Research on Optimal Scheduling of Virtual Power Plant Considering the Cooperation of Distributed Generation and Energy Storage Under Carbon Rights Trading Environment

Haiyao Wang[1](✉), Gang Du[1,2], Tao Zheng[1,2], Yulong Jin[1,2], and Tao Jing[1,2]

[1] NARI Group Corporation (State Grid Electric Power Research Institute), Nanjing 211106, China
627846195@qq.com
[2] NARI-TECH Nanjing Control System Ltd., Nanjing 211106, China

Abstract. Under the background of "Carbon Peak, Carbon Neutralization" national strategic carbon reduction goal, establishing an appropriate carbon trading mechanism is an effective way to achieve carbon reduction. This paper establishes an optimal model of economic and environmental dispatching for a virtual power plant (VPP) which contains energy storage, gas turbine, wind power and photovoltaic generation when it participates in carbon trading. Firstly, the carbon trading mechanism is introduced, and the scenario generation method considering the uncertainty of wind power based on Gaussian kernel function theory is formed to get the classical scene curve of wind power. Then, a mixed integer quadratic programming model for coordinated dispatch of distributed power and energy storage in VPP under carbon trading environment is established with the objective of minimizing the total cost of VPP. Finally, the example validation shows that the model reduces the total cost and total carbon emissions of the system, greatly improves the consumption of clean energy, and makes the scheduling of virtual power plants take into account both economic and environmental benefits.

Keywords: Distributed energy · Virtual power plant · Carbon trading · Optimal scheduling

1 Introduction

In order to achieve the goal of "carbon dioxide" and build a clean economy and sustainable energy-saving society, the electric power industry is facing enormous pressure of carbon emission reduction. Therefore, introducing the concept of "low-carbon economy" into the power industry, taking into account the energy saving and emission reduction targets in the operation and dispatch of power systems, is of great significance to the realization of "dual-carbon" goals [1].

Virtual power plant is a special power plant containing renewable energy, interruptible load, energy storage, electric vehicle and other power resources. It aggregates a large

Y. Xue et al. (Eds.): PMF 2022, *Proceedings of the 7th PURPLE MOUNTAIN FORUM on Smart Grid Protection and Control (PMF2022)*, pp. 818–834, 2023.
https://doi.org/10.1007/978-981-99-0063-3_57

number of scattered power sources or loads, and makes it participate in the operation of power system and power market as a whole without changing the grid connection mode of distributed power generation [2]. If the carbon emission in the production process of equipment is not considered, there is almost no carbon emission in the power generation process of wind power and photovoltaic generator units in VPP. For energy storage, if the wind power or photovoltaic power generation during the low load period is used for charging, it can also significantly reduce carbon emissions. VPP can achieve economic benefits and reduce carbon emissions objectively by reasonably allocating distributed resources and optimizing operation [3].

There are some research reports on the low-carbon operation of power system at home and abroad. Reference [4] introduced carbon emission quota into power system economic dispatching to improve the environmental protection of power system with a large number of distributed generators, and limited carbon emission with rigid indicators. Reference [5] constructs a power system optimization model considering carbon emissions, and uses the weight value to make a reasonable compromise between the optimization of energy conservation and emission reduction. Reference [6] optimized the scheduling of economic and environmental benefits when VPP with electric vehicles participates in green card trading, and proved that the large-scale application of electric vehicles in VPP can produce obvious environmental benefits. Reference [7] added excessive emission penalty in the design of low-carbon framework to better control carbon emissions. These references focus on the mandatory restriction, quota and punishment of carbon emissions in the traditional optimal dispatching of power system, but rarely quantify the value of carbon emission rights, and combine the carbon emission rights with environmental protection and economy. In the VPP with flexible operation and rapid output adjustment, the introduction of carbon trading mechanism to promote low-carbon emission reduction also has a large gap in the research related to this aspect.

On the other hand, with the rapid development of energy storage technology, the restriction degree of energy storage participating in power system regulation by capacity and cost is also decreasing. In recent years, it is generally believed that distributed energy storage is a high-quality adjustable resource of virtual power plant. Reference [8] combined with a wind storage system demonstration project, proposed the operation mode of energy storage system based on commercial VPP, and established a stochastic optimal scheduling model including wind light water storage with the goal of maximizing the revenue of VPP. Reference [9] establishes two distributed energy storage models of grid connected energy storage and user side energy storage, and optimizes the scheduling of virtual power plant resources based on the day ahead market time of use price. Reference [10] analyzes the operation mode of VPP composed of energy storage equipment and distributed wind power participating in system economic optimal dispatching. The above literature shows that the addition of energy storage in VPP can effectively suppress the impact of the uncertainty of wind and solar output and improve the consumption of clean energy, but it is less involved that energy storage can also replace some gas turbine output in the carbon trading environment, which has the function of improving the environmental protection of VPP as a rapid response unit in the system.

In summary, on the basis of the existing research, this paper constructs an output scenario considering the uncertainty of wind power by using the kernel density estimation method based on the Gaussian kernel function. A virtual power plant dispatch model with distributed power supply and storage synergy under the carbon trading environment is established by introducing the carbon rights trading market environment. The example results verify that the model proposed in this paper can effectively improve the economic and environmental benefits of VPP.

2 Carbon Trading Mechanism and Scenario Generation

2.1 Carbon Trading Mechanism

Carbon trading, also known as carbon emission rights trading, is a market-based measure to achieve energy conservation and emission reduction goals. Carbon emission rights trading practice is generally a carbon emission rights trading system, in which the relevant government agencies set the total amount of emissions in one or more industries, and issue a certain number of tradable quotas within the total amount. Generally, each quota corresponds to one ton of carbon dioxide emission equivalent. This paper uses the baseline method to determine the carbon trading quota of VPP [11].

For VPP including gas turbine, wind power and photovoltaic power generation, the carbon trading quota in period t can be obtained by Eq. (1).

$$M_{D,t} = \sum_{i=1}^{N} \varepsilon P_{i,t} \tag{1}$$

In the formula, N is the total number of generator units in the studied VPP. $P_{i,t}$ is the active output of generator set i at time t; ε is the distribution coefficient of VPP unit electricity emission, which is determined according to the " regional power grid baseline emission factor " issued by the national development and Reform Commission [12].

VPP can make a profit by selling emissions that do not meet the carbon emission quota. If the actual carbon emission of VPP in this period is higher than the carbon emission quota, the carbon trading fee shall be paid to purchase the emission quota. Carbon trading revenue is expressed as follows:

$$I_{\mathrm{t}}^{C} = k^{C}(Q_t^{Q} - Q_t^{N}) \tag{2}$$

$$Q_t^{Q} = \gamma^{C} P_t^{G} \tag{3}$$

In the formula, I_t^C is the income of carbon trading market; k^C is the carbon trading price; Q_t^Q is the carbon emission quota of gas turbine unit in t period; Q_t^N is the net emission of gas turbine unit in t period; γ^C is the carbon emission benchmark limit per unit of electricity [13]; P_t^G is the net output of gas turbine unit in t period.

2.2 Scenarios Generation Considering Scenery Uncertainty

VPP contains a large number of intermittent distributed power sources such as wind and photovoltaic, and its output power has strong randomness and uncertainty. If the wind and solar output data of a single historical day is selected to verify the feasibility of the model, it lacks scientific rigor and credibility. Because the scenario analysis method can clearly describe the probability distribution of uncertainty and better retain the statistical characteristics of wind and solar output data, it has become one of the main methods to deal with the uncertainty of wind and solar power generation. This paper describes the uncertainty of the scenery by generating the classical scene method with probability information, establishes the probability density function of the historical scenery output data and samples it to obtain the whole scene set with huge dimension, and then forms the classical scene set through the scene reduction technology.

The specific steps of scene generation are as follows.

(1) Based on the historical n-day wind and solar output data, the sampling period is 1H, and the nuclear density estimation method is used to establish the probability density function of fan and photovoltaic output in each period of 24 h, as follows:

$$\begin{cases} f_{h,t}(x_t) = \frac{1}{nh}\sum\limits_{d=1}^{n} G\left(\frac{x_t - X_{d,t}}{h}\right) \\ f_{h,t}(y_t) = \frac{1}{nh}\sum\limits_{d=1}^{n} G\left(\frac{y_t - Y_{d,t}}{h}\right) \end{cases} \tag{4}$$

In the formula, h is the time scale; $X_{d,t}$ is the fan output in t period of day d; $Y_{d,t}$ is the photovoltaic output in t period of day d; G is selected as Gauss kernel function.

(2) The joint probability distribution function of wind and photovoltaic output is sampled for each period, and the sample output of fan and photovoltaic is obtained by inverse transformation, and the set C of the initial scene is obtained.
(3) Set the probability of scenario P_f^i and P_f^j in C as π_i and π_j respectively, and define the distance between scenarios as $\left\| P_f^i - P_f^j \right\|_2$. Use synchronous backdating technology based on probability distance to reduce the scene and form a classical scene set[14]. The steps of the synchronous substitution reduction technique are shown in Fig. 1.

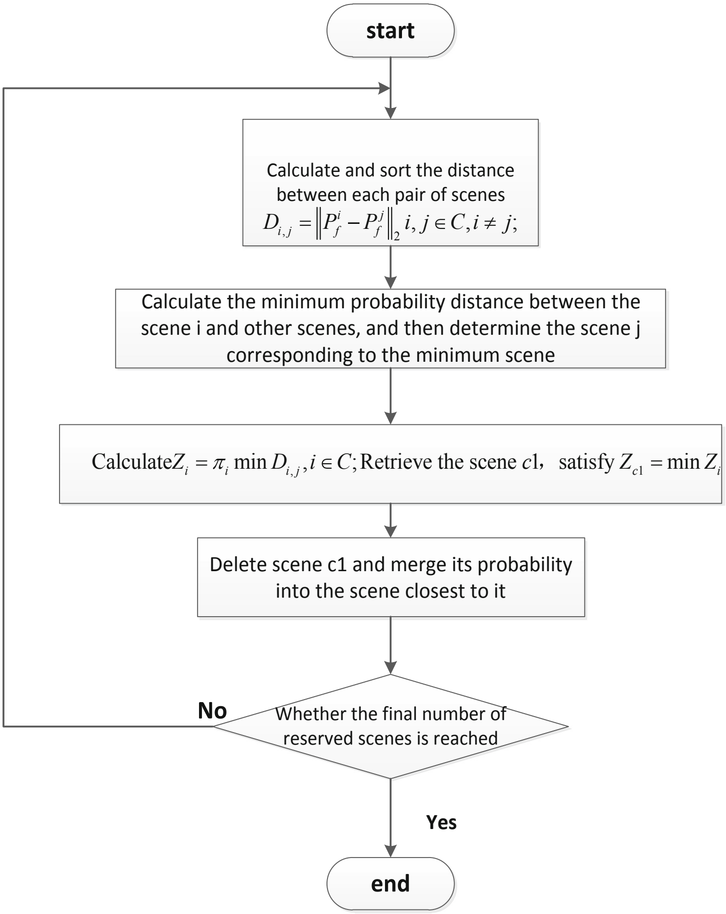


Fig. 1. Flowchart of synchronous generation reduction method

If the classical scene set is *J*, including S scenes and the deleted scene set is *J'*, the optimal scene reduction set is satisfied:

$$\min \left\{ \sum_{i \in J'} \pi_i \min_{j \in J} \left\| P_f^i - P_f^j \right\|_2 \right\} \tag{5}$$

3 Carbon Trading Mechanism and Scenario Generation

3.1 VPP Composition Unit

The composition diagram of VPP system proposed in this paper is shown in Fig. 2, including gas turbine unit, wind turbine unit, photovoltaic unit, electric energy storage and electric load. In VPP, if the output of gas turbine unit, wind turbine unit, photovoltaic unit and electric energy storage cannot meet the demand of electric load, purchase electricity from the power grid through the electric energy market; If the output of wind turbine and photovoltaic unit is not fully absorbed, the electric energy storage will be charged and stored. When the electric energy storage reaches the upper limit of capacity, the phenomenon of wind and light will be abandoned. The carbon emissions in the VPP system are mainly generated by gas turbine units. According to the actual carbon emissions, sell carbon rights in the carbon trading market for profit or purchase excess carbon rights.

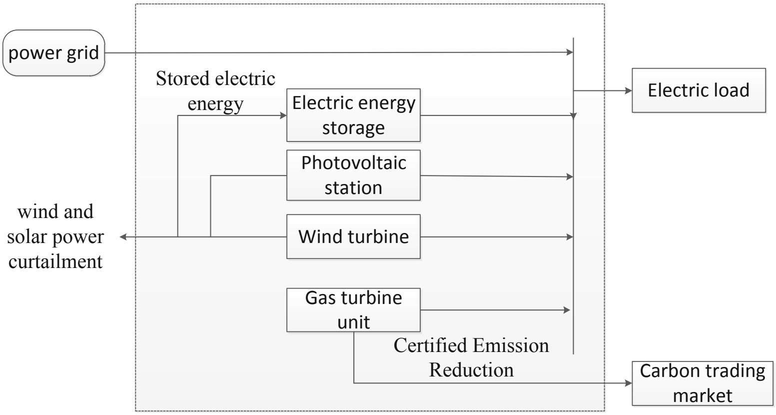


Fig. 2. Composition diagram of VPP system

By installing energy storage equipment and cooperating with distributed power generation, this paper can fully make up for the impact of wind and solar output uncertainty and fluctuation, and ensure the reliability of VPP output and operation.

3.2 Optimization Objectives

In order to reflect the economy and environmental protection of VPP, this paper takes the minimization of the net operation cost of VPP taking into account the carbon emission cost as the optimization objective. The decision variables include gas turbine output, wind power photovoltaic output, electric energy storage charge and discharge power and market power purchase. The objective function is as follows:

$$\min \sum_{t=1}^{T} (C_t^F - I_t^C + C_t^W + C_t^V + C_t^{ES} + C_t^M) \tag{6}$$

In the formula: the objective function consists of 6 parts, namely gas turbine fuel cost C_t^F, carbon asset market income I_t^C, wind turbine operation and maintenance cost C_t^W, photovoltaic power generation equipment operation and maintenance cost C_t^V, energy storage use cost C_t^{ES}, energy market power purchase cost C_t^M, and T is the total dispatching time. The specific expression of each part is as follows:

1) The fuel cost of gas turbine is [15]:

$$C_t^F = \sum_{i=1}^{l} \left(a^f + b^f P_t^G + c^f (P_t^G)^2 \right) \tag{7}$$

In the formula, a^f, b^f, c^f are the fuel cost coefficient; l is total number of gas turbines.

2) The expression of carbon asset trading income is shown in Eqs. (2)–(3). In this paper, carbon emissions are mainly caused by gas turbines, where:

$$Q_t^N = \sum_{i=1}^{l} (\lambda_i P_t^G) \tag{8}$$

In the formula, λ_i is the carbon emission correlation coefficient of gas turbine.

3) The use cost of energy storage includes two parts: investment cost and operation and maintenance cost, which can be expressed as:

$$C_t^{ES} = C_{capital} + C_t^{OM} \tag{9}$$

$$C_t^{OM} = c_{ES}(P_t^{ESC} + P_t^{ESD}) \tag{10}$$

In the formula: $C_{capital}$ is the investment cost [16], which is related to the average life of the energy storage manufacturer, which is a fixed value in the calculation example. C_{OM} is the operation and maintenance cost. c_{ES} is the operating cost per unit of energy storage. P^{ESC}, P^{ESD} is the charge and discharge power of electric energy storage.

4) The operation and maintenance cost of the fan during daily operation is:

$$C_t^W = \lambda_1 P_t^W \tag{11}$$

In the formula: P_t^W is the wind power output in t period; λ_1 is the unit maintenance cost of wind power.

5) The operation and maintenance cost of PV during daily operation is:

$$C_t^V = \lambda_2 P_t^V \tag{12}$$

In the formula: P_t^V is the photovoltaic output in t period; λ_2 is the unit maintenance cost of photovoltaic.

6) When the power is insufficient, VPP can be purchased from the power grid to meet the power load demand. The expression of power purchase cost in power market is as follows:

$$C_t^M = k_t^{EM} P_t^{EM} \tag{13}$$

In the formula: P_t^{EM} is the power purchase in the power grid in period t; k_t^{EM} is the power purchase price of power grid in period t.

3.3 Constraint Condition

The constraints are as follows:

1) Electric power balance constraint.

$$P_t^G + P_t^W + P_t^V + P_{tn.ES} = P_t^{EL} - P_t^{EM} \tag{14}$$

In the formula: P_t^{EL} is the electrical load in t period.

2) Output and climbing constraints of gas turbine unit.

$$P^{G,\min} \le P_t^G \le P^{G,\max} \tag{15}$$

$$\left|P_{t+1}^G - P_t^G\right| \le \Delta P^G \tag{16}$$

In the formula: $P^{G,\max}$, $P^{G,\min}$ are the upper and lower limits of gas turbine unit output respectively; ΔP^G is the climbing rate constraint of gas turbine unit.

3) Electric energy storage constraint.

The charging and discharging of energy storage is mainly affected by the charging state of energy storage. In this paper, the power loss of electric energy storage is considered, and its constraints are as follows:

$$S_t^{ES} = S_{t-1}^{ES}(1 - \sigma^{ES}) + \eta^{ESC} P_t^{ESC} - \frac{P_t^{ESD}}{\eta^{ESD}} \tag{17}$$

$$0 \le P_t^{ESC} \le P^{ESC,\max} \mu_t^{ESC} \tag{18}$$

$$0 \le P_t^{ESD} \le P^{ESD,\max} \mu_t^{ESD} \tag{19}$$

$$0 \le \mu_t^{ESC} + \mu_t^{ESD} \le 1 \tag{20}$$

$$S^{ES,\min} \le S_t^{ES} \le S^{ES,\max} \tag{21}$$

$$S_0^{ES} = S_{24}^{ES} \tag{22}$$

In the formula: S_t^{ES} is the storage capacity of electric energy at the end of t period. σ^{ES} is the electric loss rate of electric energy storage; η^{ESC}, η^{ESD} are the charging and discharging efficiency of electric energy storage; $P^{ESC,\max}$, $P^{ESD,\max}$ are the maximum value of charge and discharge power respectively; Boolean variables μ_t^{ESC} and μ_t^{ESD} respectively indicate whether the electric energy storage in t period is discharged. If yes, set 1, otherwise set 0; $S^{ES,\max}$, $S^{ES,\min}$ are the maximum and minimum power storage capacity respectively; S_0^{ES}, S_{24}^{ES} are the beginning and end value of the energy storage battery in a day.

4) Wind and solar output constraints

$$0 \le P_t^W \le P^{W,\max} \tag{23}$$

$$0 \le P_t^V \le P^{V,\max} \tag{24}$$

In the formula: $P^{W,\max}$, $P^{V,\max}$ are the maximum available output of scenery.

3.4 Model Solving

The 24-h power dispatching model in this paper is a mixed integer quadratic programming (MIQP) problem with complex constraints and high-dimensional variables. YALMIP is a toolbox suitable for solving planning problems in MATLAB, and CPLEX is a commercial solver for solving MIQP problems. In this paper, YALMIP/ CPLEX solver is used to solve the optimization model.

4 Example Analysis

4.1 Example Description

In order to verify the model proposed in this paper, the dispatching period is divided into 24 h. The VPP constructed contains 7 × 2 MW wind power cluster, 6 × 2 MW photovoltaic cluster and 3 × 2 MW gas turbine units. Among them, gas turbine unit 1st is a low-carbon unit with high operation cost, and the operation parameters of gas turbine unit are shown in Table 1. In this paper, the historical output data of wind power stations in a southern region for half a year are selected as wind power output samples, and the sampling interval is 1H. The parameters of each unit are given in Appendix Table A1, and the carbon quota is determined by the method in Sect. 2.1 of this paper. The typical daily load curve is shown in Fig. 3.

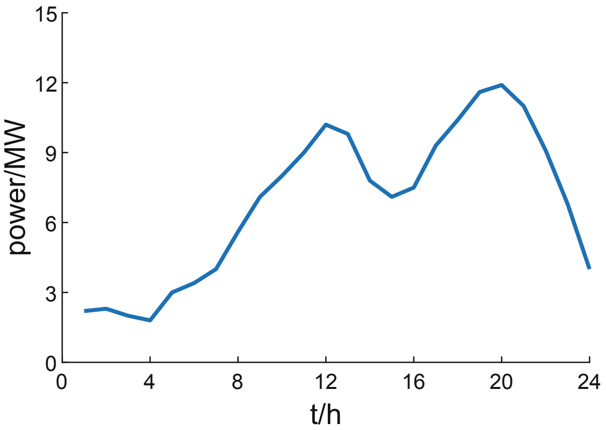


Fig. 3. Typical daily load curve

Table 1. Parameters of gas turbines

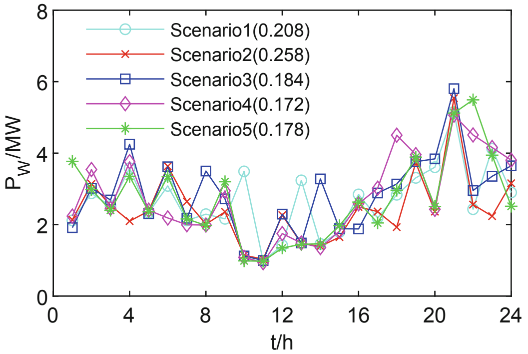
Gas turbine	a^f /yuan	b^f /(yuan·MW^{-2})	c^f /(yuan·MW^{-1})	CO_2 emission intensity/[kg·(MW·h)$^{-1}$]
1	30.0	70.21	1.2	560
2	20.0	68.80	1.0	960
3	20.0	68.80	1.0	960

4.2 Scenarios Generation Results Considering Scenery Uncertainty

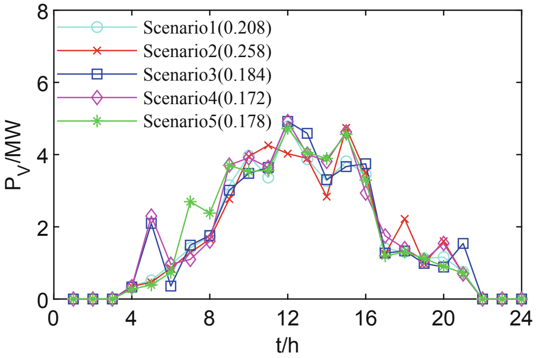
Using the scene generation method proposed in Sect. 2.2 of this paper, the selected scenery output data makes an appropriate compromise between reducing the amount of calculation and retaining the output characteristics, and the number of scenes in the scene reduction is 5. The output curve of each scenario and the corresponding probability information are shown in Fig. 3. The wind and photovoltaic output conditions meet the unit output constraints. Applying the scene generation results to the day-ahead scheduling model can better reflect the uncertainty of the wind output and make the model more reliable.

4.3 Comparison Scheme Construction and Scheduling Analysis

In order to compare, measure and analyze the impact of the introduction of carbon rights trading market and different capacity energy storage on the operation cost of VPP, scheme 2 and scheme 3 are set as comparison schemes, as shown in Table 2.



(a) Wind power output scenario generation results



(b) Photovoltaic output scenario generation results

Fig. 4. Scenarios generation results

Table 2. Three different compositions of VPP.

Scheme	Carbon trading market	Energy storage capacity/MW
1	√	12
2	×	12
3	√	6

The Sect. 4.2 wind turbine and photovoltaic output scenarios are one-to-one substituted into the 4.1 section of the example description. Based on the weighted weighting of their respective probabilities, the optimization results satisfying the constraints are obtained. According to the three schemes, the comparison of the benefit and partial cost results and the dispatch results are obtained as shown in Tables 3 and 4, respectively.

Table 3. Comparison of profit and cost result.

Scheme	Carbon trading income/10^2¥	Wind and solar power casting cost/10^2¥	System maintenance cost/10^2¥	Total system cost/10^2¥
1	2.219	0	354.625	616.207
2	–6.132	0	354.625	625.856
3	–17.176	60.181	291.463	685.094

Table 4. Comparison of scheduling results.

Scheme	Output of 1 gas turbine/MW	Carbon emissions/t	Energy market electricity purchase/MW	Amount of abandoned wind and solar/MW
1	16.714	29.416	1.500	0
2	11.206	31.613	1.500	0
3	18.109	34.528	1.589	5.471

Compared with scheme 2, scheme 1 realizes the VPP framework for the coordinated operation of gas units and wind power storage under the environment of carbon rights trading. It can be seen from Table 3 that due to the consideration of carbon emission cost, the dispatched output of gas turbine 1 with low carbon emission intensity per unit power is higher. In a scheduling cycle, scheme 1 reduces carbon emissions by 2.197t compared with scheme 2, so it also obtains positive benefits from the carbon trading market. However, the need to purchase carbon emission rights in scheme 2 increases the cost of VPP, which reduces the total cost of scheme 1 by 835.1 ¥ compared with scheme 2, so that the overall benefits and environmental protection characteristics of scheme 1 VPP are better.

Compared with scheme 3, scheme 1 uses a higher capacity energy storage device, which increases the investment cost and operation and maintenance cost of scheme 1, but sufficient energy storage capacity realizes the flexible allocation of power resources in the VPP, so that the photovoltaic output of clean energy fans in the VPP is fully absorbed. Due to the insufficient energy storage capacity of scheme 3, it is impossible to store all the wind and light output in the low load period, resulting in the phenomenon of abandoning wind and light. In addition, the electric energy provided by wind and light storage is limited in the peak load period, so VPP has to call more gas turbine output, which increases the carbon emission of scheme 3 by 5.112t and the cost by 59.89×10^2 ¥ compared with scheme 1, resulting in the poor benefit and environmental protection of VPP with insufficient energy storage capacity of scheme 3. It is worth noting that in schemes 1 and 2, the wind and light abandonment is 0, so it is meaningless to continue to increase the energy storage capacity, which will only increase the system investment cost and operation and maintenance cost, and damage the economy of VPP.

To sum up, scheme 1 of the VPP model proposed in this paper introduces the carbon rights trading environment, configures the electric energy storage with appropriate capacity, and cooperatively optimizes the scheduling with gas turbine and wind power photovoltaic, which can reduce the net cost and carbon emission of VPP, promote the consumption of clean energy and suppress the impact of load fluctuation, making VPP both economic and environmental.

4.4 Analysis of VPP Optimal Scheduling Results

According to the example simulation of the proposed model, the output and power purchase of each unit in scheme 1vpp are shown in Fig. 5, and the storage, discharge and energy storage of energy storage device are shown in Fig. 6.

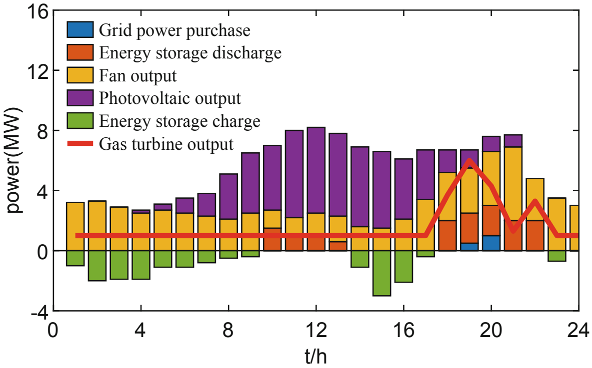


Fig. 5. Optimized scheduling results of VPP

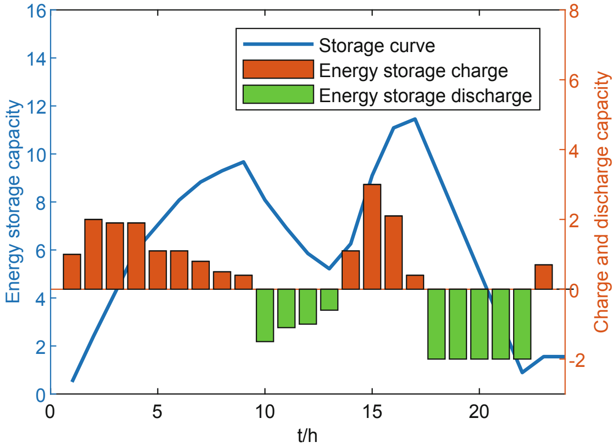


Fig. 6. Storage/discharge power and energy storage power level of energy storage device

It can be seen from Fig. 5 and Fig. 6 that during the period from 1 to 5, there is almost no output of photovoltaic at this time, the output of wind power is large and the load demand is small. At this time, the output of gas turbine does not change with the load, and the load demand can be met as long as it is kept near the minimum output power. After the wind power meets the load demand, the surplus is stored by the energy storage device, and the electric energy in the electric energy storage is increased. If there is no energy storage device in the VPP, the abandoned wind is mainly concentrated in this period.

During the 6–9 period, the load demand began to increase. Although the wind power output decreased slightly, the photovoltaic output began to show an upward trend, and the clean energy output can still meet the load demand. The electric energy storage continues to be charged, and the charging amount per unit time is lower than before. If there is no energy storage device in VPP, the light rejection is mainly concentrated in this period.

During the period of 10–13, the fan output generally shows a decreasing trend. The photovoltaic output reaches the output peak at noon, while the load demand increases rapidly, and the load curve has the first peak. VPP needs to call more gas turbine output to achieve electric energy balance. However, since this paper takes into account the economic and environmental protection VPP of carbon rights trading, the output of gas turbine should be reduced as much as possible, At this time, the energy storage discharge is used to make up for the insufficient output of the distributed generation.

During the period from 14 to 17, the photovoltaic output remains at a high level. At this time, the load demand drops, the electric energy storage is charged, and the electric energy in the energy storage is increased to the maximum capacity.

During the period of 18–21, the power load demand reaches the second peak and reaches the maximum load demand. The wind power output increases slightly and the photovoltaic output gradually decreases to zero. At this time, the stored energy is used to output electric energy at the maximum power. As there is still a power gap, VPP adopts the way of increasing the output of gas turbine and purchasing power from the power grid to meet the load demand. The carbon emission of VPP is mainly concentrated in this period.

During the period of 22–24, the load demand decreases significantly, the wind power output continues to increase, the photovoltaic output stops, the gas turbine output returns to the minimum output state, and the energy storage returns to the initial state of dispatching after one dispatching cycle, so as to prepare for the next round of dispatching.

To sum up, based on the optimal dispatching model and method of virtual power plant with carbon rights trading considering the coordination of distributed generation and energy storage proposed in this paper, the flexible coordinated dispatching and complementarity of power resources can be realized. Taking into account the uncertainty of scenery, this paper uses the classical scenario construction method to enhance the reliability of the model, and then combined with the energy storage resources with appropriate capacity, transfers the period of high power generation and low power load of distributed clean energy to the period of low power generation and high power load of distributed clean energy, so as to achieve the supply-demand balance between source loads and complete the full consumption of distributed clean energy. At the same time, in the carbon trading environment, during the energy storage and discharge period, the output of the gas turbine and the power purchase of the power grid are reduced, the non environmental phenomenon that the gas turbine is consistent with the load change trend in order to quickly respond to the wind and rain fluctuation under the traditional regulation measures is avoided, and the final dispatching structure of the established model takes into account the economy and environmental protection, which further proves the effectiveness and rationality of the model established in this paper.

5 Conclusion

In the environment of introducing carbon rights trading, considering the uncertainty of scenery, this paper establishes a virtual power plant model with energy storage and multiple distributed generators, studies its scheduling strategy, and draws the following conclusions.

(1) By considering the scene generation method of uncertain output of scenery, the characteristics of scenery output of original data are strengthened, the impact of fluctuation of scenery output on the rationality and reliability of the model is effectively reduced, and the model effect verified by an example is highlighted.
(2) By introducing the carbon trading environment, VPP can be encouraged to configure energy storage devices, so as to improve the solar energy consumption capacity, alleviate the contradiction between the output of distributed generation and the demand of electric load, and improve the regulation ability of VPP in response to the change of output of distributed generation. Under the influence of carbon emission cost in the carbon trading environment, VPP improves the output level of low-carbon units, reduces the total carbon emission, and sells excess carbon rights to improve income, reduce cost, and improve the economy and environmental protection of VPP.

There are many directions and contents of collaborative multi resource optimal scheduling in VPP, which are worthy of further research. In the following research work, we will select the scenery data with longer historical period for scene generation, and study the selection method of the optimal energy storage capacity. At the same time, the composition of the comprehensive evaluation index system for the regulation results of VPP in the carbon trading environment is also the focus of further research.

Acknowledgments. This work was financially supported by the project of "Research on adjustable Internet resources and Application Technology" of NARI-TECH Control Systems Ltd. (No. 524609220029).

Appendix A

Table A1. VPP unit parameters

$C_{capital}$ /yuan·MW^{-1}	c_{ES} /(yuan/(MW·h))	λ_1 /(yuan/(MW·h))	λ_2 /(yuan/(MW·h))	$P^{G,\min}$ /MW
1000	40	80	65	0.3

$P^{G,\max}$ /MW	ΔP^{G} /MW	σ^{ES}	η^{ESC}	η^{ESD}
2	1	0.001	0.95	0.95

$P^{ESC,\max}$ /MW	$P^{ESD,\max}$ /MW	$S^{ES,\max}$ /MW	$S^{ES,\min}$ /MW	S_0^{ES} /MW
3	2	12	0.5	0.5

$P^{ESC,\max}$ /MW	$P^{ESD,\max}$ /MW	$S^{ES,\max}$ /MW	$S^{ES,\min}$ /MW	S_0^{ES} /MW
3	2	12	0.5	0.5

k^{C} /yuan·kW^{-1}	γ^{C} / kg·kW^{-1}			
0.38	1.1			

References

1. Lu, S.F., Wu, Y,S., Lou, S.T.: A model for optimizing spinning reserve requirement of power system under low-carbon economy. IEEE Trans. Sustainable Energy **5**(4),1048–1055 (2014)
2. Zhinong Wei, F., Shuang, Yu,S., Guoqiang Sun, T.: Concept and development of virtual power plant. Autom. Electric Power Syst. **37**(13), 1–9 (2013)
3. Tianwang Wang, F., Yun Gao, S., Meng Jiang, T.: Power system optimal scheduling including distributed wind power and energy storage system via virtual power plant. Electric Power Constr. **37**(11), 108–114 (2016)
4. Suhua Lou, F., Bin Hu, S., Yaowu Wu, T.: Optimal dispatch of power system interated with large scale photovoltaic generation under carbon trading environment. Autom. Electric Power Syst. **38**(17), 91–97 (2014)
5. Xiaohua Zhang, F., Jun Xie, S., Jinquan Zhao, T.: Energy-saving emission reduction dispatching of electrical power system considering uncertainty of load with wind power and plug-in hybrid electric vehicles. High Voltage Eng. **41**(7), 2408–2414 (2015)
6. Zuoyu Liu, F., Feng Qi, S., Fushuan Wen, T.: Economic and environmental dispatching in electric vehicles embedded virtual power plants with participation in carbon trading. Electric Power Constr. **38**(9), 45–52 (2017)
7. Fulu Xu, F., Renjun Zhou, S., Junbo Cao, T.: Coordinated optimal dispatching of power-heat-gas for virtual power plant participating in multiple markets. Proc. CSU-EPSA **31**(9), 35–42 (2019)

8. Honghai Kuang, F.: Improvement research on transient stability and power quality of distributed wind power integrated system. Hunan University, Changsha (2013)
9. Shilong Wang, F., Shuangshang Song, S., Qinghua Lin, T.: Virtual power plant optimal scheduling considering distributed energy storage. Renewable Energy Resources **37**(8), 1214–1219 (2019)
10. Jiajia Xu, F.: Study on distributed generation dispatching management mode base on virtual power plant. Beijing: North China Electric Power University (2013)
11. Yanfeng Ma, F., Zhenya Fan, S., Weidong Liu, T.: Environmental and economic dispatch considering carbon trading credit and randomicity of wind power and load forecast error. Power Syst. Technol. **40**(2), 412–418 (2016)
12. Lu, Z,F., Lu, C,S., Feng,T.: Carbon dioxide capture and storage planning considering emission trading system for a generation corporation under the emission reduction policy in China. IET Generation, Transmission & Distribution **9**(1), 43–52 (2015)
13. Department of Ecological Environment. Implementation Plan for Setting and Allocating the Total Quota of National Carbon Emission Rights Trading in 2020 (2020–12–30)
14. Wu, L,F., Monhammad, S., Li, T.: Stochastic constrainedunit commitment. IEEE Trans. Power Syst. **22**(2), 800–811 (2007)
15. Guili Yuan, F., Shaoliang Chen, S., linbo Wang, T.: Economic optimal dispatch of virtual power plant considering environmental benefits. Adv. New Renewable Energy **3**(5), 398–404 (2015)
16. Gang Chen, F., Yuqing Bao, S., Jinlong Zhang, T.: Distributed cooperative control strategy of energy storage unit with life loss cost. Power Syst. Technol. **42**(5), 1495–1501 (2018)