Capacity Optimal Configuration of Wind-Hydrogen Low Carbon Energy System

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Abstract. Wind power is the most promising renewable energy source, and hydrogen energy is a clean energy carrier. The combination of the two will provide a feasible solution for achieving carbon neutrality. We combine natural gas and carbon capture systems with typical wind-hydrogen coupling systems to improve system economy, and hydrogen power generation is not considered. Oxygen-enriched combustion technology uses the oxygen obtained from hydrogen production to realize the coupling of natural gas and wind energy hydrogen production systems, which improves the efficiency of gas turbines and reduces energy consumption of carbon capture. Then, with the goal of minimizing the annualized cost including the cost of investment, maintenance, operation and wind curtailment penalty, and taking wind curtailment, carbon capture, gas storage, and power balance as constraints, construct a wind-hydrogen low carbon energy system optimal configuration model. Finally, based on CPLEX to simulate the energy supply system in a certain area, the optimal configuration plan of the system’s wind power, gas storage capacity, electrolytic cell.

Keywords: Wind-hydrogen coupled, scenario reduction, integrated energy, optimal configuration, low carbon.

1. Introduction

Low-carbon development modes with the goal of carbon neutrality have become a development trend of China to cope with climate change [1]. As the main source of carbon emissions, the power industry will become the key to achieving carbon neutrality [2]. Developing renewable energy vigorously to replace the fossil energy is one of the important ways to achieve carbon emission reduction in power generation technology [3]. The wind-hydrogen coupled system (WHCS) uses hydrogen energy as an energy carrier to promote wind power consumption, which has obvious low-carbon benefits [4]. Research on the WHCS framework and system planning and operation has become the current focus topic.

A typical WHCS includes three processes: hydrogen of wind power production, storage, and use [5]. From the perspective of hydrogen energy utilization, the WHCS can be divided into two forms: grid-connected system and off-grid system [6]. In [7], it uses the P2G and carbon capture technology to propose a dual-cycle structure of power grids, hydrogen energy storage system and natural gas network, in which, the carbon capture approach is to capture CO₂ directly from the atmosphere, and
consumes huge energy and high investment costs. Ref. [8] introduces oxygen-enriched combustion (OEC) technology into the integrated energy system to improve the above problems, however, the cost of the air separation oxygen plant (ASU) is high, which is not conducive to achieving optimal economic efficiency. The byproduct of wind power hydrogen production, O₂ and its storage tank can replace ASU. In addition, compared with grid-connected wind power systems, the structure of wind turbines in non-grid-connected wind power systems has been improved, and the efficiency of wind energy utilization has significantly improved, furthermore, greatly reducing wind power costs [4]. Therefore, based on the existing technology and structure, integrate carbon capture and OEC technology, we propose a wind-hydrogen low carbon energy system (WHLCES) with electricity, hydrogen, and natural gas as the main energy flow, which realizes the comprehensive utilization of low carbon and energy. Fuel cells are eliminated from the WHCS due to their high cost and low utilization rate [9].

The WHCS contains a variety of energies and has a complex structure. In order to ensure reliable energy supply and maximize benefits, it needs to be optimally configured. In [10], the weather forecast data is used to improve the accuracy of the optimal configuration of the WHCS to overcome the volatility and intermittency of the renewable energy. Ref. [11] uses one day's wind speed and load data in a certain, comprehensively considering the economy and power supply reliability, and optimizes the system equipment capacity. Ref. [12] proposed an off-grid wind-hydrogen coupled hydrogen supply system using hydrogen and battery hybrid energy storage technology, and optimized the system. Ref. [13] proposes a mathematical model of equipment investment planning for wind-hydrogen coupling systems. The goal is to minimize one-time equipment investment, and the constraints are full consumption of wind power and stable operation of the system. Ref. [14] aims at maximizing the overall benefits of the system, considering wind power consumption and equipment operation economy. However, none of the above studies considered oxygen storage and oxygen utilization. In addition, in terms of optimal configuration, there is a lack of research on the combination of carbon capture systems and wind-hydrogen coupling systems.

In response to the above problems, based on the WHLCES structure and combined with the output models of the various equipment of the system, a system optimization configuration model was established. The goal is to minimize the annual cost. We can obtain capacities of wind power, hydrogen storage, oxygen storage and electrolyzer, and power of gas turbine through the proposed method. Finally, an example is used to verify the effectiveness of the OEC technology in improving the economic benefits of the WHLCES.

2. Wind-hydrogen low-carbon energy system
This section first introduces the structure and energy flow of WHLCES, and then proposes the output model of each device in WHLCES.

2.1. The structure of WHLCES
The overall physical structure of the WHLCES is shown in Fig. 1.
The wind farm and the gas turbine together supply power for the electrolysis hydrogen production equipment, electric load and carbon capture process. The electrolyzer converts electric energy into hydrogen energy to supply hydrogen load, and the by-product oxygen is supplied to the gas turbine. The gas turbine uses OEC technology to generate electricity. Finally, excess hydrogen and oxygen are stored in gas storage tanks, and oxygen can also be sold on the market. The hydrogen storage equipment is to ensure the stability of hydrogen supply. The high-concentration CO₂ emitted by gas turbines is recovered and sold to the market after storage and transportation. The gas turbine is responsible for providing fuel to the gas turbine.

2.2. Equipment output model

2.2.1. Wind farm. Wind power output can be calculated by the product of installed capacity and output coefficient, expressed as

\[ P^w = \mu^w \cdot P^w_r \] (1)

where \( P^w \) denotes the wind power output; \( \mu^w \) denotes the wind power output coefficient, which represents the proportion of the wind power output to the rated power; \( P^w_r \) denotes the wind power rated power.

2.2.2. Electrolyzer. We assume that the electrolytic cell is insulated and the conversion efficiency of the electrolytic cell remains constant during its operation.

Since the heat energy of the water consumed by the electrolytic cell is much less than the electricity consumed by the electrolysis, and the heat energy required for the reaction can be provided by the heat generated by itself [15], the heat energy required by the electrolytic cell is ignored in this article. The output of the electrolytic cell can be obtained by

\[ r^{ez} = \eta^{ez} \cdot P^{ez} \] (2)

where \( r^{ez} \) indicates the rate of hydrogen production in the electrolytic cell; \( P^{ez} \) indicates the input electric power of the electrolytic cell; \( \eta^{ez} \) represents the conversion coefficient between the electric power and the hydrogen flow rate.

2.2.3. Carbon capture. In this paper, the carbon capture method adopts the carbon capture and membrane separation technology after OEC, which can reduce the energy consumption by 35% compared with the ordinary OEC capture process [16]. Carbon capture energy consumption is described as

\[ P^c = \eta_c \cdot r^{c_{CO2}} \cdot P^{ele} \] (3)

where \( P^c \) denotes the electrical energy required to capture a unit volume of CO₂; \( \eta_c \) denotes the carbon capture rate, generally ranging from 90% to 95%; \( r^{c_{CO2}} \) represents the CO₂ flowing into the carbon capture equipment.

2.2.4. Gas turbine. The relationship between gas turbine power generation and natural gas consumption is calculated as

\[ r^{gt} = \frac{\alpha \cdot P^{gt}}{\eta_{gt} \cdot Q_{gas}} \] (4)

where \( r^{gt} \) (m³/t) represents the flow of natural gas consumed by the gas turbine; \( Q_{gas} \) (kJ/m³) is the calorific value of natural gas combustion; \( \alpha \) indicates the conversion coefficient between kilowatts and kilojoules, which is 3600; \( P^{gt} \) (kW) indicates the power generation power of the gas turbine; \( \eta_{gt} \) indicates the power generation efficiency of the gas turbine.

3. System Optimization Configuration

In this section, we propose a WHLCES capacity optimization configuration model.
3.1. Objective of the Model

For WHLCES, the optimization goal is to minimize the annualized cost, including investment, maintenance, operating costs and wind curtailment costs, which can be expressed as

$$\min C_p = C_1 + C_2 + C_3 + C_4$$  \hspace{1cm} (5)

where

$$C_1 = \sum_{i=1}^{I} c_{i,\text{inv}} \cdot c_i \cdot \frac{r \cdot (1+r)^Y}{(1+r)^Y - 1}$$

$$C_2 = \lambda \sum_{i=1}^{I} c_{i,\text{inv}} \cdot c_i$$

$$C_3 = \sum_{i=1}^{S} \sum_{t=1}^{T} [c_{\text{gas}}(t) + (c_a + c_i) \cdot c_{\text{CO}_2}(t)]$$

$$C_4 = \sum_{i=1}^{S} \sum_{t=1}^{T} c_{\text{wind}}(t)$$

where $C_1$ denotes the annualized investment cost of system equipment; $I$ denotes the number of equipment types in the system, including gas turbines, fans, proton exchange membrane electrolyzers, and hydrogen/oxygen storage tanks; $c_{i,\text{inv}}$ represents the capacity of the $i$-th equipment; $c_i$ denotes the unit capacity price of the equipment; $r$ indicates the discount rate, which is 10%; the cycle $T$ is 24h; $Y$ indicates the equipment operation cycle, which is set to 20 years in this article; $C_2$ represents the system maintenance cost, and $\lambda$ is the maintenance cost coefficient, which is 0.05; $C_3$ represents the annual operating cost, which mainly includes the cost of purchasing natural gas, carbon storage and transportation; $S$ denotes the number of wind power-load time series scenarios; $c_{\text{gas}}, c_s,$ and $c_t$ are the prices of natural gas, carbon storage and transportation, respectively; $c_{\text{gas}}$ and $c_{\text{CO}_2}$ are natural gas consumption and carbon emissions; $C_4$ represents the penalty cost of wind curtailment; $c_{\text{wind}}$ denotes the amount of wind curtailment.

3.2. Constraints

The constraints of the optimal configuration model of the WHCS proposed in this paper mainly include the following parts.

3.2.1. Power balance constraint.

$$P^w(t) + P_{\text{rich}}^\text{rich}(t) + P_{\text{am}}^\text{am}(t) - P_{\text{ab}}^w(t) = P_{\text{hs}}^\text{hs}(t) + L_h^b(t) + L_{\text{ele}}^c(t) + P_{\text{rich}}^\text{rich}(t) + P_{\text{am}}^\text{am}(t)$$  \hspace{1cm} (7)

3.2.2. Hydrogen production constraints.

$$P_{\text{hs}}^\text{hs}(t) + L_h^b(t) \geq 0$$  \hspace{1cm} (8)

3.2.3. Constraints on the upper and lower limits of output.

$$0 \leq P^w(t) \leq P^w_{\text{rich}}$$

$$0 \leq P^w(t) \leq P^w_{\text{ab}}$$  \hspace{1cm} (9)

$$0 \leq P_t^\text{gb} \leq P_t^\text{gb}$$

3.2.4. Wind curtailment constraints.

$$P_{\text{ab}}^w(t) = \delta(t) \cdot P^w(t)$$

$$0 \leq \delta(t) \leq 1$$  \hspace{1cm} (11)

where $P_{\text{rich}}, P_{\text{am}}, P_{\text{hs}}, L_h, L_{\text{ele}}$ denote the power of gas turbines under OEC and air combustion conditions, hydrogen storage, hydrogen load, and electric load; $P_{\text{rich}}^\text{rich}$ and $P_{\text{am}}^\text{am}$ represent the energy consumption of carbon capture under the conditions of OEC and air combustion in a gas turbine; $P^w_{\text{rich}}$ denotes the rated power of the gas turbine; $P_{\text{ab}}^w$ denotes the abandonment air volume; and $\delta$ represents the abandonment coefficient.
3.2.5. SOC constraints of gas storage equipment

\[ S(t) = S(t-1) + \frac{r^s_i(t-1)}{r^s_{cap,i}} \]  
(13)

\[ r^s_i(t) = r^{ez}_i(t) - r^{load}_i(t) \]  
(14)

\[ r^s_2(t) = c_{in}(t) \cdot r^s_i(t) \cdot c_{out}(t) \cdot r^s_{out}(t) \]  
(15)

\[ 0 \leq c_{in}(t) \leq 1 \]  
(16)

\[ 0 \leq c_{out}(t) \leq 1 \]  
(17)

\[ S_{min} \leq S_i \leq S_{max} \]  
(18)

\[ \sum_{i=1}^{2} r^s_i(t) = 0 \]  
(19)

where \( S \) indicates the SOC value of the hydrogen storage device; \( r^s_i \) indicates the inlet flow rate of the hydrogen storage device, where \( \{i=1,2\} \) represents hydrogen and oxygen respectively; \( r^s_{cap,i} \) indicates the gas storage capacity; \( r^{load} \) is the hydrogen load flow; \( r^s_{in} \) and \( r^s_{out} \) denote the maximum oxygen flow in and out of the tank respectively; \( c_{in} \) and \( c_{out} \) denote the oxygen flow coefficients in and out of the tank respectively; \( S_{min} \) and \( S_{max} \) indicate the minimum and maximum values of the SOC of the hydrogen storage equipment, respectively.

3.2.6. Carbon capture constraints

\[ P^c(t) = E^c_{rich} \cdot r^c_{rich}(t) + E^c_{atm} \cdot r^c_{atm}(t) \]  
(20)

\[ r^{ct}_{cO\text{2}}(t) = r^{ct}_{rich}(t) \cdot \eta_{cO\text{2}} - r^{ct}_{atm}(t) \cdot \eta_{cO\text{2}} \]  
(21)

\[ 0 \leq r^{c}_{rich}(t) \leq r^{ct}_{rich}(t) \]  
(22)

\[ 0 \leq r^{c}_{atm}(t) \leq r^{ct}_{atm}(t) \]  
(23)

\[ \sum_{i=1}^{S} \sum_{t=1}^{T} r^{ct}_{cO\text{2}}(t) / \sum_{i=1}^{S} \sum_{t=1}^{T} (r^{ct}_{rich}(t) + r^{ct}_{atm}(t)) \leq \mu_{max} \]  
(24)

where \( E^c_{rich} \) and \( E^c_{atm} \) denote the energy consumption per cubic meter of carbon capture under the conditions of gas turbine OEC and air combustion, respectively; \( r^{ct}_{rich} \) and \( r^{ct}_{atm} \) denote the emissions emitted under the conditions of gas turbine OEC and air combustion, respectively CO\text{2}; \( r^c_{rich} \) and \( r^c_{atm} \) denote the amount of CO\text{2} flowing into the trap under the conditions of gas turbine OEC and air combustion respectively; \( r^c_{cO\text{2}} \) represents the actual carbon emission of the gas turbine; \( \mu_{max} \) indicates the carbon emission rate, which represents the maximum proportion of carbon emission.

4. Example Analyses

In this section, we verify the effectiveness of OEC technology in improving the economic benefits of WHLCES through examples, and study the sensitivity of the system.

4.1. Optimization results and analyses

Take the annual wind power output and power load data of a certain area in 2019 as a sample, and the data interval is 1h. Then, standardize the wind power data [17], as shown in Fig 2. On this basis, add hydrogen load data. Taking hydrogen used in coal chemical industry as an example, the hydrogen energy demand is a stable hydrogen flow with a value of 1000 m\text{3}/h. After that, the system equipment capacity is optimized by combining the above-mentioned wind power load sequence scenarios and the system optimization configuration model.
Figure 2. Annual wind power load data of a certain region in 2019.

In order to illustrate the effect of OEC on the WHLCES, this paper compares and analyzes the results of system optimization configuration under the conditions of ordinary air combustion and OEC. The configuration results are shown in Table 1. It can be seen that compared with ordinary air combustion, the use of OEC technology can reduce the total cost of the system by ¥ 8.8 million, a reduction of 12.2%. Among them, the operating cost has undergone major changes, a decrease of 5.4 million yuan, a decrease of 15.3%. The investment cost has also been reduced a lot, but due to the addition of oxygen storage equipment, additional investment costs have been increased. The overall reduction is only ¥ 1.251 million, a decrease of 4.9%. The wind curtailment rate was reduced by 2%. While improving the economy of the system, the phenomenon of wind curtailment is reduced.

Table 1. Optimal Configuration Results of Wind and Hydrogen Low-Carbon Energy System.

| Configuration variable                  | Configuration result       |
|----------------------------------------|---------------------------|
|                                        | Air burning               | Oxygen-enriched combustion |
| Wind power capacity (MW)               | 24.7                      | 22.7                        |
| Hydrogen storage capacity (m³)         | 11976                     | 8984.4                      |
| Gas turbine power (MW)                 | 16.8                      | 15.1                        |
| Power of electrolyzer (MW)             | 9.3                       | 8.3                         |
| Oxygen storage capacity (m³)           | /                         | 8985.9                      |
| Investment and maintenance costs (¥ 10, 000) | 3256.6                | 2986.3                      |
| Operating costs (¥ 10, 000)            | 3558.5                    | 3013.9                      |
| Wind abandonment penalty (¥ 10, 000)   | 405                       | 338.3                       |
| total cost (¥ 10, 000)                 | 7220                      | 6338.5                      |
| Wind curtailment rate                  | 19.1%                     | 17.3%                       |

4.2. Analysis of the impact of natural gas prices on the allocation results

In the above-mentioned WHLCES, the carbon emission rate is related to the cost of system. The smaller the carbon emission rate, the greater the energy consumption of carbon capture, the greater the capacity of the energy supply equipment, the greater the natural gas consumption, and the higher the system investment and operating costs. Study carbon emission rate constraints on the system the impact of optimize configuration results. The control carbon emission rate varies from 10% to 100% (in steps of 5%), and the annualized cost and wind curtailment rate changes are shown in Fig 3.
Figure 3. Analysis of the impact of carbon emission rate constraint on allocation results.

It can be seen from Fig. 3 that as the carbon emission rate increases, the total annualized cost gradually decreases, and the wind curtailment rate gradually decreases. This is due to the reduction in energy consumption for carbon processing and capacity of installed wind power, making wind power more easily absorbed by the hydrogen storage system and reducing wind abandonment. When the carbon emission rate is between 10% and 70%, capacity of installed wind power and power of gas turbine will be reduced, the cost of hydrogen and oxygen storage will be reduced, the consumption of natural gas will be reduced, the investment cost will be reduced, however, the operating cost will remain basically unchanged. When the carbon emission rate is between 70%-100%, the oxygen storage tank capacity is reduced to 0. Wind power is basically absorbed by the hydrogen load, electricity load and hydrogen storage system. The wind abandonment rate is caused by the wind power output being greater than the sum of all loads, and the wind abandonment cost and wind abandonment rate remain basically unchanged.

5. Conclusions
Based on the WHCS structure, this paper establishes a system optimization configuration model. The conclusions are as follows.

The WHLCES proposed in this article uses the by-product oxygen of hydrogen production to provide OEC conditions, improve gas turbine efficiency and reduce carbon capture Energy consumption, thereby effectively reducing the cost of hydrogen production from wind power.

In the WHLCES, the wind curtailment rate is a quantitative indicator to measure the level of wind power consumption. If the wind curtailment rate is too large, the wind power investment is large; on the contrary, the wind curtailment rate is too small, and the capacity of energy storage. The investment is large, and both will increase the cost. To this end, this paper sets the cost of wind abandonment penalty, and obtains a configuration plan that takes into account both reduction of abandonment and economy. In addition, when the carbon emission rate changes within a certain range, the configuration result is relatively stable.

The strategy proposed in this paper can provide certain theoretical support for the optimal configuration of WHCS. However, the model in this paper only considers the cost of oxygen storage. In future studies, the cost of OEC will be further considered to better meet the actual engineering needs.

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