Low-carbon Comprehensive Benefits Analysis Of Joint Operation Of Wind Power And Pumped Storage Station

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Abstract. Large-scale wind power integration is limited by power grid acceptance capacity, which can be solved effectively by the joint operation of wind power and pumped storage station. In order to evaluate the low-carbon comprehensive benefits of their joint operation, this paper analyzes the influence factors of the low-carbon comprehensive benefits, then the mathematical model of low-carbon comprehensive benefits of wind power-pumped storage power generation system is established, which analyzes the influence factors such as low-carbon, economic costs and gains. Finally, the validity of the model is verified by an example, and the results show that the low-carbon comprehensive benefits of wind power-pumped storage power generation system are very impressive.

1. Introduction
As a renewable energy source, wind power plays an increasingly important role in the power grid. But wind power has great volatility and large-scale wind power integration is limited by power grid acceptance capacity. Pumped storage power station has a good function of peak shaving and valley filling, so the combined operation of wind power and pumped storage station can improve the wind power generation, and effectively suppress the influence of wind power fluctuations.

In view of analysis of low-carbon comprehensive benefits for wind power-pumped storage power generation system, a lot of research work has been done by scholars at home and abroad. In the literature [1-2], the low-carbon and economic benefits of wind power are analyzed from costs and gains respectively. In the literature [3-9], the low-carbon and economic benefits of pumped-storage power station are analyzed. In the literature [10-13], a variety of optimization models of the joint operation of wind power and pumped storage station from different target optimization perspectives are proposed. In the literature [11], the optimal scheduling model of the joint operation of wind power and pumped storage station is proposed based on costs-benefits analysis. In the literature [12], a comprehensive benefit evaluation method for wind power-pumped storage power generation system is proposed, but the model does not calculate its low-carbon efficiency.

To accurately evaluate the low-carbon comprehensive benefits of the joint operation of wind power and pumped storage station, this paper analyzes the influence factors of the low-carbon comprehensive benefits, and establishes its low-carbon comprehensive benefits analysis and evaluation model, which is verified by the example. The calculation results demonstrate the effectiveness of the proposed model.
2. Analysis of Influencing Factors of Low-carbon Comprehensive Benefit
The influence factors to low-carbon comprehensive benefits of wind power-pumped storage power generation system mainly include economic costs, economic gains, carbon emission costs, and carbon gains.

2.1. Economic costs
Economic costs consist of wind power and pumped storage station costs, wind power costs mainly include initial investment costs and maintenance costs. The costs of pumped-storage power station are mainly composed of initial investment costs, pumping costs, units start-up and shut-down costs, maintenance costs.

2.2. Economy gains
Wind power can greatly reduce the output of thermal power units and save a lot of coal. Wind farms obtain economic gains through electricity sales. Pumped-storage units can pump and store energy at the low load in power system while generate electricity at the peak load, then the income of pumped storage power station is obtained from the price difference of peak and valley electricity. In addition, the combined operation of wind power and pumped storage station can effectively reduce wind power curtailment, and increase wind power generation and sale profit, and save coal at the same time.

2.3. Carbon emission costs
There is no fuel consumption in the process of wind power generation. Meanwhile, carbon emissions are generated at the stage of wind turbine manufacturing, transportation and wind farm construction. Pumped storage power station generates carbon emissions during construction, besides, the pumped storage units also produce carbon emissions when they are pumping water and storing energy at the low load in power system.

2.4. Carbon gains
Wind power can replace part of thermal power and reduce coal consumption. Pumped-storage power station can utilize surplus electric to pump water and store energy in the valley load, and replace coal-fired generating units to generate electricity during peak load, which can improve the operating efficiency of coal-fired units and save coal effectively. Combined operation of wind power and pumped storage station can also greatly reduce the wind power curtailment and increase carbon benefits.

3. Model of low-carbon comprehensive benefit of wind power-pumped storage power generation system

3.1. Economic benefits of wind power-pumped storage power generation system

3.1.1. Economic costs. The economic costs of wind power mainly include the initial investment costs and annual maintenance costs. The annual economic costs of wind farm can be expressed as follows.

\[ C_{wlc} = \frac{1}{n_w} \sum_{n=1}^{n_w} [(I_n + C_{wm}) (1+i)^{-n}] \]

Where \( C_{wlc} \) is annual economic costs of wind farm, \( I_n \) is annual capital investment costs, \( n_w \) is the designed service life, \( C_{wm} \) is annual maintenance costs, \( i \) is the discount rate.

The economic costs of pumped storage power station mainly include initial investment costs \( C_{pis} \), units start-up/shut down costs \( C_{pqg} \) and maintenance costs \( C_{pm} \). The initial investment costs mainly include the construction of the pumped storage power station and the purchase of equipment. If the
designed service life of the pumped storage power station is set to be \( n_p \), the annual investment costs of the pumped storage power station are as follows.

\[
C^*_{pi} = \frac{C_{pi}}{n_p}
\]  

(2)

The start-up/shut down costs \( C_{pq} \) can be expressed as follows\(^{[5][6]}\).

\[
C_{pq} = C_q N_q + C_t N_t
\]  

(3)

Where the \( C_q \) and \( C_t \) are respectively the costs of pump units when start-up or shut down every time, \( N_q \) and \( N_t \) are respectively the times of start-up and shut-down.

The maintenance costs \( C_{pm} \) can be calculated according to a certain proportion of the initial investment costs\(^{[5]}\), which is as follows.

\[
C_{pm} = \alpha C^*_{pi}
\]  

(4)

Where the \( \alpha \) is ratio of the maintenance costs to the initial investment costs.

3.1.2. Economy gains. The economic benefits of wind power are mainly achieved through the sale of electricity. If annual energy production of wind power is \( G_w \), the wind-electricity price is \( P_w \), then economic benefits \( E_w \) can be indicated as follows.

\[
E_w = P_w G_w
\]  

(5)

The direct economic benefits of pumped storage station are the income from peak shaving and valley filling. Due to the use of peak-valley time-of-use price in power system, pumped storage station can benefit from the price difference between peak and low load. The economic benefits \( B_{ps} \) can be expressed as follows.

\[
B_{ps} = (P_p \cdot \eta - P_v) P_c
\]  

(6)

Where \( P_p \) and \( P_v \) are respectively the electricity price at the peak of the load and the low point. \( P_c \) is the installed capacity of pumped storage system. \( \eta \) is the charge-discharge efficiency of pumped storage power station, which is generally about 75%.

3.1.3. Economic benefits. Therefore, the annual economic benefits \( B_{wp} \) of wind power-pumped storage power generation system can be expressed as follow.

\[
B_{wp} = B_{ps} - C^*_{pi} - C_{pm} - C_{pq} + E_w - C_{wlc}
\]  

(7)

3.2. Low-carbon benefits of wind power-pumped storage power generation system

3.2.1. Carbon emission costs. The carbon emission costs of wind power are mainly composed of initial carbon investment costs and maintenance carbon costs. The initial carbon investment costs include the carbon emissions during the stage of wind turbine manufacturing, wind farm construction and wind turbine transportation. The maintenance carbon costs mainly produce carbon emissions through electricity consumption, so it can be calculated according to the carbon emissions per unit of electric energy, which can be indicated as follows.

\[
CEC_{ci} = m P_w e_w
\]  

(8)

In the formula, \( m \) means the coal consumption of unit electric energy, \( P_w \) means the installed capacity of the wind farm, \( e_w \) means the electric energy consumption per unit wind power.
During the stage of wind turbine transportation, carbon emissions $CEC_{c2}$ are mainly produced by fuel combustion, which can be expressed as follows.

$$CEC_{c2} = fWd$$  \hspace{1cm} (9)

Where $f$ means carbon emissions from transport per unit weight and per unit distance, $W$ means the weight of the wind turbine, $d$ means the wind turbine transport distance.

The initial investment carbon costs $CEC_{wi}$ may be expressed as follows.

$$CEC_{wi} = CEC_{ci} + CEC_{c2}$$  \hspace{1cm} (10)

In maintenance stage of wind power, the carbon emissions costs $CEC_{wm}$ can be calculated as follows.

$$CEC_{wm} = \beta CEC_{wi}$$  \hspace{1cm} (11)

Where $\beta$ means the ratio of carbon emissions costs in the maintenance stage to initial carbon investment costs of the wind power.

The carbon emissions costs of pumped storage station are mainly composed of initial carbon investment costs and maintenance carbon costs. The initial investment carbon costs $CEC_{pi}$ can be expressed as follows.

$$CEC_{pi} = mP_p e_p$$  \hspace{1cm} (12)

Where $P_p$ is the installed capacity of the pumped storage system, $e_p$ is the electric energy consumption per unit power.

In the maintenance stage, the carbon emissions costs $CEC_{pm}$ of pumped storage station, can be calculated as follows.

$$CEC_{pm} = \beta' CEC_{pi}$$  \hspace{1cm} (13)

Where $\beta'$ means the ratio of carbon emission costs in the maintenance stage to initial carbon investment costs of the pumped storage station.

3.2.2. Carbon gains. The wind power can replace traditional energy sources and save coal. If the annual power generation of wind farm is $G_w$, the carbon gains of wind power $CE_{w}$ under the same power generation capacity can be expressed as follows.

$$CE_{w} = mG_w$$  \hspace{1cm} (14)

Pumped storage station stores energy using the units with the lowest coal consumption when the load is low, and replaces the most coal-consumed units generating electricity at the peak of the load. Therefore, the carbon benefits $CE_{p}$ of pumped storage station are the difference between them, which can be expressed as follows$^{[6]}$.

$$CE_{p} = CL_i \cdot G_g - CL_g \cdot G_p$$  \hspace{1cm} (15)

Where $CE_{p}$ is the annual carbon gains of the pumped storage power station, $CL_i$ is carbon costs of coal-fired units per unit generating power, $CL_g$ is carbon costs of pumped-storage units per unit generating power, $G_g$ is the annual power generation, and $G_p$ is power consumption of pumping water.

3.2.3. Low-carbon benefits. In summary, the low-carbon benefits $CB_{wp}$ of wind power-pumped storage power station are as follows.
According to the carbon trading mechanism, low-carbon benefits $CB'_{wp}$ can be economized as follows.

$$CB'_{wp} = P_c \cdot CB_{wp}$$

Where $P_c$ is carbon trading price.

## 4. Example Analysis

This paper makes use of the model proposed to analyze a wind power-pumped storage power generation system. According to the typical daily operating data of the system\(^{[12]}\), the annual low-carbon comprehensive benefits are estimated. The total installed capacity of the wind power plant is 2320MW, and the pumped storage power station selects 4 reversible pump storage units with the capacity of 300MW, which is 1200MW in total. The grid load, wind power, planned thermal power curve and pumped storage power station's typical daily power curve are shown in Figure 1.

The annual maintenance costs of wind power account for about 2% of the total investment. The on-grid price of wind power is 580 yuan/MW h. The operating efficiency of pumped-storage power station is 75%, and the maximum number of start-up and shut-down times of the pumped storage units is 7 every day, the costs are calculated by 20 yuan/MW. According to peak-valley time-of-use price, the economic benefits of wind power-pumped storage power generation system can be obtained, which is shown in Table 1.

| Costs/Benefits | Economic costs | Economic benefits | Total |
|----------------|----------------|-------------------|-------|
| Money(billion yuan) | 29.37 | 52.45 | 23.08 |

Low-carbon benefit parameters are shown in Table 2, the coal consumption of the replacement units is 0.480 kg/(kWh), the coal consumption of the pumped-storage units is 0.27 kg/(kWh), so the low-carbon benefits are shown in Table 3. According to the carbon trading mechanism, the carbon trading price is 107.5 yuan/t, therefore the economic benefits of saving coal are 688 million yuan.

| Parameters | Value |
|------------|-------|
| $m$(kg/kWh) | 0.76 |
| $e_w$(kwh/kw) | 9.04 |
| $f$(kg/(t·km)) | 0.267 |
| $W$(t) | 1648 |
| $d$ (km) | 400 |
| $\beta$ | 5% |
| $e_p$(kwh/kw) | 17.32 |
In summary, the low-carbon comprehensive benefits of the example analyzed according to the model proposed in this paper are significant. The wind power-pumped storage power generation system can not only play a great role in peak shaving and valley filling, optimize the power structure of the system, but also save a lot of coals.

5. Conclusions
In this paper, the mathematical model of low-carbon comprehensive benefits of wind power-pumped storage power generation system is established, the economic benefits and low-carbon benefits of the wind power-pumped storage power generation system are analyzed. The results of the example show that there are great low-carbon comprehensive benefits for the wind power-pumped storage power generation system. The model proposed in this paper provides a way for the comprehensive benefit calculation of multi-energy joint operation. The calculation results have some reference significance for the low-carbon comprehensive benefit of the combined power generation system.

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