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Low-Carbon Economic Dispatch Based on a CCPP-P2G Virtual Power Plant Considering Carbon Trading and Green Certificates

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Abstract: To improve the economic benefits of power systems in the process of achieving multi-energy complementation and decarbonization, this paper proposes a dispatching optimization model for virtual power plants (VPP) that considers carbon trading and green certificates. Firstly, the structure of the VPP system integrating wind and solar generators (WP and PV), power-to-gas (P2G), carbon capture power plants (CCPP) and price-based demand response (PBDR) is established. Secondly, the two-way interactive trading models among the VPP, carbon trading and green certification market are constructed. Then, the dispatching optimization model of the VPP is constructed. Finally, the numerical example is solved and analyzed by the chaotic particle swarm optimization algorithm, which verifies the rationality and effectiveness of the new model. The results show that: (1) when the VPP considers the CCPP-P2G, the cost of the system is reduced by USD 2550.48, while the CO₂ emissions are reduced by nearly 50%; (2) the addition of PBDR reduces the CO₂ emissions of the thermal power unit, which has reduced the cost of carbon tax by nearly 27.8%, further reducing the cost of the VPP; (3) the introduction of the carbon trading and green certificate market has reduced the operating cost of the VPP by nearly 22.24%.

Keywords: dispatching optimization; carbon capture; power-to-gas; carbon trading; green certificate

1. Introduction

The consumption of fossil energy produces a large amount of carbon dioxide gas, which promotes global warming and triggers frequent severe weather. As this scientific fact is confirmed and recognized, the promotion of low-carbon strategies and the development of a low-carbon economy have become a major development trend in all countries [1]. China puts forward the goal of “strive to reach the peak of CO₂ emissions by 2030 and strive to achieve carbon neutrality by 2060” (‘dual carbon’ goal) [2], which will play a constructive role in achieving global sustainable development. As one of the key areas for the power industry to help achieve the “dual carbon” goal, its primary task is to promote the low-carbon transformation of energy and build a new power system with new energy as the mainstay.

In recent years, with the increasingly serious problems of energy scarcity, climate change and environmental pollution, countries around the world have begun to reform their energy structure, and energy consumption has gradually shifted to renewable energy sources such as wind energy and photovoltaics [3]. According to data released by the International Renewable Energy Agency (IRENA), as of the end of 2020, the total global installed capacity of wind power and photovoltaics was 1446 GW, which has increased four times in the past 10 years, showing a trend of rapid development. In 2020, China’s renewable energy continued to develop rapidly, adding 139 million kilowatts of renewable energy power generation capacity, especially wind power and photovoltaic power generation, adding 120 million kilowatts [4]. However, the inherent volatility, randomness...
and intermittent nature of renewable energy have greatly hindered its promotion and application [5]. In order to solve this problem, researchers have put forward the concept of the “virtual power plant” (VPP). The virtual power plant is mainly composed of conventional units, renewable energy units, energy storage devices and flexible loads. As a highly flexible and adaptable resource integration method, virtual power plants can play a role in suppressing the fluctuation of renewable energy and promoting energy consumption [6].

In addition, the power-to-gas technology, as a new energy conversion method, realizes the effective use of CO₂. P2G has shown great advantages in terms of increasing the capacity of absorbing renewable and clean energy and cutting peaks and filling valleys of power loads by way of converting hard-to-consume wind power and photovoltaics into easily stored natural gas. The current research on P2G is mainly in the aspects of coupling electric–gas energy networks, improving wind–solar absorbing capacity and system operation flexibility [7]. Xu et al. [8] built a VPP electrical and thermal coordination dispatching optimization model with P2G, and the numerical example shows that P2G can improve the flexibility and economy of a system. Schiebahn et al. and Götz et al. [9,10] introduced the working principle and performance of P2G and evaluated it in the economic dimension. Cui et al. [11] proposed a P2G-based integrated energy dispatching optimization model for thermoelectric coupling areas to improve economy and energy utilization.

However, there is a lack of research on the sources of CO₂ materials and operating costs of P2G. A carbon capture power plant (CCPP) can be used as an excellent way to provide CO₂ for P2G. A CCPP is transformed from coal-fired thermal power plants through carbon capture technology, which can significantly reduce carbon emissions. Zhou et al. [12] considered that, compared with traditional thermal power units, adding carbon storage units to a CCPP has more convenient and flexible adjustment capabilities. Sun et al. [13] introduced carbon capture units to reduce carbon emissions and proposed a multi-region VPP optimal scheduling model in the energy market. Lu et al. [14] verified the occupancy role of the CCPP in reducing the system’s additional backup expenditure and ensuring the economic efficiency of the system when it is used as a virtual spinning reserve. Zhou et al. and Chen et al. [15,16] constructed a P2G-CCPP system framework, using the CO₂ captured by the CCPP to provide the P2G device with raw material. Sheng et al. [17] introduced a carbon capture device into the system for optimization: firstly, the wind abandoning penalty factor is used to convert the wind abandoning amount into the wind abandoning cost, then a low carbon economic operation model of an electric integrated energy system with carbon capture is established, which takes the system operating cost and carbon emission as its objectives. Although the above-mentioned research put forward the mechanism of CCPP-P2G, they lack the analysis of the impact on the dispatch of the VPP considering CCPP-P2G.

At the same time, the demand response (DR) as a means to increase the consumption of renewable energy and reduce CO₂ emissions also needs to be considered in the VPP. For the research on the optimization role of the DR in the integrated energy system, Müller et al. [18] analyzed the availability and flexibility of the demand response (DR) and studied its role in the renewable energy system. Wang et al. [19] analyzed the impact of the demand response on the optimal dispatch of power systems and provides theoretical guidance on how to apply the DR to multi-source combined power generation systems. Newsham et al. [20] confirmed that the price-based demand response (PBDR) has a positive effect on reducing the load peak-valley gap. Deng et al. [21] studied the PBDR and interruptible load method to encourage users to optimize the power load curve actively. Luo et al. [22] established a load response model based on PBDR, analyzed the influence of PBDR on the optimal dispatch of a power system and proved the positive promoting effect on energy consumption and system revenue. The above-mentioned research has not introduced DR into the VPP with CCPP-P2G for research. Therefore, this paper will consider the price-based demand response (PBDR) in the VPP system to improve the stability of system operation.
In addition, it is worth mentioning that, in order to ensure the realization of the goal of “carbon peak and carbon neutrality”, China has successively introduced carbon quota policies and renewable energy consumption guarantee mechanisms, which put forward higher requirements for the operation and scheduling of the power system [23,24]. In order to coordinate the interest relationship between the conventional energy power system and the power system with a high proportion of renewable energy, carbon trading and green certificate trading have been developed as an efficient market means, realizing the transformation of environmental benefits of renewable energy power generation to economic benefits. At present, scholars at home and abroad have carried out a lot of research on the carbon trading mechanism and green certificate trading mechanism. Chen et al. [25] introduced the carbon trading mechanism, put forward an economic scheduling strategy considering carbon emissions and confirmed the effectiveness of the carbon trading mechanism in reducing system carbon emissions. Liang et al. [26] established an economic dispatch model of wind power grid-connected energy saving under the renewable energy quota, and the effectiveness of the model in promoting wind power consumption was confirmed. Xue et al. [27] established a green certificate trading mechanism model, a carbon offset mechanism model and a wind power system optimal dispatch model with the goal of minimizing the total cost. Su et al. [28] added the cost of a carbon trading-green certificate into the operating cost, and at the same time, the “source-load” interaction factor is considered to construct an optimal dispatching model for the power system, which proves that the introduction of flexible loads can better promote the consumption of wind and solar and the utilization of carbon trading and the green certificate mechanism. Therefore, as an effective means to improve the operating economy of the system, it has important theoretical and practical value to carry out research on the VPP low-carbon economic dispatch that considers the participation of the carbon trading market and the green certificate market.

In summary, we can find that: (1) most scholars regarded CCS and P2G technologies as separate strategies for emission reduction and renewable energy consumption, and yet they failed to construct a CCS-P2G-integrated energy system and conduct research on their coupling effects; (2) the research on the optimal dispatch of VPP ignores the optimization effect of PBDR, and the volatility and randomness of wind and solar energy still cannot be eliminated, which affects the operating and environmental benefits of the system; (3) under the carbon quota and renewable energy consumption guarantee mechanism, the VPP lacks consideration of renewable consumption rights and neglects the role of the carbon trading market and the green certificate market in improving the economic efficiency of the system. Based on this, the innovations of this article are as follows:

1. A virtual power plant (VPP) is constructed with the integration of CCPP-P2G. Since the coupling effects of CCPP-P2G have not yet been widely studied, this paper constructs a VPP where wind and photovoltaic generators (WP and PV), a carbon capture power plant (CCPP) and a power-to-gas converter (P2G) are employed. Moreover, PBDR is applied to encourage users to voluntarily adjust their power consumption plans, thus showing the flexibility of power load.

2. The paper fully considers the new requirements of the carbon quota mechanism and the renewable energy consumption guarantee mechanism for VPP dispatching, and it realizes the conversion of renewable energy environmental benefits to economic benefits by introducing carbon trading markets and green certificate trading markets. The scheduling of a VPP that considers carbon trading and green certificates can not only complete system emission reduction and renewable energy consumption tasks, but also improve the economic benefits of system operation.

3. An economical and environmentally friendly VPP optimal dispatching model is constructed. In this paper, the objective function is to minimize the net cost of the system. In addition to the operating cost of the unit, it also considers the cost of the carbon tax, the cost of carbon storage and the benefits of participating in the carbon trading market and the green certificate market. In addition, on the basis of meeting the operating constraints...
of the power system equipment, the carbon quota mechanism and renewable energy consumption weight constraints have been added. While achieving the goal of minimizing net costs, the emissions of CO$_2$ and the consumption of renewable energy are controlled.

2. Operating System of VPP

2.1. Operating Structure of VPP

In the VPP system, the power supply side includes wind power, photovoltaic and thermal power generation. The dispatch center arranges the power generation plan of each unit by responding to the user’s power demand. PBDR is used to smooth the fluctuation of the power load curve. The capture and utilization of CO$_2$ are realized by way of coupling the CCPP and P2G. The power required for P2G operation is provided by renewable energy generator sets. In addition, through the two-way interaction of the VPP with the carbon trading market and the green certificate market, the needs of the carbon quota and renewable energy consumption of the VPP are met. Figure 1 shows the operating structure of the VPP.

![Figure 1. Operating structure of the VPP.](image)

2.2. CCPP-P2G Operating System

2.2.1. Operating Structure of CCPP-P2G

Combining the application status of the CCPP and P2G in promoting the carbon emission reduction of the VPP and the synergy in enhancing the emission reduction effect, the CCPP-P2G operation system constructed in this paper is shown as Figure 2. In the system, the CO$_2$ captured by the CCPP is provided to P2G devices as raw materials to produce CH$_4$, which achieves a true reduction in CO$_2$. The CH$_4$ produced by P2G is transported to the natural gas market for trading to make up for the operating cost of P2G. In addition, the second role of P2G is to promote the consumption of renewable energy. Therefore, the P2G unit will only operate when there is abandonment of wind and energy in the system, which leads to the incoordination of the CO$_2$ processing time between the CCPP and the P2G. This paper solves this problem by installing carbon storage equipment. The CO$_2$ emissions due to capture and storage efficiency go directly to the atmosphere.
2.2.2. Operating Cost Model of CCPP-P2G

The operating costs of CCPP-P2G include the generation cost of the CCPP, the cost of the carbon tax, carbon storage cost and the operating cost of P2G, which is expressed by Formula (1):

$$C_{op,t} = C_{CCPP,gen,t} + C_{ct,t} + C_{cs,t} + C_{P2G,op,t} \quad (1)$$

where:
- $C_{op,t}$ is the operating cost of CCPP-P2G in time period $t$;
- $C_{CCPP,gen,t}$ is the generation cost of CCPP in time period $t$;
- $C_{ct,t}$ is the carbon tax in time period $t$;
- $C_{cs,t}$ is the carbon storage cost in time period $t$;
- $C_{P2G,op,t}$ is the operating cost of P2G in time period $t$.

1. Generation cost of CCPP

The generation cost of the CCPP is composed of fuel cost and start-up and stop cost, which is expressed as follows [29]:

$$C_{CCPP,gen,t} = a(P_{TP,t})^2 + bP_{TP,t} + c + C_{TP,t}(1 - \lambda_t - 1)\lambda_t \quad (2)$$

where:
- $P_{TP,t}$ is the equivalent output of the thermal power unit in time period $t$;
- $a$, $b$, $c$ are the energy consumption cost coefficients of the thermal power unit;
- $C_{TP,t}$ is the start–stop cost of the thermal power unit in time period $t$;
- $\lambda_t$ is the start–stop state of thermal power unit in time period $t$; $\lambda_t = 1$ indicates that the thermal power unit is in operation, $\lambda_t = 0$ indicates that the thermal power unit is in a shutdown state; $P_{pl,t}$ is the power provided to the electric power load in time period $t$; $P_{CC,t}$ is the power provided to the carbon capture unit in time period $t$; $P_{CC,op,t}$ is the operating power of the carbon capture unit in time period $t$.

2. The cost of carbon tax

The cost of carbon tax represents the tax paid by the CCPP to discharge CO$_2$ to the atmosphere, which is proportional to the total amount of CO$_2$. The calculation formula is as follows:

$$\begin{align*}
C_{ct,t} &= p_{ct}Q_{CO_2,t} \\
Q_{CC,t} &= e_{CO_2,TP,t}P_{TP,t} - Q_{CO_2,t} \\
Q_{CC} &= p_{CC,op,t}P_{CC,op,t} - \eta_{CC}Q_{CO_2,t}P_{TP,t} \quad (3)
\end{align*}$$

where:
- $p_{ct}$ is the unit carbon tax price;
- $Q_{CC,t}$ is the CO$_2$ emissions of the CCPP in time period $t$;
- $e_{CO_2,TP,t}$ is carbon emission intensity of the thermal power unit;
- $Q_{CC}$ is the CO$_2$ captured by the carbon capture unit in time period $t$; $\eta_{CC}$ is the amount of CO$_2$ produced per unit of energy consumption of the carbon capture unit; $\eta_{CC}$ is the capture efficiency of the carbon capture unit.
3. Carbon storage cost of CCPP

The cost of carbon storage is the cost of CO₂ storage consumed by the carbon storage equipment, which is related to the carbon storage capacity of the carbon storage equipment. The calculation formula is as follows [7]:

\[
\begin{align*}
C_{\text{CS},t} & = p_{\text{cs}} Q_{\text{CS}}^t \\
Q_{\text{CS}}^t & = Q_{\text{CS}}^{t-1} + \left(1 - \omega_{\text{cs}}\right) Q_{\text{CO}_2,t} - Q_{\text{CO}_2,t}^{\text{P2G}} \\
Q_{\text{CS}}^{\text{min}} & \leq Q_{\text{CS}}^t \leq Q_{\text{CS}}^{\text{max}}
\end{align*}
\]  

(4)

where: \( p_{\text{cs}} \) is unit carbon storage price; \( Q_{\text{CS}}^t \) is the carbon storage capacity of the carbon storage equipment in time period \( t \); \( \omega_{\text{cs}} \) is the loss factor of the carbon storage equipment; \( Q_{\text{CO}_2,t}^{\text{P2G}} \) is the CO₂ provided to P2G in time period \( t \); \( Q_{\text{CS}}^{\text{min}} \) and \( Q_{\text{CS}}^{\text{max}} \) are the minimum and maximum capacity of the carbon storage equipment.

4. The operating cost of P2G

The operating cost of P2G in time period \( t \) depends on the amount of wind and solar abandonment during this time period. In addition, the CO₂ required for P2G operation is also determined by the amount of wind and solar abandonment. The calculation formula is as follows [7]:

\[
\begin{align*}
& P_{\text{P2G}}^t \leq \min \left\{ p_{\text{WP}}^t p_{\text{WP}}^{\text{ab}}, t + p_{\text{PV}}^t p_{\text{PV}}^{\text{ab}}, t, p_{\text{P2G}}^t \right\} \\
& C_{\text{op},t}^{\text{P2G}} = \beta_{\text{P2G}} P_{\text{P2G}}^t - k_{\text{CH}_4} V_{\text{CH}_4,t} \\
& Q_{\text{CO}_2,t}^{\text{P2G}} = a_{\text{CO}_2} P_{\text{P2G}}^t p_{\text{P2G}}^t \\
& V_{\text{CH}_4,t}^{\text{P2G}} = 3.6 \beta_{\text{P2G}} P_{\text{P2G}}^t / H_{\text{CH}_4}
\end{align*}
\]  

(5)

where: \( P_{\text{P2G}}^t \) is the operating power of P2G in time period \( t \); \( p_{\text{WP}}^t p_{\text{WP}}^{\text{ab}}, t \) and \( p_{\text{PV}}^t p_{\text{PV}}^{\text{ab}}, t \) are the amount of wind and solar abandonment in time period \( t \); \( P_{\text{max}}^{\text{P2G}} \) is the maximum operating power allowed by P2G; \( \beta_{\text{P2G}} \) is the unit operating cost of P2G; \( k_{\text{CH}_4} \) is the unit natural gas price in the natural gas market; \( a_{\text{CO}_2} \) is the amount of CO₂ consumed per unit of natural gas output; \( \beta_{\text{P2G}} \) is the conversion efficiency of P2G; \( V_{\text{CH}_4,t}^{\text{P2G}} \) is the amount of CH₄ produced by P2G in time period \( t \); \( H_{\text{CH}_4} \) is the calorific value of natural gas, and the value is 39 MJ/m³.

2.3. Renewable Energy Operating System

2.3.1. Renewable Energy Consumption Mechanism

This paper uses two methods to absorb the power generation of renewable energy. One is to supply users with electricity power load through the VPP dispatch center; the other is to supply excess power generation to the P2G operation. The renewable energy power generation consumption and waste in time period \( t \) can be expressed as follows:

\[
\begin{align*}
& \begin{cases} 
  p_{\text{WP}}^{\text{ge}}, t + p_{\text{PV}}^{\text{ge}}, t = p_{\text{WP}}^{\text{pl}}, t + p_{\text{PV}}^{\text{pl}}, t + p_{\text{WP}}^{\text{ab}}, t + p_{\text{PV}}^{\text{ab}}, t \\
  p_{\text{RE}}^{\text{ab}}, t = p_{\text{WP}}^{\text{ab}}, t + p_{\text{PV}}^{\text{ab}}, t - p_{\text{P2G}}^{\text{pl}}, t
\end{cases}
\end{align*}
\]  

(6)

where: \( p_{\text{WP}}^{\text{ge}}, t \) and \( p_{\text{PV}}^{\text{ge}}, t \) are the power generation of WP and PV units in time period \( t \); \( p_{\text{WP}}^{\text{pl}}, t \) and \( p_{\text{PV}}^{\text{pl}}, t \) are the power provided by WP and PV to the electrical power load; \( p_{\text{RE}}^{\text{ab}}, t \) is the amount of renewable energy wasted in time period \( t \).

2.3.2. Cost Model of Renewable Energy System

The costs of the renewable energy system include the power generation cost of WP and PV units and the penalty cost of renewable energy abandonment, which can be expressed as follows:

\[
C_{\text{op},t}^{\text{RE}} = C_{\text{WP},t}^{\text{WP}} + C_{\text{PV},t}^{\text{PV}} + C_{\text{RE}}^{\text{RE},t}
\]  

(7)

where: \( C_{\text{op},t}^{\text{RE}} \) is the operating cost of the renewable energy system in time period \( t \); \( C_{\text{WP},t}^{\text{WP}} \) is the power generation cost of WP in time period \( t \); \( C_{\text{PV},t}^{\text{PV}} \) is the power generation cost of
PV in time period \( t \); \( C_{\text{RE,} t} \) is the penalty cost of renewable energy abandonment in time period \( t \).

1. Power generation cost of WP and PV units

The power generation cost of WP and PV units in time period \( t \) can be expressed as follows:

\[
\begin{align*}
C_{\text{WP,} t} &= \epsilon_{\text{WP,} t} P_{\text{WP,} t} \\
C_{\text{PV,} t} &= \epsilon_{\text{PV,} t} P_{\text{PV,} t}
\end{align*}
\]

where: \( \epsilon_{\text{WP,} t} \) is the unit power generation cost of WP; \( \epsilon_{\text{PV,} t} \) is the unit power generation cost of PV.

2. Penalty cost of renewable energy abandonment

The penalty cost of renewable energy abandonment in time period \( t \) can be expressed as follows:

\[
C_{\text{RE,} t} = \epsilon_{\text{RE,} t} P_{\text{RE,} t}
\]

where \( \epsilon_{\text{RE,} t} \) is the unit penalty cost of renewable energy abandonment.

2.4. Two-Stage Model of PBDR

Price-based demand response (PBDR) includes three forms of electricity price response: time-of-use electricity price, real-time electricity price and peak electricity price. In actual operation, the time-of-use electricity price is usually the main form. According to the characteristics of power load, the time-of-use electricity price divides the load at 24 o’clock a day into peak, flat and valley periods, and it sets prices for different periods according to the user’s price sensitivity. The user receives the price signal and actively adjusts the power plan to achieve the effect of peak shaving and valley filling. This paper optimizes the load curve with PBDR by constructing a two-stage model. In the first stage, the demand price elasticity theory is used to calculate the total amount of load changes of peak, valley and flat periods; in the second stage, the total amount of load changes in each period of the first stage is allocated with the goal of stabilizing the fluctuation of the load curve.

2.4.1. Demand Price Elasticity Model

According to the economics demand price elasticity theory, PBDR can be expressed by the demand elasticity coefficient:

\[
\epsilon = \frac{(E^{af} - E^{be}) / E^{be}}{(p^{af} - p^{be}) / p^{be}}
\]

where: \( E^{be}, E^{af} \) are the load of users before and after the implementation of the peak-valley time-of-use electricity price; \( p^{be}, p^{af} \) are the electricity price before and after the implementation of the peak-valley time-of-use electricity price; \( \epsilon \) is the demand elasticity coefficient, including the self-elasticity coefficient \( \epsilon_{\text{it}} \) and the cross-elasticity coefficient \( \epsilon_{\text{st}} \).

The self-elasticity coefficient represents the impact of price changes in the current period on electricity consumption, and the cross-elasticity coefficient represents the impact of price changes in the current period on electricity consumption in other periods. Therefore, according to the three time periods of peak, flat and valley, the elasticity matrix of electricity demand price can be expressed as follows:

\[
A = \begin{bmatrix}
\epsilon_{pp} & \epsilon_{pf} & \epsilon_{pv} \\
\epsilon_{fp} & \epsilon_{ff} & \epsilon_{fv} \\
\epsilon_{vp} & \epsilon_{vf} & \epsilon_{vv}
\end{bmatrix}
\]

where: \( \epsilon_{pp}, \epsilon_{ff}, \epsilon_{vv} \) are the self-elasticity coefficient of the peak, flat and valley periods; the remaining elements represent the cross-elasticity coefficient. Based on the electricity
demand elasticity matrix, the electricity consumption of users after the implementation of the peak-valley time-of-use electricity price can be obtained:

\[
\begin{bmatrix}
E_p^f & E_p^v \\
E_f^f & E_f^v \\
E_v^f & E_v^v
\end{bmatrix} = \begin{bmatrix}
E_p^e & 0 & 0 \\
0 & E_f^e & 0 \\
0 & 0 & E_v^e
\end{bmatrix}
\begin{bmatrix}
e_{pp} & e_{pf} & e_{pv} \\
e_{fp} & e_{ff} & e_{fv} \\
e_{vp} & e_{vf} & e_{vv}
\end{bmatrix}
\begin{bmatrix}
(p_p^f - p_p^e)/p_p^e \\
(p_f^f - p_f^e)/p_f^e \\
(p_v^f - p_v^e)/p_v^e
\end{bmatrix} + \begin{bmatrix}
E_p^e \\
E_f^e \\
E_v^e
\end{bmatrix}
\]

(12)

where: \(E_p^f, E_p^v, E_f^f, E_f^v, E_v^f, E_v^v\) are the electricity consumption of the peak, flat and valley periods; \(E_p^e, E_f^e, E_v^e\) are the electricity consumption of the peak, flat and valley periods before the implementation of the time-of-use electricity price; \(p_p^f, p_f^f, p_v^f\) are peak, flat and valley electricity prices after the implementation of the time-of-use electricity price; \(p_p^e, p_f^e, p_v^e\) are the peak, flat and valley electricity prices before the implementation of time-of-use electricity price, where the values of these parameters are the same.

2.4.2. Load Allocation Model

In order to stabilize the volatility of the user power load, this paper uses the least square method to minimize the deviation between the load curve after the demand response and the average daily load value to construct a load distribution model for each period. Take the load during peak hours as an example to build the allocation model, as follows:

\[
\min \ F = \sum_{t=1}^{T_p} \left( p_t^{p,af} - \bar{P}_t \right)^2
\]

(13)

\[
\begin{align*}
P_{av} &= \frac{E_p^f + E_f^f + E_v^f}{T_p} \\
p_t^{p,af} &= p_t^{p,bf} + \Delta P_t^{p,af} \\
\sum_{t=1}^{T_p} \Delta P_t^{p,af} &= E_p^f - E_p^e
\end{align*}
\]

(14)

where: \(T_p\) is the number of time points included in the peak period; \(p_t^{p,af}\) is the load of the time period \(t\) after the implementation of the time-of-use electricity price; \(P_{av}\) is the average value of the power load in the entire power cycle after the implementation of the time-of-use electricity price; \(p_t^{p,bf}\) is the load in the time period \(t\) before the implementation of the time-of-use electricity price; \(\Delta P_t^{p,af}\) is the increase in power load of the time period \(t\).

2.5. Carbon Trading Market Transaction Model

When the actual carbon emissions of the VPP in time period \(t\) are higher than the allowances, the excess carbon emission rights need to be purchased from the carbon trading market; if the actual carbon emissions are lower than the allowances, the remaining carbon emissions can be sold in the carbon trading market. The carbon emission trading model based on carbon emission allowances and actual carbon emissions can be expressed as follows:

\[
\begin{align*}
C_{CT,t} &= p_{CT} (Q_{ct,t} - Q_{CCPP}^{cc}) \\
Q_{ct,t} &= \kappa_{eq} p_{CCPP}^{eq}
\end{align*}
\]

(15)

where: \(p_{CT}\) is the unit carbon trading price; \(Q_{ct,t}\) are the carbon emission quotas of the VPP in time period \(t\); \(\kappa_{eq}\) is the carbon emission quota coefficient of VPP.

2.6. Green Certificate Market Transaction Model

For the VPP system with a high proportion of wind and wind power generation, the renewable energy quota system stipulates the proportion of renewable energy power generation in the system. At the same time, the green certificate mechanism is implemented.
The insufficient part needs to purchase green certificates from the green certificate market. In addition, the green certificate obtained by the VPP system through renewable energy power generation can be sold in the green certificate market for additional revenue. The green certificate market transaction model in the evaluation period can be expressed as follows:

\[
\begin{align*}
T \sum_{t=1}^{T} \left( \sum_{j=1}^{N_{W}} P_{WN}^{t} + \sum_{m=1}^{N_{PV}} P_{VN}^{t} \right) + Q_{\text{buy}}^{TGC} & \geq \xi \sum_{t=1}^{T} \left( \sum_{j=1}^{N_{W}} P_{WN}^{t} + \sum_{m=1}^{N_{PV}} P_{VN}^{t} + \sum_{i=1}^{N} P_{i}^{TGC} \right) \\
Q_{\text{pro}}^{t} & = \sum_{j=1}^{N_{W}} P_{WN}^{t} + \sum_{m=1}^{N_{PV}} P_{VN}^{t} \\
C_{TGC} &= P_{TGC} \left( \sum_{t=1}^{T} Q_{\text{pro}}^{t} - Q_{\text{buy}}^{TGC} \right)
\end{align*}
\]

where: \( Q_{\text{buy}}^{TGC} \) is the number of certificates purchased by the VPP from the green certificate market; \( \xi \) is the weight of renewable energy consumption; \( Q_{\text{pro}}^{t} \) is the number of green certificates generated by the system at time period \( t \); \( C_{TGC} \) indicates the system’s gains from participating in the green certificate market; \( P_{TGC} \) is the price of the green certificate.

3. Dispatching Optimization Model of VPP

3.1. Objective Function

In order to reflect the economics of the VPP, this paper constructs a generation scheduling optimization model with the goal of minimizing the net cost of the system. The objective function is:

\[
\min \sum_{t=1}^{T} \left( C_{\text{op},t} - P_{\text{op},t} + C_{\text{RE},t} + C_{\text{CT},t} \right) + C_{TGC}
\]

In the formula, the objective function has four parts. These are the operating cost of CCPP-P2G, the cost of renewable energy system, carbon trading cost and green certificate transaction cost.

3.2. Constraints

1. Power balance constraint of the VPP is:

\[
p_{\text{pl},t}^{\text{CCPP}} + p_{\text{pl},t}^{\text{WP}} + p_{\text{pl},t}^{\text{PV}} = p_{\text{pl},t}
\]

where \( p_{\text{pl},t} \) is the user’s electric power load in time period \( t \).

2. Reserve capacity constraint of the VPP [7] is:

\[
\sum_{g=1}^{G} \left[ g_{\max}(t)(1-\theta)(1-l) \right] \geq D(t) + R(t)
\]

where: \( D(t) \) is the load demand of the system at time \( t \); \( R(t) \) is the reserve demand of the system at time \( t \); \( l \) is line loss rate of the system; \( \theta \) is units self-consumption rate; \( g_{\max}(t) \) is the maximum output of the units at time \( t \).

3. Constraints on CCPP-P2G are:

\[
\begin{align*}
\left( \frac{1}{9} \right) & \quad \frac{p_{\text{TP},t}^{\text{min},j}}{p_{\text{TP},t}^{\text{max},j}} \leq \frac{p_{\text{TP},t}^{\text{min},j}}{p_{\text{TP},t}^{\text{max},j}} \\
p_{\text{CC}}^{T} & \leq p_{\text{CC}}^{\text{max}} \\
| p_{\text{TP},t}^{j} - p_{\text{TP},t}^{j-1} | & \leq \Delta p_{\text{TP}} \\
| p_{\text{CC}}^{T} - p_{\text{CC}}^{T-1} | & \leq \Delta p_{\text{CC}}
\end{align*}
\]

where: \( p_{\text{TP},t}^{\text{min},j} \) is the lower limit of equivalent output; \( p_{\text{TP},t}^{\text{max},j} \) is the upper limit of equivalent output; \( p_{\text{CC}}^{\text{max}} \) is the upper limit of energy consumption for carbon capture equipment in
time period \( t \); \( \Delta P_{TP} \) is constraint on the ramp rate of the thermal power unit; \( \Delta P_{CC} \) is constraint on the ramp rate of energy consumption of the carbon capture equipment.

4. \( \text{CO}_2 \) used constraints on P2G

\[
0 \leq Q^{\text{P2G CO}_2}_{t} \leq Q^{\text{CS}}_{t-1} + (1 - \omega_{cs})Q^{\text{CC}}_{\text{CO}_2,t}
\]

(21)

where \( Q^{\text{CS}}_{t-1} + (1 - \omega_{cs})Q^{\text{CC}}_{\text{CO}_2,t} \) indicates the amount of \( \text{CO}_2 \) that can be provided to P2G in time period \( t \).

5. Constraints on carbon emission allowances and carbon transaction costs are shown in Section 2.5.

6. In conjunction with the renewable energy consumption guarantee mechanism, the system needs to meet the weight constraint of renewable energy consumption, as shown in the Section 2.6.

3.3. Model Solving

The model proposed in this paper is solved by the chaotic particle swarm algorithm. The basic particle swarm algorithm has a faster convergence speed, but it is easy to fall into the local optimum, while the chaotic search has better ergodicity, which makes up for the local optimum defect of the particle swarm algorithm. The specific algorithm principle is referred to in [30], and the solution steps are shown in Figure 3.

![Figure 3. Solution steps.](image)

4. Case Study

4.1. Basic Data

In order to verify the applicability of the dispatching optimization model constructed in this paper for improving the economic and environmental benefits of VPP operation, data from a certain area are selected for simulation analysis. The parameter setting of this paper refers to references [7,29,31,32]. The length of the dispatching period selected in the case is 24 h \((T = 24)\). The parameters of CCPP-P2G are shown in Table 1. The operating cost of WP \( \epsilon_{\text{WP}}^{\text{OP}} \) is 110 USD/MW, the operating cost of PV \( \epsilon_{\text{PV}}^{\text{OP}} \) is 50 USD/MW; the unit penalty cost of renewable energy abandonment \( \epsilon_{\text{RE}}^{\text{ab}} \) is 100 USD/MW, the carbon allowance per unit of electricity \( \kappa_{\text{cq}} \) is 0.76 t/MW-h, the price of carbon transaction \( P_{\text{CT}} \) is 19.8 USD/t, the price of per unit CH\(_4\) \( k_{\text{CH}_4} \) is 0.419 USD/m\(^3\), the transaction price of green certificate \( P_{\text{TGC}} \) is 30.94 USD/MW-h and the renewable energy consumption weight \( \xi \) is set to 0.8.
Table 1. Parameters of CCPP-P2G.

| Thermal Power Unit Parameters | P2G Parameters |
|-------------------------------|----------------|
| Minimum Output P_{TPmin}/MW   | Maximum Operating Power P_{TPmax}/MW |
| 0                             | 3              |
| Maximum Output P_{TPmax}/MW   | Carbon Consumption a_{CO2}/(t/MW·h) |
| 10                            | 0.2            |
| Cost Factors                  | Operating Cost k_{P2G}/(USD/MW·h) |
| a 0.01                        | 20             |
| b 5                           | Conversion Efficiency β_{P2G} |
| c 50                          | 0.6            |
| Carbon Emission Intensity c_{TP}/(t/MW·h) | 0.96 |

| Carbon Capture Device Parameters | Carbon Storage Device Parameters |
|----------------------------------|----------------------------------|
| Fixed energy consumption P_{CCf}/MW | Carbon capture efficiency η_{CC} |
| 0.015                            | 0.9                              |
| Carbon capture efficiency γ_{CC}  | Loss factor ω_{cs} |
| 3.717                            | 0.3                              |
| The amount of CO2 captured per unit of energy consumption \(\dot{\gamma}_{CC}\)/(t/MW·h) | Minimum capacity Q_{min}^{CS}/t |
| 0.1                              | 0                               |
| Maximum capacity Q_{max}^{CS}/t | Maximum capacity Q_{max}^{CS}/t |
| 10                               | 100                             |
| Carbon storage price p_{cs}/(USD/t) | 4.89 |

In addition, the end-user electricity price is 0.73 USD/(KW·h) before the PBDR is implemented. The elasticity matrix of the electricity demand price A used for PBDR is shown in Table 2 and the time-of-use electricity prices are shown in Table 3.

Table 2. Elasticity matrix of the electricity demand price.

| Period of Electricity Price Change | Peak  | Flat Section | Valley |
|------------------------------------|-------|--------------|--------|
| peak                              | −0.18 | 0.06         | 0.1    |
| flat section                      | 0.06  | −0.18        | 0.08   |
| valley                            | 0.1   | 0.08         | −0.18  |

Table 3. Time-of-use electricity price.

| Power Load Period | Electricity Price | Time Period     |
|-------------------|-------------------|-----------------|
| peak              | p_{pf} / 1.12     | 12:00–20:00     |
| flat section      | p_{pf} / 0.67     | 5:00–11:00/21:00–22:00 |
| valley            | p_{pf} / 0.33     | 23:00–4:00      |

The output of the renewable energy system during the dispatch period is shown in the Figure 4.

Figure 4. Output curve of the renewable energy system.
4.2. Scenario Setting

In order to compare and analyze the impact of the CCPP-P2G coupling model and price-based demand response mechanism in the VPP considering carbon trading and green certificate, the following four scenarios are set up:

Scenario 1 (S1, i.e., basic scenario): without CCPP-P2G, without considering PBDR.
Scenario 2 (S2): without CCPP-P2G, considering PBDR.
Scenario 3 (S3): containing CCPP-P2G, without considering PBDR.
Scenario 4 (S4): containing CCPP-P2G, considering PBDR.

The output and power consumption of each unit of the VPP in scenarios 1–4 are shown in Figure 5.

4.3. Results of Scenarios

The comparison of the dispatching results of each scenario is shown in Tables 4 and 5.

| Cost Scenario | Carbon Tax | Generation Cost of CCPP | Carbon Trading | Carbon Storage | P2G | WP and PV | Green Certificate | Renewable Energy Curtailment | Total Cost |
|---------------|------------|-------------------------|----------------|----------------|-----|----------|-------------------|-------------------------------|------------|
| S1            | 1190.26    | 827.74                  | 61.37          | 0.00           | 0.00| 8720.07  | −2137.53          | 1730.18                      | 10,392.09  |
| S2            | 858.25     | 606.06                  | 44.25          | 0.00           | 0.00| 8720.07  | −2123.26          | 1686.88                      | 9792.25    |
| S3            | 604.62     | 856.86                  | −170.54        | 62.93          | −36.91| 8629.98  | −2112.19          | 107.27                       | 7942.02    |
| S4            | 444.58     | 628.58                  | −125.40        | 46.27          | −39.28| 8629.98  | −2097.92          | 101.30                       | 7388.11    |

Figure 5. Power consumption and output of each unit.
Table 5. Comparison of environmental effects.

| Scenario | Carbon Capture Equivalent Output/MW | Carbon Emission/t | Carbon Capture/t | Carbon Storage/t | P2G Power/MW | CO₂ Consumed by P2G/t | Renewable Energy Curtailment/MW |
|----------|-------------------------------------|-------------------|------------------|-----------------|---------------|----------------------|-------------------------------|
| S1       | 15.50                               | 14.88             | 0.00             | 0.00            | 0.00          | 0.00                 | 11.85                         |
| S2       | 11.18                               | 10.73             | 0.00             | 0.00            | 0.00          | 0.00                 | 12.31                         |
| S3       | 21.28                               | 7.56              | 18.38            | 12.87           | 11.51         | 1.38                 | 0.34                          |
| S4       | 15.65                               | 5.56              | 13.52            | 9.46            | 12.25         | 1.47                 | 0.06                          |

4.3.1. Scenario 1

Scenario 1 is the basic scenario. In the VPP, only PV, WP and thermal power units in the CCPP operate. The output of each unit is shown in Figure 5. During the dispatch period, the total output of WPP and PV is 77.89 MW and 3.05 MW, respectively, which is used to meet the power load demand. The amount of renewable energy curtailment reaches 11.85 MW, resulting in an abandonment cost of USD 1730.18. It can be seen from Figure 5 that there is no wind abandonment in 15 periods, where the thermal power unit is started to maintain the power load demand. The carbon emission of the VPP is 14.88 t. All the CO₂ generated by the power generation unit is emitted into the atmosphere. Higher carbon emissions have resulted in high carbon tax costs (USD 1190.26), and carbon emission allowances need to be purchased in the carbon trading market (USD 61.37). The proportion of renewable energy consumption is 81.68%, the green certificate transaction income is USD 2137.53 and the total cost in this scenario reaches USD 10,392.09.

4.3.2. Scenario 2

Scenario 2 includes thermal power units, PV, WP and considers the effect of PBDR. Based on the two-stage model of PBDR, we have obtained the power load curve after the demand response is implemented, which is shown in Figure 6. Through the PBDR, the peak-to-valley difference of the load curve is reduced, that is, the load fluctuation rate becomes smaller. In the peak period (12:00–20:00), the electric power load dropped by about 15.6%. In addition, the electric power load during the valley period (23:00–4:00) increased by about 14.5%. To a certain extent, this has achieved the goal of “peak cutting and valley filling”. There is an increase in the amount of wind curtailment because of the decline in electrical power load demand. In this scenario, 10.73 t of carbon emissions are generated. The proportion of renewable energy consumption is 86.00%, the green certificate transaction income is USD 2123.26 and the net operating cost of the VPP is USD 9792.25.

4.3.3. Scenario 3

Scenario 3 adds CCS and P2G units on the basis of Scenario 1. It can be seen from Figure 5 that the main period for the start-up of thermal power units is from 9:00 to 22:00. During the dispatch period, the total output of the CCPP is 21.28 MW, and the amount of CO₂ captured by CCS is 18.38 t. The P2G equipment is activated to absorb excess wind power, using part of the CO₂ previously captured and stored as raw materials. Since the wind power absorption capacity of the P2G system depends on the maximum operating capacity of the P2G, it cannot absorb all the curtailed wind. A total of 11.51 MW of curtailed wind power is used to reduce carbon emissions. Based on the above process, 7.56 t of CO₂ is emitted in this scenario, and the carbon tax cost and carbon trading revenue are USD 604.62 and USD 170.54, respectively. Through the sale of natural gas, the P2G operation has achieved profitability with a revenue of USD 36.91. The proportion of renewable energy consumption is 80.71%, the green certificate transaction income is USD 2112.19 and the total cost of VPP operation is USD 7942.02.
4.3.4. Scenario 4

In Scenario 4, the PBDR is additionally considered on the basis of Scenario 3. Referring to the optimized power load demand curve after PBDR, on the one hand, when the power load demand drops, the abandonment period increases, and the abandonment power available for P2G also increases. On the other hand, the output of the thermal power units decreases, and carbon emissions are reduced. The increase in the amount of natural gas sold by the system has led to an increase in the revenue generated by the operation of P2G. The income of the P2G operation is USD 39.28. The carbon emission in this scenario is 5.56 t. The proportion of renewable energy consumption is 84.97%, the green certificate transaction income is USD 2097.92 and the total cost of the VPP is USD 7588.11.

4.4. Analysis of Results

4.4.1. CCPP-P2G Operation Effect Analysis

Comparing Scenario 3 and Scenario 1, the CCPP-P2G coordinated operation framework is realized. An amount of 18.38 t of CO$_2$ captured by CCPP is provided as raw material to the P2G equipment, which reduces net carbon emissions by nearly 50% and reduces carbon tax costs by USD 589. In addition, the addition of P2G units has eliminated excess wind power, which has greatly reduced the cost of wind abandonment, and the cost has been reduced by USD 1622.91. In addition, through the sale of natural gas, the P2G operation has achieved profitability with a revenue of USD 36.91. Taking the above factors into consideration, the net cost of Scenario 3 is reduced by USD 2550.48. It can be seen that the introduction of the CCPP-P2G collaborative operation framework can promote the carbon capture system to capture CO$_2$ to achieve carbon emission reduction, and the P2G equipment can fully absorb excess renewable energy and realize the effective use of internal resources.

4.4.2. PBDR Implementation Effect Analysis

Comparing Scenario 2 and Scenario 1, the output of the thermal power units has been reduced by 4.32 MW, and the carbon emissions have also been reduced by 4.15 t with the addition of the PBDR mechanism. The cost has dropped by 27.9%, and the net cost of the VPP has been reduced by USD 614.11, indicating that PBDR plays a positive role in the system’s low-carbon economic dispatch. Similarly, comparing Scenario 4 and Scenario 3, carbon emissions are reduced by 2 t, and the net cost is also reduced by USD 350.95, which once again proves the role of PBDR.
4.4.3. Carbon Trading Benefit Analysis

With the introduction of the carbon trading market, the VPP system can obtain benefits by trading excess carbon emission rights while meeting the quota standards. Comparing Scenario 1 and Scenario 3, the revenue of carbon trading has been increased by USD 231.91 due to the introduction of CCPP-P2G. In addition, comparing Scenario 2 and Scenario 4, the revenue of carbon trading has been reduced by USD 62.26 due to the introduction of PBDR on the basis of CCPP-P2G, which is the result of a decrease in the total power load caused by PBDR. It can be seen from the results that there is a good interaction mechanism between CCPP-P2G and the carbon trading market, which reduces the operating cost of the VPP.

4.4.4. Green Certificate Benefit Analysis

The proportion of renewable energy consumption in the four scenarios is up to the standard, and the VPP system’s benefits from the green certificate market are USD 2137.53, USD 2123.26, USD 2112.19 and USD 2097.92, respectively, and the proportion of compensation costs is 17.06%, 17.82%, 20.67% and 21.25%, which is shown in Figure 7. It can be seen that under the renewable consumption guarantee mechanism, the implementation of the green certificate mechanism can effectively improve the economic benefits of the VPP system based on renewable energy power generation.

![Figure 7. Results of the green certificate benefit.](image)

In summary, building a CCPP-P2G collaborative operation framework and introducing the PBDR mechanism can effectively reduce the carbon emissions of the VPP system, realize the full use of internal resources and optimize the energy structure, improve the efficiency of renewable energy utilization and stabilize the fluctuations of the power load curve. The emergence of the carbon trading market and the green certificate market can effectively compensate for the economic losses caused by the large-scale development of renewable energy and the increase in the proportion of renewable energy power generation.

4.4.5. CO₂ Emission Reduction Benefit Analysis

The benefit of CO₂ emission reduction can be reflected in unit cost per 1 ton of CO₂ emissions (price of emission reduction). The CO₂ that exceeds the quota requires an additional carbon transaction cost. Thus, the total costs of CO₂ emissions include carbon the tax and carbon trading cost. Based on this, the price of emission reduction of each scenario is given as shown in Figure 8. It can be seen that the introduction of the carbon
trading market can truly reflect the actual price of emission reduction. If the carbon emissions do not meet the carbon quota standard (Scenario 1 and Scenario 2), the system’s carbon transaction costs will increase, which in turn will lead to an increase in the price of carbon emission reduction. Under the effect of CCPP-P2G, the price of emission reduction has been greatly reduced by 28% (Scenario 3 and Scenario 4), and the emission reduction benefit of the VPP has been greatly improved.

![Figure 8. Price of emission reduction.](image)

4.4.6. Unit Power Generation Cost Analysis

In order to further illustrate the impact of CCPP-P2G, PBDR, green certificate, carbon trading and other factors on the system power generation cost, the unit power generation cost in each scenario is shown in the Figure 9. It can be seen that the introduction of CCPP-P2G has reduced the unit power generation cost by about USD 0.03, a reduction of about 23%, which well reflects the positive effect of CCPP-P2G in reducing the unit power generation cost of the VPP. Although PBDR will cause a minimal increase in unit power generation cost, its benefits in reducing the VPP reserve capacity investment can make up for it [33,34].

![Figure 9. Unit power generation cost.](image)
4.4.7. WP and PV Output Fluctuation Analysis

It can be seen from Table 4 that the power generation costs of WP and PV are the main component of the VPP operating cost. In addition, the output of WP and PV is greatly affected by environmental factors and installed capacity, which leads to a certain flexibility in the actual output curves of the two types of renewable resources in Figure 4, resulting in a certain flexibility in the power generation cost of the renewable energy system. Therefore, this section analyzes the impact of WP and PV output changes on the operating costs of the VPP, and the results are shown in Figure 10. The output variation range of WP and PV is 80–120%. Through observation, it can be seen that the operating cost of the VPP is positively correlated with wind power output and negatively correlated with photovoltaic output. At the same time, the impact of changes in wind power output is greater than that of changes in photovoltaic output. Within a certain range, the operating cost of the VPP system can be cut down by reducing wind power output and increasing photovoltaic output.

![Graph showing changes in operating cost of VPP vs changes in output](image)

Figure 10. Results of the analysis.

5. Conclusions

On the premise of promoting the decarbonization of the power system, ensuring the effective consumption of renewable energy and improving the utilization efficiency of renewable energy, achieving the economic operation of the system is the main goal of VPP dispatching optimization. Based on this, this paper proposes a low-carbon economic dispatch optimization model for a WPP-PV-CCPP-P2G VPP that considers carbon trading and green certificates. The results of case study show that:

1. On the one hand, CCPP-P2G coupling can realize the use of carbon, reduce the emission of carbon dioxide in the atmosphere and improve the economy of the system; on the other hand, P2G realizes the energy conversion between electricity and natural gas, which can reduce the system’s cost. The cost of abandonment of wind will further improve the capacity of wind and solar absorption, which is conducive to optimizing resource allocation, improving energy utilization efficiency, economic efficiency of system operation and flexibility of dispatching. The results show that the optimized model reduces the net cost of the virtual power plant by about 27.94%, greatly improves the profitability and reduces carbon emissions by nearly 50%, which promotes the realization of low-carbon systems.

2. PBDR can guide users to respond to system dispatch through the implementation of peak-valley time-of-use electricity prices, which reduces the power load during the tight period of load supply and demand, smooths the load curve and improves the
system’s ability to adjust to changes in renewable energy output. While optimizing the energy structure and reducing carbon emissions, it also reduces the net cost of the system and improves the economics of the system.

(3) Under the policy environment of carbon quotas and the renewable consumption guarantee mechanism, the use of a carbon trading market and green certificate trading market can meet the requirements of the VPP for carbon emissions and renewable consumption. Moreover, the operating cost of the VPP can be greatly compensated by trading abundant carbon emission credits and green certificates. Therefore, in the process of increasing the proportion of renewable energy power generation and achieving the goal of “dual carbon”, the use of carbon trading and the green certificate market can effectively coordinate the balance of environmental and economic benefits.

The analysis of the calculation example proves the effectiveness of the optimization model proposed in this paper in improving the economic benefits of VPP system operation. It is worth mentioning that the model only considers the optimization of operating cost reduction during the dispatching process and lacks consideration of the capacity allocation and the fluctuation of output of WP and PV in the planning stage. Therefore, the influence of the above factors on the VPP system can be further studied to expand the model.

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