Optimized Capacity Allocation for a Hybrid Wind Turbine-Photovoltaic-Carbon Capture Coal-Fired Power Unit-Energy Storage System Considering Deep Peaking

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Abstract: With the rapid expansion of wind and photovoltaic energy production, coupled with stricter environmental regulations, traditional coal-fired power plants face the risk of obsolescence. Nonetheless, many coal-fired power units (CFPUs) remain economically viable and technically operational, with substantial service life remaining. To maximize the utility of these CFPUs during the energy transition, this study presents a hybrid system integrating wind turbine, photovoltaic, energy storage system, and carbon capture coal-fired power unit (CCPU). This system leverages modified carbon capture utilization and storage (CCUS) technology to improve the deep peaking capability of CCPU. By designing different scenarios, the case study shows that the deep peaking capability of CCPU can effectively improve the utilization of renewable energy, reduce the capacity demand of the energy storage system, and ultimately realize the reduction of system cost.

Keywords: Coal-fired power unit;Carbon capture utilization and storage;Energy storage; Deep peaking; Capacity optimization

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1.Introduction

As global technology advances, electricity consumption has significantly increased worldwide [1, 2]. Currently, fossil fuels remain the dominant source of electricity generation. However, the carbon dioxide produced by fossil fuels exacerbates the greenhouse effect and causes environmental pollution. Therefore, it is crucial to accelerate the transformation of the power system [3].

Increasing the installed capacity of renewable energy sources (RES) is essential for achieving deep decarbonization. Wind turbines (WT) and photovoltaic (PV) systems, key RES technologies, play a critical role in alleviating environmental pressures [4]. While renewable energy offers many advantages, its intermittent nature can lead to grid imbalances. Energy storage (ES) systems are vital for ensuring a stable power supply and enhancing system reliability but are limited in widespread application due to high costs [5].

Against the rise of WT and PV power generation and stricter environmental standards, many traditional coal-fired power units (CFPUs) face potential obsolescence [6]. However, most CFPUs remain economically and technically viable with considerable operational life left. Given the pressures of energy structure transformation, effectively integrating and optimizing these CFPUs to maximize their effectiveness in this transition is a critical issue [7].

In recent years, Carbon Capture Utilization and Storage (CCUS) technology has gained prominence as a carbon reduction strategy [8]. By retrofitting CFPUs with CCUS technology, not only can they significantly reduce carbon emissions during their operation, but they can also maintain their status as the main power supply to the grid and avoid the fate of being forced to be phased out due to carbon emission restrictions [9].

Therefore, with a view to further improving energy efficiency and promoting the energy transition, this paper discusses the reasonable size of the wind energy storage system based on the deep peaking of coal-fired units modified by CCUS technology.

2.Planning model of WPCE system

2.1.Objective function

An objective function has been formulated with the aim of minimizing the overall expenditure associated with WPCS, expressed as follows:

$$\min F = C_{WT,inv} + C_{PV,inv} + C_{BT,inv} + C_{T,inv} + C_{WT,om} + C_{PV,om} + C_{BT,om} + C(P_{i,t}^{g}) + C_F + C_w - B_{cp} - B_{dp} \#(1)$$

where $C_{WT,inv}$ is the total investment cost of WT; $C_{PV,inv}$ is the total investment cost of PV; $C_{BT,inv}$ is the total investment cost of BT; $C_{T,inv}$ is the total investment cost of CCUS; $C_{WT,om}$, $C_{PV,om}$ and $C_{BT,om}$ are the operation and maintenance (O&M) costs of WT, PV and BT; $C(P_{i,t}^{g})$ is the cost of i C_F is the transportation and storage (TS) cost of CCUS; C_w is the loss cost associated with solvents in CCUS processes; B_{cp} is the capacity price compensation benefit, B_{dp} is deep peak shaving compensation benefit.

2.2.Case description

The WPCE system constructed in this study consists of a WT power plant, a PV power plant, a battery energy storage system, and a CFPP containing a 1000 MW CCPU and a 600 MW CCPU. In order to verify the low carbon and economic performance of deep peaking of CCPUs, the following three scenarios are established for analysis:

Scenario 1: Only the ES peaking. In this scenario, we assume that the power system uses only ES for peaking.

Scenario 2: Peaking with ES and conventional peaking with CCPU. In this scenario, ES is considered for conventional peaking in conjunction with CCPU.

Scenario 3: Peaking with ES and deep peaking with CCPU. In this scenario, the operation strategies of ES and CCPU are further optimized to achieve deep peaking.

2.2.1.Results and analysis

In cases of Scenario 1, 2 and 3, the capacities of WT, PV, and ES are shown in Table 1.

Table 1 Three scenario results

Parameter	Value		
	Scenario 1	Scenario 2	Scenario 3
WT (MW)	7702.727	6059.502	6248.772
PV (MW)	7725.916	6285.113	6374.63
ES (MWh)	2765.535	2100.331	1794.127
Cost (billion CNY)	10.963	10.347	10.302
PCR (%)	7.013	0	0

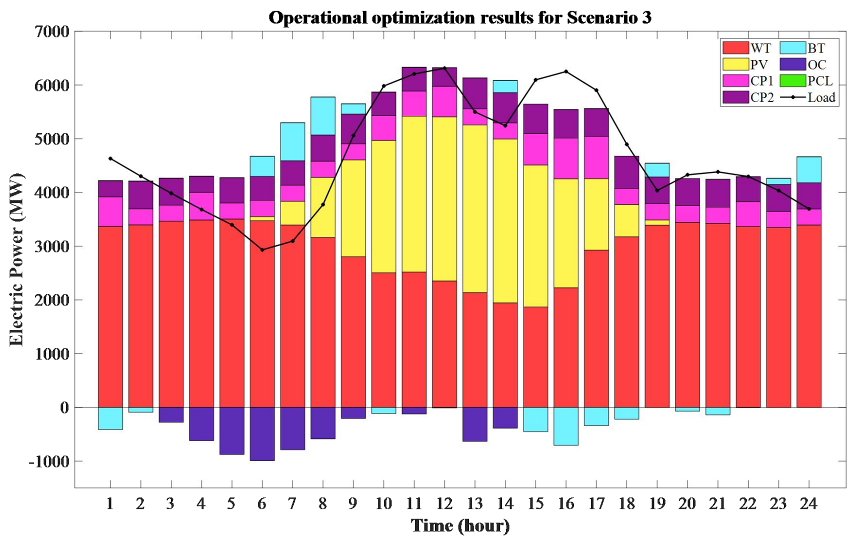

Fig. 1 shows the results of the operational optimization for Scenario 3.

Fig. 1. Operational optimization results for Scenario 3

In Scenario 3, a 1000 MW CCPU is considered for the deep peaking task. In this configuration, the calculated capacities of the WT, PV and ES are 6248.772 MW, 6374.630 MW and 1794.127 MWh, respectively. This data, compared to Scenario 2, shows an increase in the capacities of WT and PV by 189.270 MW and 89.517 MW, respectively. At the same time, the ES capacity decreases by 306.205 MWh.

This change is most likely due to the effective utilization of the deep peaking capability of CCPU in Scenario 3, which provides additional power regulation capability to the system. The deep peaking capability of CCPU means that it is able to further reduce the power output during periods of low power demand, which reduces the dependence on the ES and reduces the need for charging of the ES during the low hours. As a result, the capacity requirements of the ES are reduced, which is one of the reasons for the reduction in ES generation.

The total cost of Scenario 3 is 10.302 billion CNY, which is 44 million CNY lower than the total cost of Scenario 2. This cost reduction reflects the economic benefit of deep peaking capability of CCPUs. By reducing the reliance on ES, the operating cost of the system is optimized, and it also demonstrates that CCPUs are feasible for improving system performance and economics in power systems.

In summary, Scenario 3 demonstrates that by integrating the deep peaking capability of CCPUs. It is possible to improve the utilization efficiency of renewable energy, reduce the capacity demand of ES, and ultimately achieve cost reduction while maintaining system stability, which provides a strong technical support and economic justification for the sustainable development of the power system and accelerates the energy transition.

3.Conclusion

Based on the analysis results, this paper draws the following conclusions:

Renewable energy utilization efficiency can be significantly improved by optimizing the capacity of photovoltaic (PV) systems, wind turbines (WT) and energy storage (ES), and improving the deep peak shaving capabilities of combined cycle power units (CCPUs). This optimization can also reduce the total cost of wind-solar combined cycle energy systems (WPCE) and increase the proportion of renewable energy used.

The case study of the hybrid WT-PV-CCPU-ES system shows that utilizing the deep peaking capability of the CCPU can improve the efficiency of renewable energy utilization and increase the capacity of renewable energy generation.

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