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Research Article

Electricity-Carbon Joint Trading of Virtual Power Plant with Carbon Capture System

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With the establishment and rapid development of the national carbon emission trading market, new energy system participates in the carbon emission trading market. Analysing the potentiality of virtual power plant trading in carbon emission trading market, this paper designs a two-stage joint trading mechanism for electricity and carbon market with a weekly cycle according to their characteristics, which contain multiple transaction types for both markets. In addition, this paper introduces a carbon capture system (CCS) in gas turbine, which reduces the actual carbon emissions and increases the carbon market income of virtual power plant. Furthermore, it improves the comprehensive and flexible operation capability by adjusting the operation level of CCS, which is conducive to the timely consumption of renewable energy. Aiming at the uncertainty of renewable energy output and electricity price, the paper adopts a multiscenario analysis method to deal with it and establishes a stochastic optimization model to maximize joint earnings. Finally, through example analysis with GAMS, the effectiveness of the scheduling model is verified with simulation results. The overall income of the virtual power plant is improved, and the low carbon power is realized.

1. Introduction

To cope with the global warming and reduce CO_2 emissions during energy production, more and more countries actively accelerate the development of distributed energy. However, distributed energy has problems, such as uneven resource distribution, uncoordinated management, and scheduling. Through advanced control, measurement, and communication technologies, the virtual power plant aggregates distributed energy resources (DERs) to enable coordinated and optimized operation, thereby improving overall stability and competitiveness for participation in electricity market [1–4]. At present, virtual power plants have been piloted and practiced in multiple provinces like and participate multiple market types including ancillary services and spot market. Among them, the Jibei Virtual Power Plant has participated in the market clearing of the North China Power Market throughout the process since its commissioning in December 2019 and has provided online continuous service for more than 3,200 h, generating a total of 34.12 GWh of additional new energy power [5]. Besides, on July 16 2021, China's national carbon trading market was officially launched, among which the power industry with carbon emissions was the first to be included in the carbon emission management [6]. Therefore, it has become the vital problem of virtual power plants to deal with impact of the carbon trading market, reduce their own carbon emissions, participate in the trading of electricity and carbon markets, and improve the overall economic and environmental benefits.

Although the electricity market and the carbon market are different in terms of trading mechanisms, there is a certain coupling between them. Reference [7] indicates that the relationship between electricity and carbon markets is a direct bidirectional correlation and designs the joint operation mode. Reference [8] analyses the relationship and interaction mechanism between the electricity market and the carbon market and explores the interface mechanism for the coordinated development between the markets. Literature [9] propose a two-layer dynamically iterative model between electricity and carbon market to investigate the relationships between electricity price, carbon price, and power generation capacity. In terms of virtual power plants, the studies of [10, 11] consider the impact of carbon emission constraints on virtual power plant bidding and establish a robust optimization bidding model and a stochastic optimization model, respectively. Reference [12] builds a stepped carbon trading model to further constrain system carbon emissions for virtual power plant. Reference [13] establishes the virtual power plant operation system and operating income model under the carbon trading mechanism, sells surplus carbon emission allowances in the market per hour, and improve the economic benefits of virtual power plant. However, most models are built from the perspective of the carbon emissions cost and do not take the actual trading form of carbon market into account. The actual carbon trading market is characterized by low carbon price fluctuation, low trading frequency of participants, and large single trading volume. Therefore, the electricity market and carbon trading market cannot be coupled simply. Meanwhile, it is not been considered that renewable energy in virtual power plants to participate in the carbon market, which is the unique nature of virtual power plants in the carbon market.

The establishment of the carbon trading market has promoted power generation enterprises to replace old growth drivers with new ones and realize transformation and upgrading [14]. Among them, carbon capture and storage (CCS) technology, as an important way to reduce carbon emissions, is the optimal choice to quickly realize low carbon power. Reference [15] analyses the "energy time-shift characteristics" of carbon capture power plants and achieves peak shaving and valley filling by means of liquid storage operation. Reference [16] establishes the double carbon quantity model of liquid storage carbon capture systems. With the goal of maximizing the net income in the electricity market and carbon trading market, it builds the day-ahead and real-time double-phase low carbon economic scheduling model. In literature [17], operating mechanisms of Carbon Capture Power Plant (CCPP) and carbon transmission systems are taken into account together with the economic dispatch model. Furthermore, the study of [18] introduces the carbon capture system and tower solar thermal power station into virtual power plants, which verifies the efficient coordination capacity of the carbon capture system and the renewable energy power station. Therefore, carbon capture systems are expected to further improve flexible scheduling capabilities and the advantage of virtual power plants in the carbon market.

For the uncertainty and multistage problems in optimization programming, the study of [19] taken nonanticipativity constraints into account to guarantee the decisions should only depend on the information of realized uncertainties up to the present stage. Considering the uncertainties in net load demand, a multistage stochastic programming model is proposed for the expansion coplanning of gas and power networks. Reference [20] established a multistage stochastic programming model to minimize the expected total costs considering the uncertain renewable energy in the day-ahead optimal dispatch of energy and reserve. References [21, 22] simulated capricious weather, photovoltaic power generation, thermal load, power flow, and uncertainty programming based on the above-given SML model, which improved efficiency of problem solving. In this paper, a multiscenario stochastic optimization method considering nonanticipativity constraints is used to address the uncertainty of renewable energy output and electricity price. Based on previous researches, convergent wind unit, photovoltaic unit, carbon capture gas turbine, electric vehicle group, and interruptible load form virtual power plant in this paper. And, the contributions of the paper can be summarized as follows:

(1) A virtual power plant electricity-carbon joint trading mechanism with a weekly scheduling cycle is established according to trading characteristics of the electricity and carbon emission trading market, which includes bilateral contracts performance and day-ahead market transactions in the electricity market, allowance, and CCER transactions in the carbon emission market.

(2) According to the working principle of carbon capture system, the energy consumption model and carbon emission model of carbon capture system are established, which realizes the decoupling of carbon emission absorption process and regeneration process in time. Consequently, flexible operation of virtual power plant and timely consumption of renewable energy are realized.

(3) Based on the proposed transaction mechanism, using multiscenarios analysis to describe the uncertainty of renewable energy output and market price, a two-stage electricity-carbon joint trading model of virtual power plant is built to maximize the joint trading profits. Then, the influence of VPP behaviour and carbon price change on the virtual power plant market trading and optimal scheduling is studied by example analysis.

2. Virtual Power Plant Electricity-Carbon Joint Trading Mode

Carbon emission market generally adopt annual allowance allocation cycle. When the performance cycle begins, all enterprises with emission control are issued with certain carbon emission allowance (CEA), which is the main trading species of the carbon market. After that, enterprises can sell their surplus carbon allowance if the final actual carbon emissions are lower than the carbon allowances they have; otherwise, they should buy others to fill their own shortage in the carbon market. In daily production activities, enterprises with emission control should pay much attention to their actual carbon emissions and participate in the carbon market trading actively. Therefore, they could pass verification of testing institutions at end of performance cycle and complete the annual carbon emission performance. Otherwise, they will face corresponding fines and notification [23, 24].

The national carbon market has certain entry thresholds, especially concerning high carbon emission units in industry and manufacturing. In this paper, the virtual power plant is composed of wind power and photovoltaic units, gas turbine, electric vehicle group and interruptible load. Because of the existence of gas turbine, production activities of virtual power plant will produce certain carbon emissions, which provides access to participate in carbon emission allowance (CEA) market trading.

At present, China's carbon trading market allowance is mainly distributed for free, according to the amount of electricity generation. This paper allocates the carbon emission allowance of gas turbine in virtual power plant according to The 2019-2020 National Carbon Emission Trading Total Allowances Setting and Allocation Implementation Plan (Power Generation Industry), namely, the benchmark method:

$$E_{w,p,s}^{\text{quota}} = \sum_{\text{t}}^{T} P_{w,p,s}^{\text{GT}} B^{\text{GT}}, \tag{1}$$

where B^{GT} is the power supply benchmark value of the unit category. $P_{w,p,s,t}^{\text{GT}}$ is the output of gas turbine at time t (MW).

In addition, Chinese Certified Emission Reductions (CCERs) are another auxiliary trading species in the carbon market. According to January 2021, the Ministry of Ecology and Environment issued the Measures for the Administration of Carbon Emission Trading, which allows carbon emissions reductions from renewable energy, forestry carbon sinks, methane utilization, and other carbon emissions to offset certain percentage of carbon emission allowances for industrial enterprises, so as to activate the carbon trading market. Therefore, renewable energy output in virtual power plant can apply to be converted into CCER to offset their own carbon emissions or participate in carbon market trading for profits. The CCER quota from VPP is calculated by the following formula:

$$E_{w,p}^{\text{CCER}} = \sum_{t}^{T} \eta\left(P_{w,t}^{W} + P_{p,t}^{PV}\right), \tag{2}$$

where η is the certified emission reduction (t) of per unit renewable energy generation [25].

At present, carbon emission trading should be conducted through the national carbon emission trading system, which can be adopted by agreement transfer, one-side bidding or other ways up to specification [26]. In fact, the trading frequency of enterprises participating in the carbon market is not fixed, and the trading cycle is different. Compared with the power day-ahead market, carbon price in the carbon market fluctuates less over time, and the price is stable. Medium and long-term power markets often adopt the form of bilateral negotiation. By signing medium and long-term contracts, buyers and sellers carry out power wholesale transactions with periods of years, year, quarter, month, week, and multiple days. As can be seen, carbon trading market has a strong interaction with the medium and long-term power markets [27–29]. Therefore, this paper will propose a weekly electricity-carbon market joint trading mode and process, in which the electricity market is based on the day-ahead market under the performance of medium and long-term contracts. The transaction process is shown in Figure 1.

3. Work Model of Carbon Capture Gas Turbine

In this paper, carbon capture system is combined with gas turbine in virtual power plant to form the carbon capture gas turbine. The structure of typical liquid storage carbon capture system is shown in Figure 2. A set of solution reservoir is installed between the absorption tower and regeneration tower, as the rich solution reservoir and barren solution reservoir, respectively. In this way, CO_2 is absorbed and stored in the rich solution reservoir with rich liquid without immediately entering the regeneration tower for subsequent processing, which makes the CO_2 absorption process and regeneration process independent relatively and improves the comprehensive flexible operation capacity of the gas turbine [30].

The workflow of carbon capture system mainly includes absorption, regeneration, and compression. Specifically, it inhales CO_2 of carbon capture system in the absorption tower and barren solution for contact absorption; the barren solution is transferred into rich solution with much CO_2 and stored in rich solution reservoir; then rich solution enters the regeneration tower for CO_2 heating separation; and finally, CO_2 is compressed and stored by compressor.

The working energy consumption of carbon capture system can be divided into basic consumption and operating consumption. Therein, the operating energy loss of carbon capture system produced in the CO_2 absorption, decomposition, and compression is related to the operation level of carbon capture system. The more the carbon capture is, the greater the corresponding operating energy consumption is, which takes up most of the carbon capture system energy consumption [16]. Therefore, the basic loss is ignored in this paper, and the operating energy consumption of the carbon capture system is expressed as follows:

$$P_{w,p,s,t}^{\text{CCS}} = \varphi E_{w,p,s,t}^{\text{CCS},2}, \tag{3}$$

where φ is the operating energy consumption of carbon capture system processing unit CO_2. $E_{w,p,s,t}^{\text{CCS}.2}$ is the CO_2 amount that carbon capture system is decomposing and compressing in period t.

The carbon emission model of carbon capture gas turbine is

$$\begin{aligned} S_{w,p,s,t}^{\text{CCS}} &= S_{w,p,s,t-1}^{\text{CCS}} + \beta E_{w,p,s,t}^{\text{CCS},1} - E_{w,p,s,t}^{\text{CCS},2}, \\ E_{w,p,s,t}^{\text{GT}} &= e_{GT} P_{w,p,s,t}^{\text{GT}} - E_{w,p,s,t}^{\text{CCS}.2}, \\ E_{w,p,s,t} &= \sum_{t}^{T} E_{w,p,s,t}^{\text{GT}}, \end{aligned} \tag{4}$$

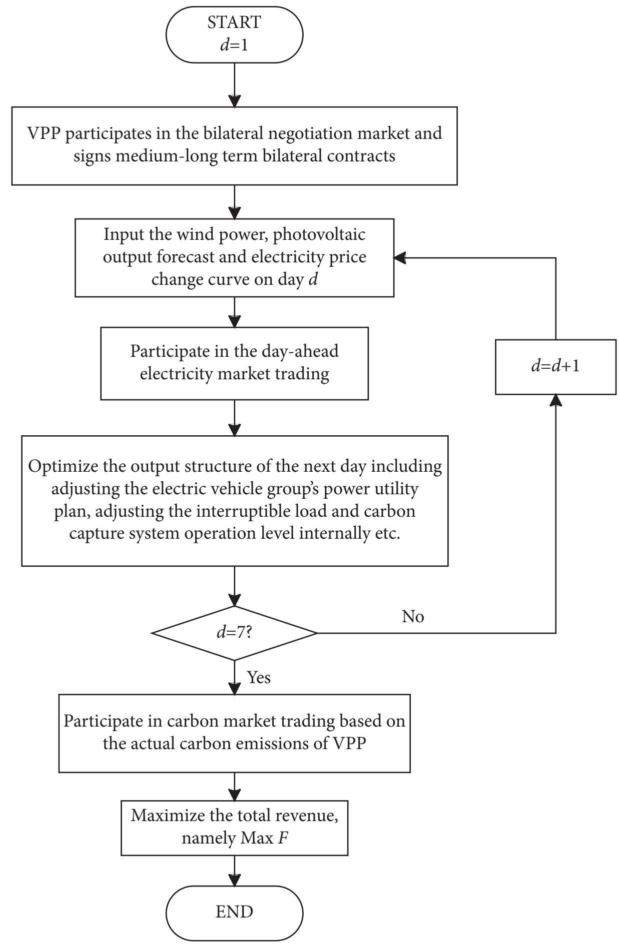


Figure 1: Virtual power plant electricity-carbon joint trading process.

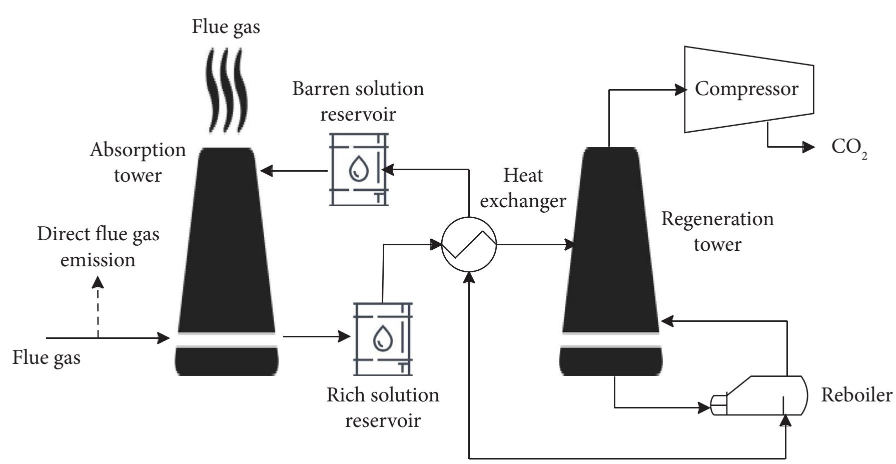


Figure 2: Structure of liquid storage carbon capture system.

where $S^{CCS}_{w,p,s,t}$ is the CO_2 reserves stored in the rich solution reservoir in period t; β is the carbon capture efficiency. $E^{CCS.1}_{w,p,s,t}$ is the CO_2 amount discharged into the absorption tower in period t; $E^{GT}_{w,p,s,t}$ is the net carbon emissions of the gas turbine in period t; and $E_{w,p,s}$ is the actual total carbon emissions of virtual power plant in one trading cycle.

4. Electricity-Carbon Joint Trading Model of Virtual Power Plant

In this paper, VPP consists of wind power (W), photovoltaic (P), gas turbine (GT) containing carbon capture system (CCS), electric vehicle group (EV), and interruptible load

(IL). This paper establishes the joint trading model of virtual power plant participating in both the power market and the carbon trading market. Therein, the power market includes the medium and long-term power contract signing, the power day-ahead market trading, the carbon trading market includes Carbon Emission Allowance (CEA), and Chinese Certified Emission Reductions (CCER) trading.

In addition, the VPP capacity built in this paper is relatively small and difficult to directly affect the market price. Therefore, VPP only participates in the electricity market and the carbon trading market as a price recipient.

4.1. Objective Function. To maximize the combined benefit of VPP in the electricity market and the carbon market:

$$\max F = \sum_{w=1}^{n_w} \pi(w)\bullet \sum_{p=1}^{n_p} \pi(p)\bullet \sum_{s=1}^{n_s} \pi(s) \bullet\left(f^{E}_{w,p,s} + f^{C}_{w,p,s} - C^{GT}_{w,p,s} - C^{EV}_{w,p,s} - C^{IL}_{w,p,s}\right), \tag{5}$$

where $f^{E}_{w,p,s}$ and $f^{C}_{w,p,s}$ are the benefits of VPP participating in the electricity market and the carbon trading market, respectively; $C^{\mathrm{GT}}_{w,p,s}$ is the operating cost of the gas turbine; $C^{\mathrm{EV}}_{w,p,s}$ and $C^{\mathrm{IL}}_{w,p,s}$ are the economic subsidy cost calling the EV group and interruptible load to participate in the electricity market, respectively.

4.1.1. VPP Electricity Market Profits

$$f^{E}_{w,p,s} = \lambda^{E1}\sum_{t}^{T} Q^{E1}_{t} + \sum_{t}^{T} \lambda^{E2}_{s,t} G^{E2}_{s,t}. \tag{6}$$

The VPP power market returns include the medium and long-term contract profit and the day-ahead market trading profit. Therein, Q^{E1}_{t} is the power supply quantity (MW) stipulated in the medium and long-term bilateral contract in period t. $G^{E2}_{s,t}$ is the power trading volume (MW) of VPP in period t with the positive value representing power sold to the market and the negative value representing power bought from the market in t period. λ^{E1} and $\lambda^{E2}_{s,t}$ are the bilateral contract electricity price and the day-ahead market electricity price in period t, respectively.

4.1.2. VPP Carbon Trading Market Profits

$$f^{C}_{w,p,s} = -\lambda^{C}\left[E_{w,p,s} - (1+\alpha)E^{\mathrm{quota}}_{w,p,s}\right] + \lambda^{\mathrm{CCER}}\left(E^{\mathrm{CCER}}_{w,p,s} - \alpha E^{\mathrm{quota}}_{w,p,s}\right), \tag{7}$$

where λ^{C} and λ^{CCER} are the market price of carbon emission allowance (CEA) and certified emission reduction (CCER) in the carbon market, respectively. α is the maximum offset proportional coefficient specified by the carbon offset mechanism.

4.1.3. Operating Cost of Carbon Capture Gas Turbine

$$C^{\mathrm{GT}}_{w,p,s} = \sum_{t}^{T}\left(kv^{\mathrm{GT}}_{w,p,s,t} + \sum_{i=1}^{3} k_i g^{\mathrm{GT}}_{w,p,s,i,t} + k' \nu^{\mathrm{GT}}_{w,p,s,t}\right),$$
$$P^{\mathrm{GT}}_{w,p,s,t} = \sum_{i=1}^{3} g^{\mathrm{GT}}_{w,p,s,i,t}. \tag{8}$$

In this paper, the operating cost of gas turbine is described with the piecewise linear function. Therein, k and k' are the fixed cost and start-up cost of the gas turbine, respectively; k_i is the power generation cost slope of the gas turbine section j; $v^{\mathrm{GT}}_{w,p,s,t}$ and $\nu^{\mathrm{GT}}_{w,p,s,t}$ are the state variables indicating whether the gas turbine works and starts in period t, respectively; $g^{\mathrm{GT}}_{w,p,s,i,t}$ is the output of gas turbine section i in period t; and $P^{\mathrm{GT}}_{w,p,s,t}$ is the total output of gas turbine in period t.

4.1.4. Economic Subsidy Cost for Electric Vehicle Users

$$C^{\mathrm{EV}}_{w,p,s} = \sum_{t}^{T}\left(a + \delta\lambda^{E2}_{s,t}\right)P^{\mathrm{EV}.D}_{w,p,s,t},$$
$$S^{\mathrm{EV}}_{w,p,s,t} = S^{\mathrm{EV}}_{w,p,s,t-1} + \eta^{\mathrm{EV}.C}P^{\mathrm{EV},C}_{w,p,s,t} - \frac{P^{\mathrm{EV}.D}_{w,p,s,t}}{\eta^{\mathrm{EV}.D}}. \tag{9}$$

To attract electric vehicle users to register and participate in the scheduling, VPP needs to offer users certain economic subsidies. In this paper, the user subsidy consists of two parts: basic and dynamic subsidy [15]. a is the basic subsidy price; δ is the dynamic subsidy coefficient; $S^{\mathrm{EV}}_{w,p,s,t}$ is the power storage volume of EV in period t, $P^{\mathrm{EV}.D}_{w,p,s,t}$ and $P^{\mathrm{EV}.C}_{w,p,s,t}$ are the discharge power and charge power of the EV in period t; $\eta^{\mathrm{EV}.C}$ and $\eta^{\mathrm{EV}.D}$ are the charge and discharge efficiency of the EV, respectively, indicating the power consumption in the charge and discharge process.

4.1.5. Economic Subsidy Cost for Interruptible Load Users

$$C^{\mathrm{IL}}_{w,p,s} = \sum_{t=1}^{T}\left(\sum_{j=1}^{3}\lambda^{\mathrm{IL}}_{j} g^{\mathrm{IL}}_{w,p,s,j,t}\right),$$
$$P^{\mathrm{IL}}_{w,p,s,t} = \sum_{j=1}^{3} g^{\mathrm{IL}}_{w,p,s,j,t}. \tag{10}$$

In the formula, $\lambda^{\mathrm{IL}}_{j}$ is the load interruption compensation price at level j; $g^{\mathrm{IL}}_{w,p,s,i,t}$ is the interruptible load response at level j in period t; and $P^{\mathrm{IL}}_{w,p,s,t}$ is the total response of interruptible load in period t.

4.2. Constraints

4.2.1. Operation Constraints of Carbon Capture Gas Turbine

$$\begin{aligned}
&0 \le S^{\mathrm{CCS}}_{w,p,s,t} \le S^{\mathrm{CCS.\,max}}\\
&0 \le E^{\mathrm{CCS},1}_{w,p,s,t} \le e_{\mathrm{MT}} P^{\mathrm{MT}}_{w,p,s,t}\\
&0 \le E^{\mathrm{CCS},2}_{w,p,s,t} \le S^{\mathrm{CCS}}_{w,p,s,t-1} + \beta E^{\mathrm{CCS},1}_{w,p,s,t}\\
&0 \le E^{\mathrm{CCS},2}_{w,p,s,t} \le E^{\mathrm{CCS.\,max}}\\
&0 \le P^{\mathrm{GT}}_{w,p,s,t} \le \upsilon^{\mathrm{GT}}_{w,p,s,t} P^{\mathrm{GT.\,max}}\\
&-R^{d} \le P^{\mathrm{GT}}_{w,p,s,t} - P^{\mathrm{GT}}_{w,p,s,t-1} \le R^{u}.
\end{aligned} \tag{11}$$

In the formula, $S^{\mathrm{CCS.\,max}}$ represents the maximum CO_2 storage of solution reservoir in the carbon capture system; $E^{\mathrm{CCS.\,max}}$ is the maximum CO_2 capture in the carbon capture system per hour; and R^d and R^u are the maximum upward and downward climbing rate of the gas turbine, respectively.

4.2.2. Constraints of Electric Vehicle Group

$$\begin{aligned}
&0 \le P^{\mathrm{EV},C}_{w,p,s,t} \le \upsilon^{\mathrm{EV},C}_{w,p,s,t} P^{\mathrm{EV.Cmax}},\\
&0 \le P^{\mathrm{EV},D}_{w,p,s,t} \le \upsilon^{\mathrm{EV},D}_{w,p,s,t} P^{\mathrm{EV.Dmax}},\\
&\upsilon^{\mathrm{EV},C}_{w,p,s,t} + \upsilon^{\mathrm{EV},D}_{w,p,s,t} \le 1,\\
&\mathrm{Soc}^{\mathrm{EV.\,min}} \le \frac{S^{\mathrm{EV}}_{w,p,s,t}}{S^{\mathrm{EV.\,max}}} \le \mathrm{Soc}^{\mathrm{EV.\,max}}.
\end{aligned} \tag{12}$$

In the formula, $\upsilon^{\mathrm{EV},C}_{w,p,s,t}$ and $\upsilon^{\mathrm{EV},D}_{w,p,s,t}$ represent the charge and discharge state variable of EV in period t, respectively. If it is charging/discharging, the value is 1 and otherwise 0; $S^{\mathrm{EV.\,max}}$ and $P^{\mathrm{EV.Dmax}}$ represent the maximum EV charge and discharge power per hour, respectively [31]; $S^{\mathrm{EV.\,max}}$ is the maximum power storage volume of EV; and $\mathrm{Soc}^{\mathrm{EV.\,min}}$ and $\mathrm{Soc}^{\mathrm{EV.\,max}}$ are the maximum and minimum Soc state of EV energy storage [32].

4.2.3. Constraints of Interruptible Load

$$\begin{aligned}
&0 \le P^{\mathrm{IL}}_{w,p,s,t} \le b Q^{E1}_{t},\\
&P^{\mathrm{IL}}_{w,p,s,t-1} + P^{\mathrm{IL}}_{w,p,s,t} \le Q^{\mathrm{IL.\,max}}.
\end{aligned} \tag{13}$$

In the formula, b is the maximum response ratio coefficient of the interruptible load, which is used to constrain the maximum value that users can participate in the load interruption response. $Q^{\mathrm{IL.\,max}}$ represents the maximum response of interruptible load in continuous time periods, which prevents the decline in user satisfaction caused by the continuous call of interruptible load [33].

4.2.4. Constraints of Bilateral Contract.

$$\begin{aligned}
&(1-h) Q^{E1}_{t} \le P^{E1}_{w,p,s,t} \le (1+h) Q^{E1}_{t},\\
&\sum_{t}^{T} P^{E1}_{w,p,s,t} = \sum_{t}^{T} Q^{E1}_{t},
\end{aligned} \tag{14}$$

where $P^{E1}_{w,p,s,t}$ is the actual power delivery volume of virtual power plant in period t according to the bilateral contract; h is the allowable deviation coefficient between the power supply volume stipulated in the bilateral contract and the actual delivery volume in period t.

4.2.5. Constraints of Energy Balance t

$$\begin{aligned}
P^{E1}_{w,p,s,t} + G^{E2}_{t} + \frac{P^{\mathrm{EV},C}_{w,p,s,t}}{\eta^{\mathrm{EV}.C}} + \theta E^{\mathrm{CCS},2}_{w,p,s,t} = P^{W}_{w,p,s,t} + P^{\mathrm{PV}}_{w,p,s,t} + P^{\mathrm{GT}}_{w,p,s,t}\\
+ \eta^{\mathrm{EV}.D} P^{\mathrm{EV}.D}_{w,p,s,t} + P^{\mathrm{IL}}_{w,p,s,t}.
\end{aligned} \tag{15}$$

In the formula, θ is the energy consumption required for carbon capture system to separate and compress unit CO_2 per hour, that is, the electricity volume required to capture per ton of CO_2.

5. Case Study

In this paper, a gas turbine GT with carbon capture system (CCS), photovoltaic power station PV, wind power plant W, electric vehicle group EV, and interruptible load IL are aggregated to form a virtual power plant. While ensuring the actual power delivery according to the signed medium and long-term bilateral contracts, VPP should also dispatch the aggregated units according to the electricity price fluctuations and renewable energy output, especially control the comprehensive and flexible operation of carbon capture gas turbine, so as to formulate the VPP bidding strategy in the day-ahead electricity market. Meanwhile, at the end of a scheduling period, VPP liquidates the actual carbon emissions in this cycle and participates in the carbon emission rights market to sell surplus carbon allowance and purchase shortage carbon allowance.

In addition, VPP capacity built in this paper is relatively small and difficult to directly affect the market price. VPP only participates in the electricity market and carbon trading market as the price recipient. In addition, compared with the continuous fluctuation of the electricity price in the electricity market, the carbon price of the carbon trading market is relatively stable. Therefore, the carbon price is set as fixed in a joint scheduling cycle in this paper.

5.1. Model Parameter Setting. Relevant parameters of each aggregated unit and electricity-carbon market in the virtual power plant are shown in Table 1. The medium and long-term bilateral contract electricity price signed by the virtual power plant is 212.86 ¥/MW [34]. The allowable deviation coefficient of power supply h is 0.05. And, the bilateral contract curve is shown in Figure 3 [35]. In different scenarios, the output curve of renewable energy power stations and the price fluctuation curve of the electricity day-ahead market are shown in Figures 4–6, respectively. According to The 2019-2020 National Carbon Emission Trading Total Quota Setting and Allocation Implementation Plan (Power Generation Industry), the carbon emission benchmark value of gas turbine is set at 0.392 t/MW. The carbon allowance (CEA) price in the carbon emission rights market is 100 ¥/t, and the certified emission reduction (CCER) price is slightly lower than CEA at 75 ¥/t.

5.2. Optimization Results and Analysis

5.2.1. Impact of VPP Behaviour on Profit. To measure the impact of virtual power plant with carbon capture system participating in the electricity-carbon market on the overall operating income, four operating schemes are set up as shown in Table 2.

The above-given four schemes are solved by using GAMS solver and CPLEX optimizer with obtained results shown in Table 3.

As can be seen from Table 3, Scheme 1 indicates the income situation of virtual power plant only participating in the electricity market. Because gas turbine's carbon emission does not confine by relevant institutions, output of gas turbine is at a high level. In Scheme 2, virtual power plant simultaneously participates in the electricity market and the CEA of carbon trading market. Under the constraints of total carbon allowance, gas turbine total output and VPP total income are significantly lower than Scheme 1. Besides, the virtual power plant carbon income at this time is negative. This is because the gas turbine carbon emission intensity in this paper is set as higher than the benchmark value of power generation industry. In Scheme 3, the virtual power plant declares renewable energy output as CCER and sell it in the carbon market. VPP carbon income and total income increase a lot, which demonstrates the unique advantages of virtual power plant in carbon trading market compared with conventional power generation. The introduction of carbon trading market will further improve the virtual power plant in the electricity market trading and promote the development of renewable energy. In Scheme 4, VPP introduces the carbon capture system into the gas turbine to form the carbon capture gas turbine, reduces the actual carbon emissions through CO_2 capture, and then sells the surplus allowance in the carbon market for profit. The results show that the carbon income of VPP has increased slightly and the total output of the gas turbine has increased. To sum up, VPP's participation in both the electricity market and the carbon trading market can improve the overall income; the introduction of carbon capture system can further improve the profit in the trading of both markets and reduce carbon emissions. Meanwhile, the carbon trading mechanism will suppress the output of high carbon emission gas turbines, resulting in a corresponding reduction in the total output of VPP. But comparing the VPP total output of scheme 3 and scheme 4, it can be found that although the increase in MT total output is greater than VPP's, and carbon capture system operation losses is the main reason.

5.2.2. Characteristic Analysis of Comprehensive and Flexible Operation of Carbon Capture System under Different Carbon Prices. By 2021, the carbon market in China has explored and developed for 10 years. The average deal price of most regional pilot carbon markets is around 20 yuan. The carbon price of the national carbon market initiated last year has remained around 50 yuan for a long time. Although our carbon market is in the fast track of construction and development and beginning to take shape, the current price level is far from reaching the "social carbon reduction marginal cost." Therefore, it is necessary to briefly analyse the carbon capture system scheduling condition in different scenarios at different carbon trading prices as shown from Figures 7–9, where the wind power and photovoltaic output and electricity price curves are taken from Scenarios 2, Scenario 3, and Scenario 5, respectively.

First of all, as shown in the curve of carbon capture quantity $E_{w,s,p,t}^{\mathrm{CCS},2}$ and reservoir carbon reserves $S_{w,s,p,t}^{\mathrm{CCS}}$ over time in Figures 7(a)–9(a), the carbon capture system presents a periodic working law, namely, to absorb CO_2 emitted by gas turbine during the peak period and to intensely capture CO_2 absorbed in the reservoir during midnight and morning. This is because, during peak load periods, gas turbine requires a relatively high net output power to meet the load requirements. By reducing the rich solution flowing into the regeneration tower from reservoir, CO_2 supply to the regeneration tower is reduced so that the operation level of carbon capture system is lowered to realize the goal of energy consumption reduction. During the off-peak periods in the small hours of the night, electricity price falls. At this time, the carbon capture system increases the rich solution flowing from reservoir into the regeneration tower and raises power consumption to capture the prereserved CO_2. This reduces the additional cost of frequent start and stop of gas turbine and provides a channel for the timely renewable energy consumption, which realizes the comprehensive and flexible operation of the carbon capture gas turbine.

Secondly, the histograms of net carbon emissions per day are shown in Figures 7(b)–9(b), with the increase of carbon emission allowance price, the operation frequency and intensity of carbon capture system continue to improve. And, the net CO_2 emission level of gas turbine is significantly reduced. In addition, under three carbon prices the carbon capture system reduces the carbon emission of virtual power plant by 55.125 tons, 156.892 tons, and 240.930 tons, respectively and increases income in the carbon market by 2,988.8 yuan, 12,551.36 yuan, and 28,911.6 yuan, respectively.

5.2.3. Optimal Scheduling Analysis of Virtual Power Plant. The specific optimization results of each aggregated unit of VPP and the electricity purchase and sale situation of in the day-ahead electricity market are shown in Figures 10–12. According to the energy optimal scheduling results, when the equivalent load and electricity price are low at night, the charge power of EV group in VPP gets large and VPP even purchases electricity to support the operation of carbon capture system. When the equivalent load get large in daytime and the electricity price is greater than the power generation cost, the EV group discharges, the gas turbine output level increases, and the electricity is sold to the electricity market to make profits. If the gas turbine or EV

Table 1: Parameters of aggregated units in VPP.

	Parameters	Value
Gas turbine	1/2/3 section cost curve slope/(¥/MW)	282/318/353
	Maximum/minimum output power/(MW)	5.67/2.5
	Maximum up/down climbing power/(MW)	3/3
	Start cost/¥	212.0
	Fixed cost/¥	212.0
	Carbon emission intensity/(t/MW)	0.42
Carbon capture system	Capture efficiency	0.90
	Solution reservoir maximum CO_2 storage/t	5.6
	Regeneration tower CO_2 capture ability/(t/h)	2
	Required power for unit CO_2 capture/(t/MW)	0.269
Electric vehicle group	Capacity upper and lower limits/MW	40/5
	Initial power reserve/MW	25
	Charge/discharge efficiency	0.9/0.9
	Maximum charge power/MW	15
	Maximum discharge power/MW	18
	Basic subsidized price/(¥/MW)	70.7
	Dynamic subsidized coefficient	0.1
Interruptible load	Economic subsidy coefficient	0.10
	1/2/3 level load outage compensation price	212/247/282
	Maximum load response ratio	0.10
	Maximum load call at continuous time/MW	2.5

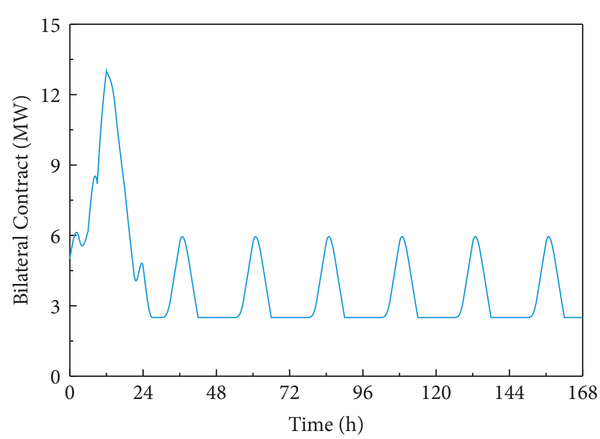


Figure 3: Bilateral electricity contract curve.

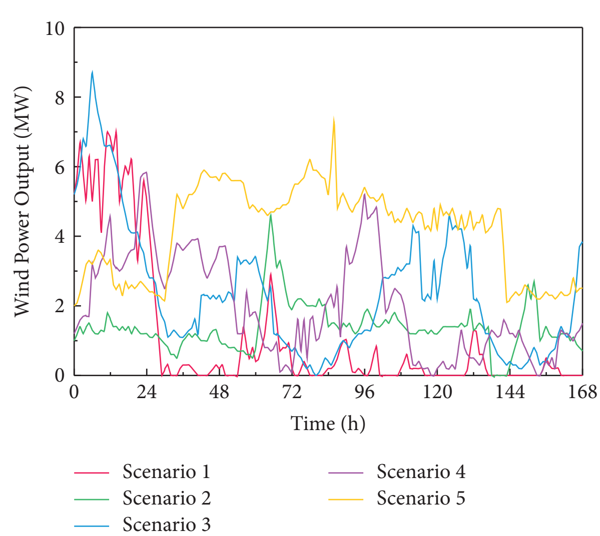


Figure 4: Wind power output in different scenarios.

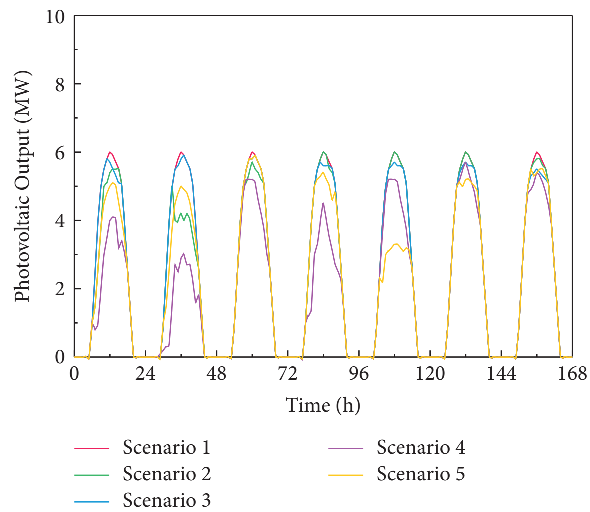


Figure 5: Photovoltaic output in different scenarios.

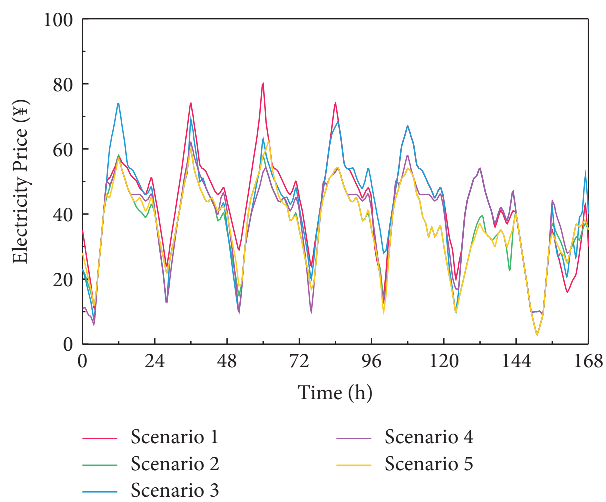


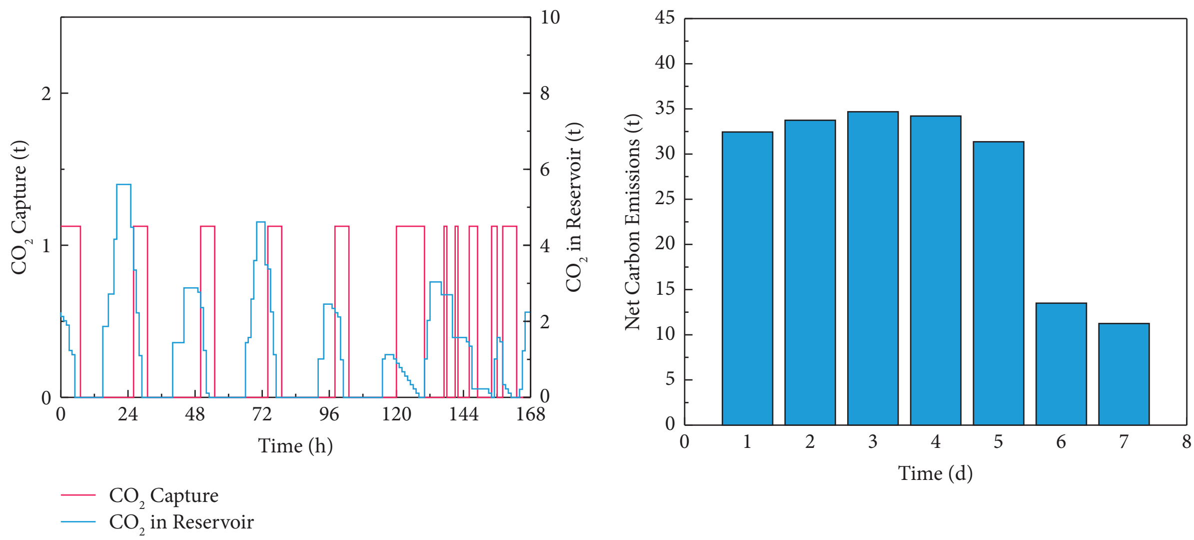
Figure 6: Electricity price in different scenarios.

Table 2: Five different operation modes of VPP.

Schemes	Participating in electricity market	Carbon capture system	Participating in carbon market	
			CEA	CCER
1	√	×	×	×
2	√	×	√	×
3	√	×	√	√
4	√	√	√	√

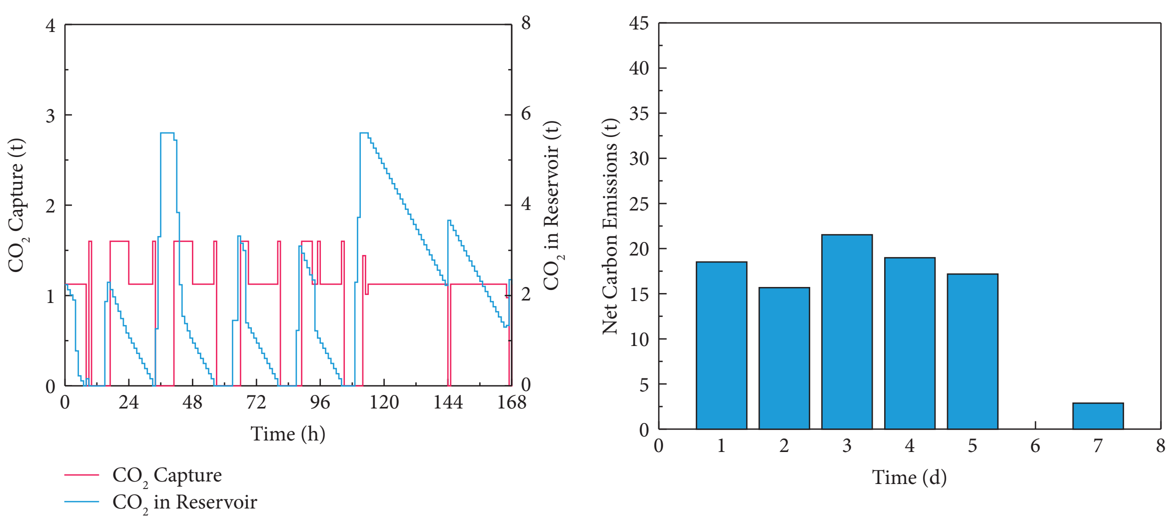
Table 3: Power output and income situation of VPP under different operation modes.

Schemes	GT total output (MW)	VPP total output (MW)	Carbon income (¥)	Total income (¥)
1	606.65	1632.7	0	300294.5
2	591.93	1618.0	−3433.2	296844.1
3	591.98	1620.0	41878.2	304082.8
4	628.47	1649.6	65934.3	310850.8



(a) (b)

FIGURE 7: Operation condition of the carbon capture gas turbine unit when $\lambda^{C} = 50E$. (a) Carbon capture and CO_2 in reservoir. (b) Net carbon emissions of the gas turbine.



(a) (b)

FIGURE 8: Operation condition of the carbon capture gas turbine when $\lambda^{C} = 80E$. (a) Carbon capture and CO_2 in reservoir. (b) Net carbon emissions of the gas turbine.

group output has reached the maximum but still could not meet the user load demand, the virtual power plant needs to purchase power in the electricity market to meet the power supply balance. The load interruption amount at all levels is shown in Figure 12. The virtual power plant can conduct load interruption during peak time, and the load interruption order is determined by the compensation price. As a result, virtual power plant can increase their profitability by reducing user-side power loads, thereby increasing power sale quantity during the high electricity price period.

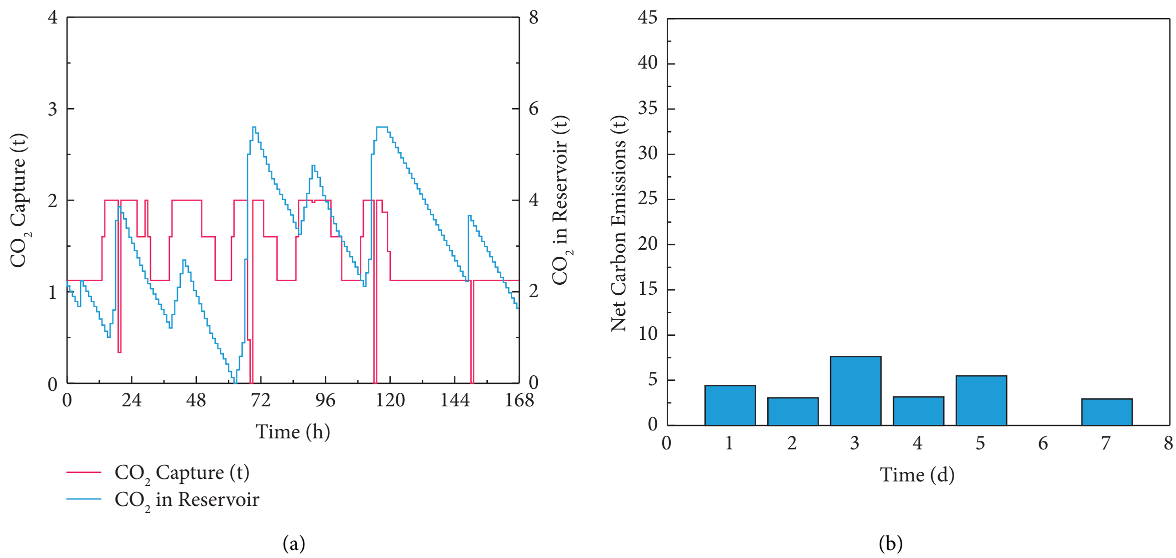


Figure 9: Operation condition of the carbon capture gas turbine when $\lambda^{C} = 120E$. (a) Carbon capture and CO_2 in reservoir. (b) Net carbon emissions of the gas turbine.

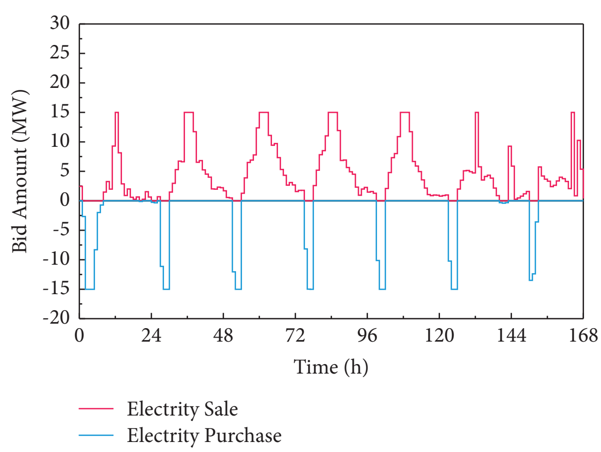


Figure 10: Electricity trading situation in day-ahead market.

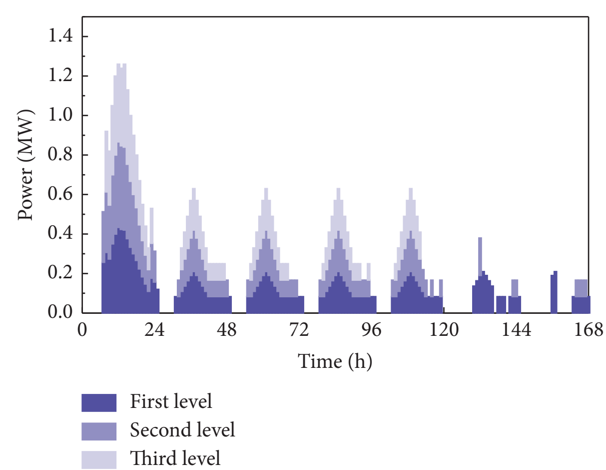


Figure 12: Optimal scheduling situation of interruptible load.

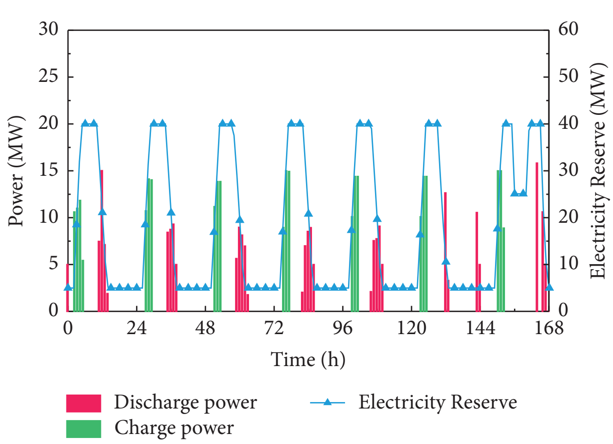


Figure 11: Optimal scheduling situation of electric vehicles.

6. Conclusion

This paper analyses the trading mode of virtual power plant participating in the carbon trading market, establishes virtual power plant electric-carbon joint optimization scheduling model with the carbon capture system, uses random scenario planning methods to deal with uncertain factors, such as electricity price and renewable energy output factors, and finally verifies the model effectiveness through simulation examples. The conclusions are as follows:

(1) It could help the virtual power plant to get more income by participating in the carbon market trading, where the Chinese Certified Emission Reduction (CCER), are highly significant. In addition, the introduction of carbon capture system can

reduce the actual virtual power plant carbon emissions level, reduce the turbine carbon emission cost, and improve the virtual power plant joint income in electricity-carbon market. But at present, China's carbon market is still in the rapid development stage, and relevant policies need to be further improved.

(2) On the premise of ensuring quota enterprises' enthusiasm to participate in carbon market trading, the higher carbon market price, the higher operation level of carbon capture system, the greater CO_2 capture, the better overall emission reduction effect of virtual power plant, and the greater economic income obtained.

(3) The optimal scheduling of electric vehicle group and interruptible load, and the periodic operation law of carbon capture system can realize the comprehensive and flexible operation mode of virtual power plant from multiple aspects, which reduce the start and stop cost of gas turbine and promote the timely consumption of renewable energy.

Data Availability

The constraint and parameter data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors DL, FX, PX, and YK was employed by the company Hubei Electric Power Research Institute, Wuhan, China. XJ and MZ were employed by the company State Grid Hubei Electric Power CO., LTD., Wuhan, China. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflicts of interest.

Authors' Contributions

DL and FX contributed to the conception and design of the study. JW organized the simulation, analysed the results, and wrote parts of the manuscript. XJ gave suggestions to technical support. PX and MZ contributed to writing parts of the manuscript. YK contributed to the improvement of the study design.

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