Optimal Capacity Planning of a Bundled Wind–Photovoltaic–Thermal Generation System Considering Carbon Emission Trading

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Abstract. In view of the situation of the bundled wind-photovoltaic-thermal generation system (BWPTGS) in China's new energy bases and the demand of carbon emissions reduction in generation system, this paper constructs a capacity planning method for wind-photovoltaic-thermal bundling power supply considering the life cycle carbon emissions. Based on the concept of low-carbon economy, this paper introduces carbon emission trading (CET) method into capacity planning of BWPTGS. Then, this paper calculates the carbon emissions cost of the generation system under the carbon emissions trading mechanism. With the objective of minimizing the comprehensive cost of generation system taking into account the cost of CET, the paper constructs an optimal generation system planning model for new energy bases considering carbon emission trading. The optimization model is applied to a BWPTGS for a new energy base in north-western China. Case studies are conducted to demonstrate the effectiveness of this proposed model and method.

1. Introduction
Global warming is one of the biggest problems and challenges facing human beings. Domestic and foreign academia believe that carbon emissions caused by excessive consumption of fossil fuels is the main cause of global warming. It has become the consensus of all countries to develop low-carbon economy, speed up the adjustment of energy structure, and vigorously develop new energy sources such as scenery to replace fossil energy [1]. China is a big carbon emitter, accounting for about 20% of the global CO2 emissions, of which thermal power accounts for 50% of the total carbon emissions [2]. The Chinese government has expressed its strong determination to save energy and reduce emissions, promising to achieve carbon peak by 2030 and carbon neutralization by 2060. The development of China's power industry is facing tremendous pressure of emission reduction. The transition from fossil fuel-based power generation to low-carbon new energy-oriented power generation has become a key proposition of China's power system planning in the future. By the end of 2020, the installed capacity of wind power and photovoltaic in China has reached 281GW and 253GW respectively, and the installed capacity of new energy accounts for 24.3% of the total installed capacity [3].
The distribution of new energy resources such as wind energy and solar energy in China is highly concentrated and inversely distributed with the load centre. With the development of wind power and photovoltaic installed capacity, the new energy consumption capacity in new energy-rich areas tends to be saturated. It becomes an important means for China to promote the development of new energy by sending new energy power to load centre through ultra-high voltage direct current (UHVDC) transmission by bundled new energy-thermal generation system (BNETGS) [4].

In general, research regarding the coordination of new energy-thermal generation systems can be categorized into two areas: the coordinated operation research and the coordinated planning research. For the coordinated operation problem, Literature [5] considered the carbon emission cost (CEC) of thermal power generation, and constructed the optimal scheduling model of bundled wind-photovoltaic-thermal generation system under the CET mechanism, which reduced the total cost and the power curtailment rate of the power system. On the basis of Literature [5], Literature [6] compared the influence of CET prices and initial quotas on the optimal scheduling of bundled wind-photovoltaic-thermal generation system. For the coordinated planning problem, Literature [7] proposed a capacity planning method of bundled wind-thermal power generation system with the given wind farms, which can obtain the optimal type and capacity of thermal power units. Considering the capital cost, maintenance cost and system loss of transmission line of converter station, a planning model of UHVDC-based bundled wind-thermal power generation and transmission system is established in Literature [8]. These literatures have done fruitful research on the coordination of BNETGS. However, to the best of the authors’ knowledge, few previous work on taking CET carbon emissions into account in BNETGS planning. In this paper, the CET model of BWPTGS is established. On this basis, the carbon emissions trading cost model under the carbon trading mechanism is proposed. With the objective of optimizing the comprehensive cost of BWPTGS of the generation system including carbon emissions trading cost, a power planning model suitable for high proportion of new energy power supply system is constructed. Finally, the optimization model is applied to a BWPTGS for a new energy base.

2. Optimal capacity planning model of BWTPGS considering CET

2.1. Objective function

Based on the concept of low-carbon economy, the benefit of carbon emission reduction has increasingly become an indispensable factor in power planning. On this paper, economy and the benefit of carbon emissions reduction are considered as a whole, and from the point of view of global optimization, the optimization objective is to minimize the comprehensive cost of electric power production taking into account the CET cost. The objective function is as follows:

$$\min F = \min (F_B + F_T + F_{\text{loss}} + F_{\text{CO}_2})$$  \hspace{1cm} (1)

where $F_B$, $F_T$, $F_{\text{CO}_2}$ and $F_{\text{loss}}$ stand for the costs of generation units construction, operation, carbon emissions and loss of load respectively. They are calculated as follows:

$$F_B = \sum_{i \in \Omega^G} f_{G,i} x_{G,i} \lambda_{\text{CRF},i} \sum_{i \in \Omega^G} f_{G,i} x_{G,i} (1 + r)^{-Y_i} - 1$$  \hspace{1cm} (2)

where $\Omega^G$ represents the set of units to be built, $f_{G,i}$ stands for the capital cost of the generation unit $i$. Meanwhile, $x_{G,i}$ is the 0-1 variable of power units to be built. This means that the power units will be built when $x_{G,i} = 1$ or not be built when $x_{G,i} = 0$. $\lambda_{\text{CRF},i}$ is the fund recovery coefficient of unit $i$, $r$ is the discount rate, and $Y_i$ is the lifetime of the generating unit $i$.

$$F_T = f_{\text{coal}} M_{\text{coal}} = f_{\text{coal}} \sum_{i=1}^{N_c} a_i P_{T,i}^2 + b_i P_{T,i} + c_i$$  \hspace{1cm} (3)
where $M_{i,t}$ refers to the standard coal consumption of the thermal unit $i$ at time $t$, $M_{\text{coal}}$ expresses the coal consumption of thermal power units. $P_{T_{i,t}}$ illustrates the power output of thermal power unit $i$ at time $t$, $N_{T}$ defines the amount of thermal power units. Meanwhile, $\varphi$ is the coefficient of standard coal to raw coal, $a_i$, $b_i$ and $c_i$ are parameters of the coal consumption function.

$$F_{\text{loss}} = f_{\text{loss}}E_{\text{loss}}$$  \hspace{1cm} (4)

where $f_{\text{loss}}$ represents the penalty cost coefficient for loss of load, which relates to the level of economic development in the sending-end and receiving-end regions, $E_{\text{loss}}$ illustrates expected electrical quantity loss of load.

$$F_{\text{CO}_2}=f_{\text{CO}_2}(E_{\text{T}}-E_0)=f_{\text{CO}_2}(g_{\text{CO}_2}\sum_{i=1}^{T} \sum_{t=1}^{N_T} M_{i,t} - \beta \eta \sum_{i=1}^{T} \sum_{t=1}^{N_T} P_{T_{i,t}})$$  \hspace{1cm} (5)

where $F_{\text{CO}_2}$ denotes the cost from carbon emission trading, $f_{\text{CO}_2}$ refers to the carbon emission trading price, $E_{\text{total}}$ indicates the total carbon emission of BWPTGS, and $E_0$ stands for the initial quotas of BWPTGS. According to the trading principles, when $F_{\text{CO}_2} > 0$, the power system has incurred CET costs, otherwise it can be regarded as benefits; $\beta$ indicates the load correction parameter, which indicates the free carbon emissions quota revision rate, and $\eta$ represents the allocation of emissions per unit of electricity, which can be determined from the “Emissions factors of regional grid baselines”, issued by the National Development and Reform Commission.

2.2. Constraints

2.2.1. Power balance.

The power supply and demand of power system must keep balance in real time:

$$\sum_{i=1}^{N_T} P_{T_{i,t}} + \sum_{k=1}^{N_k} P_{W_{i,k}} + \sum_{l=1}^{N_l} P_{P_{i,l}} = P_{L_{t}} + P_{loss,t}$$  \hspace{1cm} (6)

where $P_{W_{i,k}}$ and $P_{P_{i,l}}$ denote power output of wind power unit $k$ and photovoltaic power unit $l$ at time $t$ respectively, $P_{L_{t}}$ refers to the power output of UHVDC transmission at time $t$, and $P_{loss,t}$ stands for the load loss power of the power system at time $t$.

2.2.2. Thermal power unit constraints

2.2.2.1. Output constraint of thermal power units. The output power of thermal power units needs to be within the following limit:

$$u_{i,t} P_{\text{min}} \leq P_{T_{i,t}} \leq u_{i,t} P_{\text{max}}$$  \hspace{1cm} (7)

where $u_{i,t}$ refers to the state variable of the thermal power unit $i$ at time $t$, and the thermal power unit $i$ operate when $u_{i,t}=1$ or stop when $u_{i,t}=0$. $P_{\text{max}}$ and $P_{\text{min}}$ illustrate maximum and minimum output of the thermal power unit $i$ respectively.

2.2.2.2 Output climbing/falling speed constraint of thermal power units. Although thermal power can be adjusted flexibly in real time, the power output cannot be changed too quickly, so that the power output in adjacent time should follow the following rules:
where \( P_{Ti}^{up} \) and \( P_{Ti}^{down} \) stand for the power output climbing and falling speed of thermal power unit \( i \) respectively.

2.2.2.3 Thermal unit start-up and shutdown time constraints. The start-up and shutdown duration times of thermal power units should be limited as follows:

\[
(u_{i,t} - u_{i,t-1})T_{i,min}^{on} + \sum_{k=1}^{t-1} u_{i,k} \geq 0
\]

\[
(u_{i,t-1} - u_{i,t})T_{i,min}^{off} + \sum_{k=1}^{t-1} (1 - u_{i,k}) \geq 0
\]

where \( T_{i,min}^{on} \) and \( T_{i,min}^{off} \) represent the minimum continuous operating time and downtime of thermal power unit \( i \) respectively.

2.2.3. Wind and photovoltaic unit constraints.

As with thermal power units, the output power of wind and photovoltaic power units is in a range:

\[
P_{Pl}^{min} \leq P_{Pl,t} \leq P_{Pl}^{max}
\]

\[
P_{Wk}^{min} \leq P_{Wk,t} \leq P_{Wk}^{max}
\]

where \( P_{Pl}^{max} \) and \( P_{Pl}^{min} \) represent maximum and minimum output of the PV unit \( l \); \( P_{Wk}^{max} \) and \( P_{Wk}^{min} \) represent maximum and minimum output of the wind power unit \( k \) respectively.

2.2.4. Installed capacity constraints of generating units.

Due to resource endowment constraints and economic reasons, the theoretical installed capacity of thermal power, wind power and photovoltaic power units is within a certain range:

\[
0 \leq C_{T,W,P} \leq C_{T,W,P}^{max}
\]

where \( C_{T} \), \( C_{W} \) and \( C_{P} \) represent the installed capacity; \( C_{T}^{max} \), \( C_{W}^{max} \) and \( C_{P}^{max} \) refer to the maximum installed capacity of the three types of power units respectively.

3. Case studies

In order to verify the effectiveness of the capacity planning method considering carbon emission trading, some case studies are conducted. The case studies are based on building a BWPTGS to transmit the bundled wind-photovoltaic-thermal power from the northwest China's energy base to the Central China's load centre by UHVDC.

3.1. Basic data

The system parameters are set as follows: the upper limit of wind, photovoltaic and thermal power units are 10000MW, 5000MW and 8000MW respectively. The detailed parameters of the unit are referred to the literature [9]; The unit investment cost of wind, photovoltaic and thermal power projects is 6.5, 4.5 and 3.5 million yuan/MW [10]; the discount rate is 8%; the penalty cost is 10000 yuan/MWh. According to the national development and reform commission price monitoring centre released data, the unit price of coal is 550 yuan/t; carbon trading price is 50 yuan/t; \( \beta \) is 90 %. 
3.2. Scene clustering of new energy output

Considering the randomness and uncertainty of wind power and photovoltaic output, it is impossible to analyse and evaluate each photovoltaic output scenario in the actual process. In order to better simulate the characteristics of new energy output, this paper uses the improved K-means clustering algorithm to cluster the output scenarios of wind power and photovoltaic. Based on the prediction data of wind power and photovoltaic output of a province in northwest China, this paper assumes that the prediction error satisfies the normal distribution, and randomly generates 100 wind power and photovoltaic output scenarios by using the Monte Carlo method. The output sampling period is 1 h, and the target clustering number is set to 5. The clustering results are shown in Figure 1.

![Figure 1. Clustering scenarios of wind and photovoltaic power output](image)

3.3. UHVDC load curve

In order to facilitate the power consumption of the receiving end system, the DC transmission curve should be matched with the load characteristic curve of the receiving end grid. In addition, so as to ensure the economy of UHVDC transmission project, the annual utilization hours of UHVDC should meet the design requirements. In this study, the nominal power of UHVDC is assumed to be 8000MW, and annual utilization hours of UHVDC are set at 6000h. Based on the typical daily load characteristic curve of a province in central China, the UHVDC load curve is drafted as Figure 2.

![Figure 2. UHVDC load and receiving load](image)

3.4. Optimal capacity planning for BWPTGS

Based on MATLAB platform, this paper uses YALMIP toolbox to program and calls the commercial optimization software CPLEX to solve the model, and sets the following generation capacity planning schemes to compare and analyse the planning results to verify the correctness and effectiveness of the model.
Scheme 1: Without considering the cost of carbon emission trading.
Scheme 2: Considering the cost of carbon emission trading.
The economic indicators of each planning scheme are shown in Table 1.

| Scheme | Capacity planning (MW) | Cost (billion yuan) | Carbon emissions (MtCO2eq) |
|--------|------------------------|---------------------|----------------------------|
|        | Thermal | Wind | PV | Construction | Operation | CET | Load loss | Total |                     |
| ①      | 7260    | 0    | 0  | 3.33        | 11.03      | 0.92 | 0          | 15.28 | 35.72                 |
| ②      | 6600    | 3487 | 4436 | 6.60      | 7.75       | 0.65 | 0.30       | 14.64 | 25.08                 |

As we can see from Table 1, compared with scheme 1, scheme 2 considering CET cost has higher new energy installations, lower total costs and carbon emissions. The introduction of CET costs in the planning model improves the competitiveness of new energy in BWPTPGS and is conducive to the consumption of new energy.

4. Conclusion
The capacity planning model considering carbon emission trading costs for BWPTPGS is proposed. Compared with the traditional model without considering CET costs, the power planning model proposed in this paper can reduce the total cost and carbon emissions of BWPTPGS. This method greatly improves the economy and environmental benefits of power system. The next step research plan is taking into the different carbon trading prices to adapt to various emission reduction scenarios.

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