td>
<td>56,000</td>
<td>51,478</td>
</tr>
<tr>
<td>Carbon trading costs / CNY</td>
<td>416,629</td>
<td>−27,280</td>
<td>38,742</td>
<td>−46,852</td>
</tr>
<tr>
<td>Wind curtailment cost / CNY</td>
<td>46,783</td>
<td>34,255</td>
<td>32,451</td>
<td>11,032</td>
</tr>
<tr>
<td>Virtual energy storage / CNY</td>
<td></td>
<td>68,745</td>
<td>65,241</td>
<td></td>
</tr>
<tr>
<td>Carbon emissions / t</td>
<td>8758.42</td>
<td>3927.84</td>
<td>8461.72</td>
<td>2677.81</td>
</tr>
</tbody>
</table>

Table 2 illustrates that Scenario 1 incurs the highest wind curtailment costs, carbon trading costs, and total costs among the four scenarios analyzed. In contrast, Scenario 4,
which integrates the joint peak shaving capabilities of CCPP units and virtual energy storage devices, achieves the optimal reduction in total cost. The wind curtailment costs in Scenarios 2 and 3 are diminished by 26.78% and 30.6%, respectively, compared to those in Scenario 1, demonstrating the effectiveness of the CCPP units and virtual energy storage in enhancing the consumption of renewable energy. Furthermore, the total cost in Scenario 2 is 6% lower than that in Scenario 1, indicating the CCPP units’ contribution to improving the system’s economic efficiency. Notably, Scenario 4 presents a reduction in the total cost and wind curtailment cost by CNY 147,955 and CNY 19,572, respectively, compared to that of Scenario 2, underscoring the synergistic effect of combining CCPP units with virtual energy storage. This combination not only facilitates increased renewable energy consumption but also mitigates the incremental costs associated with conventional thermal power units managing the load variability.

Furthermore, Scenario 1 exhibits the most significant wind curtailment issue among the four scenarios due to the system’s lack of adjustable flexibility resources and the inadequate response capability of conventional thermal power units to load and wind power fluctuations. In Scenario 2, the introduction of CCPP units contributes to peak shaving and valley filling via energy consumption shifting, thus mitigating the wind curtailment challenge. However, it does not facilitate complete wind power consumption. Additionally, the peak load stage demands high output from thermal power units, resulting in elevated carbon emission costs and the underutilization of the CCPP units’ potential. To address the limitations of independent CCPP operation during peak shaving, Scenario 4 implements a complementary synergy mechanism between virtual energy storage and the CCPP, enhancing the wind power integration. This approach not only reduces wind curtailment costs but also eases the burden of carbon emissions from CCPP units, diminishes the system’s net load peak–valley disparity, and promotes renewable energy consumption.

Virtual energy storage, as a flexible resource for peak shaving, can improve the peak–valley difference in the system load. Figure 5 shows the net load curves after introducing virtual energy storage in Scenarios 3 and 4, taking into account the variability in both the wind power and load. It is evident that the peak–valley difference in the load under Scenario 4 is smaller than that under Scenario 3, and the pressure on conventional thermal power units to produce peak outputs during high-load periods is reduced.

![Figure 5. Day-ahead virtual energy storage resource scheduling results.](image)

### 4.2.2. Analysis of Intraday Results

The intra-day optimal dispatch is carried out based on known results, such as the unit start/stop plan obtained from the day-ahead dispatch plan and the PDR response curve in relevant scenarios. The time scale of intra-day dispatch is taken as 15 min and is executed every 1 h to determine the amount of adjustment for resources such as energy storage, IDR load, etc. The intraday scheduling results of the system under each scenario are shown in Table 3.
Table 3. Intraday scheduling results.

<table>
<thead>
<tr>
<th>Scheduling Results</th>
<th>Scene 1</th>
<th>Scene 2</th>
<th>Scene 3</th>
<th>Scene 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal consumption cost/CNY</td>
<td>2,341,826</td>
<td>2,573,414</td>
<td>2,408,742</td>
<td>2,319,445</td>
</tr>
<tr>
<td>Carbon trading costs/CNY</td>
<td>432,652</td>
<td>−26,527</td>
<td>159,788</td>
<td>−56,492</td>
</tr>
<tr>
<td>Wind curtailment cost/CNY</td>
<td>6987</td>
<td>2684</td>
<td>3658</td>
<td>0</td>
</tr>
<tr>
<td>Virtual energy storage cost/CNY</td>
<td>-</td>
<td>-</td>
<td>73,561</td>
<td>73,941</td>
</tr>
<tr>
<td>Total cost/CNY</td>
<td>3,064,383</td>
<td>2,723,658</td>
<td>2,752,369</td>
<td>2,632,541</td>
</tr>
<tr>
<td>Carbon emissions/t</td>
<td>7456.2</td>
<td>2369.46</td>
<td>7365.28</td>
<td>2796.35</td>
</tr>
<tr>
<td>Abandoned air volume/(MW-h)</td>
<td>2,341,826</td>
<td>2,573,414</td>
<td>2,408,742</td>
<td>2,319,445</td>
</tr>
</tbody>
</table>

As can be seen from the table above, the changing trends of various costs in the intraday scheduling stage are similar to those in the day-ahead stage, so they will not be described again. Compared with the previous day, the wind curtailment costs of each scenario during the day have been significantly reduced, especially under Scenario 4, in which the full consumption of wind power was achieved, which illustrates the rationality of the unit start-up and shutdown plan in the current stage. The wind curtailment problem occurs in Scenarios 1–3, but the cost of wind curtailment is much less than that in the day-ahead dispatch stage, and the wind curtailment time is mostly concentrated in periods of high wind power generation and low loads.

As a flexible peak shaving resource, virtual energy storage is capable of fast responses that can smooth the load curve. Joint peak shaving with CCPP units can significantly improve the peak shaving capability of the system. In the intraday phase, virtual energy storage can dispatch various resources. The result is shown in Figure 6. It can be seen that the response results of the Class A and Class B IDRs in the intraday dispatching process are similar. In the early morning (0:00–2:00), when the load is low and wind power is high, the two types of IDRs increase demand to promote the consumption of new energy. During peak periods, the output of wind power is small. Lowering the demand for the two types of IDRs can play a role in peak shaving, which can alleviate the peak shaving pressure of thermal power units (conventional and carbon capture). The response characteristics of actual energy storage devices are similar to those of IDR resources, charging during low load periods and discharging during peak load periods; however, due to limitations in energy storage capacity and charging and discharging costs, actual energy storage only works during the net load peak and valley stages. From the above analysis, it can be seen that the adjustment flexibility characteristics of virtual energy storage devices can effectively alleviate the peak load pressure of thermal power units and improve the reliability of power supply in power systems.

![Figure 6. Virtual energy storage resource intraday response results.](image-url)
Figure 7 shows the carbon capture energy consumption under Scenarios 2 and 4 in the intraday dispatch phase. It can be seen that the carbon capture energy consumption trends in Scenarios 2 and 4 are similar. Due to the energy time-shifting feature of CCPP units, the energy consumption for carbon capture is highest during periods of low loads. In scenario 4, the introduction of virtual energy storage devices alleviated the pressure from energy losses, consequently reducing the energy consumption for carbon capture.

4.2.3. Effect of Flue Gas Split Ratio

In the day-ahead and intra-day stages, the value of the flue gas split ratio can significantly affect the optimization results. This paper takes the day-ahead dispatching stage as an example to study the changes in the total system cost and carbon emissions under different flue gas split ratios. Figure 8 below shows the changes in total costs and carbon emissions in Scenarios 2 and 4 under different flue gas split ratio values.

It can be seen that as the flue gas split ratio increases, the total cost and carbon emissions show an obvious downward trend; this is because the higher the value of the flue gas split ratio is, the stronger the adjustability of the CCPP unit. At the same level of carbon emissions, in this case, the carbon capture capacity is improved, the cost of carbon trading is greatly reduced, and the total cost is reduced; in addition, after the flue gas split ratio is increased, the role of the CCPP unit energy time transfer is also more significant and can increase the consumption of wind power and further reduce the operating costs of the system.
As the flue gas split ratio approaches its limit value, the rate of operational cost reductions in Scenario 2 slows down, or even stabilizes. This is because, at a flue gas split ratio of one, the carbon capture power plant maximizes carbon capture and sequestration efforts to achieve higher carbon revenues. However, the adjustable capacity of the CCPP is insufficient. In scenarios of sudden load or wind power fluctuations, this may result in increased wind curtailment or a reduction in carbon capture volume, thereby elevating operational costs.

Within the above value range of the flue gas split ratio, the total cost and carbon emissions of Scenario 4 show a relatively obvious downward trend. This is because scenario 4 is equipped with a virtual energy storage device with adjustment flexibility characteristics, which can improve the shortcomings of the carbon capture power plant, improve the effectiveness of carbon capture, and further reduce the carbon transaction cost of the system. Compared with Scenario 2, the adjustment cost of virtual energy storage is lower than the income from carbon trading and the cost of wind curtailment, and the reduction in the total system cost is significant.

5. Conclusions

Based on CCPP units, this paper established a day-ahead and intraday two-stage dispatching model for the joint peak shaving of virtual energy storage and carbon capture power plants, taking into account carbon emissions, wind curtailment, and system operating costs. The effectiveness of the proposed model was verified through a simulation, and the relevant conclusions are as follows:

1. Compared with conventional thermal power units, CCPP units can reduce carbon emissions in the system and reduce carbon transaction costs. The energy time-drift characteristics of CCPP units can play a role in peak shaving and valley filling and promote the consumption of new energy.

2. Compared with CCPP peak shaving alone, virtual energy storage and CCPP units combined with peak shaving can better stabilize load fluctuations, reduce peak and valley differences in the system, and improve the peak output capacity of carbon capture units; in addition, due to the adjustment flexibility characteristics of virtual energy storage, the carbon capture capacity of CCPPs was also significantly improved.

3. Through the day-ahead and intraday two-stage model, various resources in virtual energy storage and the adjustment capabilities of CCPP units can be better utilized, which is conducive to formulating more accurate dispatch strategies to achieve the full consumption of wind power.

It should be noted that this paper primarily focuses on the research of the peak shaving capabilities of carbon capture equipment and virtual energy storage, without taking into consideration the practical technical requirements and construction costs of energy storage devices. In subsequent research, the authors will continue to delve deeper into these issues, as well as to refine and expand our work.

Author Contributions: Conceptualization, Y.L.; Methodology, Y.Z.; Software, S.Z.; Validation, Z.H. and Y.X.; Investigation, Y.Z. and X.H.; Resources, Y.Z. and Z.H.; Data curation, Z.H.; Writing—review & editing, S.Z., Y.L., X.H. and Y.X.; Supervision, Y.Z. and Y.X. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by State Grid Fujian Electric Power Company Research Program (B3130N23001H).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDR</td>
<td>Price-based demand response</td>
</tr>
<tr>
<td>CCPP</td>
<td>Carbon capture power plant</td>
</tr>
<tr>
<td>IDR</td>
<td>Integrated demand response</td>
</tr>
<tr>
<td>( p_{GT,i} )</td>
<td>The net output of the CCPP unit</td>
</tr>
<tr>
<td>( p_{GT,i} )</td>
<td>The total output of the thermal power unit</td>
</tr>
<tr>
<td>( p_{GT,i} )</td>
<td>The fixed energy consumption of the CCPP unit</td>
</tr>
<tr>
<td>( p_{GT,i} )</td>
<td>The operating energy consumption of the CCPP unit</td>
</tr>
<tr>
<td>( \lambda_{GE} )</td>
<td>The energy consumption per unit of carbon dioxide captured</td>
</tr>
<tr>
<td>( Q_{cr,i} )</td>
<td>Total capture of carbon dioxide</td>
</tr>
<tr>
<td>( Q_{ct,i} )</td>
<td>Total carbon dioxide amount produced by the power plant</td>
</tr>
<tr>
<td>( Q_{ct,i} )</td>
<td>Carbon dioxide amount flowing into the CCPP unit</td>
</tr>
<tr>
<td>( Q_{ct,i} )</td>
<td>Carbon dioxide amount flowing into the atmosphere</td>
</tr>
<tr>
<td>( \eta_C )</td>
<td>Flue gas split ratio</td>
</tr>
<tr>
<td>( \eta_C )</td>
<td>Carbon emission intensity coefficient</td>
</tr>
<tr>
<td>( Q_{ch,i} )</td>
<td>Carbon dioxide captured in absorption tower</td>
</tr>
<tr>
<td>( \mu_C )</td>
<td>Capture rate in absorption tower</td>
</tr>
<tr>
<td>( Q_{r-in,i} )</td>
<td>Inflow of the rich liquid</td>
</tr>
<tr>
<td>( Q_{r-out,i} )</td>
<td>Outflow of the rich liquid</td>
</tr>
<tr>
<td>( \lambda_C )</td>
<td>The ratio of outflow to inflow in the rich liquid storage</td>
</tr>
<tr>
<td>( \Delta P_{PDR,i} )</td>
<td>The load after PDR is implemented in period ( t )</td>
</tr>
<tr>
<td>( e_{th,i} )</td>
<td>Charging price</td>
</tr>
<tr>
<td>( e_{th,i} )</td>
<td>Discharging price</td>
</tr>
<tr>
<td>( e_{ESS,i} )</td>
<td>Charge capacity</td>
</tr>
<tr>
<td>( e_{ESS,i} )</td>
<td>Discharge capacity</td>
</tr>
<tr>
<td>( C_G )</td>
<td>Cost of unit start-up</td>
</tr>
<tr>
<td>( \Delta P_{PDR,i} )</td>
<td>Transfer amount of load at time ( t )</td>
</tr>
<tr>
<td>( \lambda_{PDR,i} )</td>
<td>Maximum transfer coefficient</td>
</tr>
<tr>
<td>( P_{PDR,i} )</td>
<td>Total amount of load that can be transferred at time ( t )</td>
</tr>
<tr>
<td>( R_{min} )</td>
<td>Minimum value of user satisfaction</td>
</tr>
<tr>
<td>( P_{bid} )</td>
<td>The spin-up reserve capacity of thermal power units</td>
</tr>
<tr>
<td>( P_{bid} )</td>
<td>The spin-up reserve capacity of CCPP</td>
</tr>
<tr>
<td>( P_{bid} )</td>
<td>The minimum adjustment capacities of Class B IDR load</td>
</tr>
<tr>
<td>( P_{bid} )</td>
<td>The maximum adjustment capacities of Class B IDR load</td>
</tr>
<tr>
<td>( x_i )</td>
<td>The calling status of Class B IDR load at time ( t )</td>
</tr>
<tr>
<td>( N_{max} )</td>
<td>The maximum number of adjustments</td>
</tr>
<tr>
<td>( t_{on} )</td>
<td>The minimum continuous calling time</td>
</tr>
<tr>
<td>( t_{off} )</td>
<td>The minimum calling time interval</td>
</tr>
<tr>
<td>( C_H )</td>
<td>Coal consumption cost</td>
</tr>
<tr>
<td>( C_W )</td>
<td>The wind curtailment cost</td>
</tr>
<tr>
<td>( R )</td>
<td>The maximum change rate allowed for Class A IDR load</td>
</tr>
<tr>
<td>( C_Z )</td>
<td>The depreciation cost</td>
</tr>
<tr>
<td>( C_{FL} )</td>
<td>The peaking cost of the flexible load</td>
</tr>
<tr>
<td>( C_T )</td>
<td>The carbon emission cost</td>
</tr>
<tr>
<td>( N_{G1} )</td>
<td>The number of conventional thermal power units</td>
</tr>
<tr>
<td>( N_{G2} )</td>
<td>The number of CCPPs</td>
</tr>
<tr>
<td>( G_i )</td>
<td>The start/stop cost of the ( i )th unit</td>
</tr>
<tr>
<td>( u_i )</td>
<td>The operational status</td>
</tr>
<tr>
<td>( F_{ESS,i} )</td>
<td>The net power of the energy storage device</td>
</tr>
<tr>
<td>( P_{s,i} )</td>
<td>The power of the shiftable load after response</td>
</tr>
<tr>
<td>( \sigma_y )</td>
<td>The unit coal consumption cost</td>
</tr>
<tr>
<td>( P_{GL,i} )</td>
<td>The equivalent output of unit ( i ) in period ( t )</td>
</tr>
<tr>
<td>( f_{cut} )</td>
<td>The penalty cost</td>
</tr>
<tr>
<td>( P_{wpr,i} )</td>
<td>The predicted output values of wind power</td>
</tr>
<tr>
<td>( P_{m,i} )</td>
<td>Actual output values of wind power</td>
</tr>
<tr>
<td>( C_Z )</td>
<td>Daily depreciation cost of CCPP</td>
</tr>
<tr>
<td>( C_{cc} )</td>
<td>Total investment cost of CCPP</td>
</tr>
<tr>
<td>( r )</td>
<td>Discount rate of CCPP</td>
</tr>
<tr>
<td>( N_{cc} )</td>
<td>Depreciation life of CCPP</td>
</tr>
<tr>
<td>( C_{ss} )</td>
<td>Investment cost of the unit volume solution storage</td>
</tr>
<tr>
<td>( V_{ss} )</td>
<td>Volume of the solution storage</td>
</tr>
<tr>
<td>( N_{ss} )</td>
<td>Depreciation life of the solution storage</td>
</tr>
<tr>
<td>( K_M )</td>
<td>Carbon trading price</td>
</tr>
<tr>
<td>( E_c )</td>
<td>Total carbon emissions</td>
</tr>
<tr>
<td>( \delta_i )</td>
<td>Carbon emission quota of thermal power plants</td>
</tr>
<tr>
<td>( Q_{i,R},\max )</td>
<td>Maximum storage volumes of rich liquid</td>
</tr>
<tr>
<td>( Q_{i,L},\max )</td>
<td>Maximum storage volumes of lean liquid storage</td>
</tr>
<tr>
<td>( \xi_1 )</td>
<td>The uncertainty factors of load</td>
</tr>
<tr>
<td>( \xi_2 )</td>
<td>The uncertainty factors of wind power</td>
</tr>
<tr>
<td>( R_i )</td>
<td>The start/stop cost of the ( i )th unit</td>
</tr>
<tr>
<td>( e_{ESS,i} )</td>
<td>Charge and discharge status</td>
</tr>
<tr>
<td>( P_{dis} )</td>
<td>Discharge power</td>
</tr>
<tr>
<td>( F_{ESS,i} )</td>
<td>The net charging power of the energy storage device</td>
</tr>
<tr>
<td>( P_{min} )</td>
<td>Minimum value of user satisfaction</td>
</tr>
</tbody>
</table>

## References


11. Ding, Y. Research on Load Flexible Scheduling Based on Value Exploration; Southeast University: Nanjing, China, 2018.


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.