Optimization of Power Supply Structure Considering Carbon Emissions and Flexibility

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Abstract: Against the backdrop of China's promotion of green and low-carbon energy transformation, the large-scale and high-proportion development of new energy has made flexible regulation of power supply planning a key link in the flexible construction of the power system. Considering the balance of flexible supply and demand and minimizing carbon emissions, a mid to long-term collaborative planning model for electricity and flexibility is proposed. According to the planning principles of economic efficiency, clean environmental protection, and safety and reliability, a dynamic planning model was constructed to minimize the total cost of electricity production and carbon emissions in the entire society. Taking into account constraints such as carbon peaking goals and electricity balance, taking a certain region in China as an example, a flexible power supply structure optimization planning is carried out to solve carbon emission levels and system costs, output carbon peaking time, and optimal path plan.

1 Introduction

Under the guidance of China's dual carbon goals, building a low-carbon and sustainable power structure has become an important principle in power planning to achieve low-carbon development of the energy system. At present, relevant scholars at home and abroad have carried out some research on power structure optimization considering flexibility and carbon emissions and analyzed the sustainable development of renewable energy from the perspective of power supply[1]. In terms of model construction, some scholars have established a low-carbon economic power planning model based on multi-scenario modeling technology[2]. Based on the analysis of the operation characteristics of carbon capture power plants, a low-carbon power planning model considering carbon emissions and coal-fired constraints was established[3]. Considering the economy and reliability of the system, a low-carbon power planning model is constructed [4].

With the low-carbon and green transformation of energy, some scholars have studied the optimization model of power planning under carbon trading to minimize economic costs and maximize comprehensive energy efficiency[5]. Establish a multi-objective model with the minimum annual comprehensive cost and minimum carbon emissions, considering constraints such as electricity, electricity, and carbon emissions reduction [6]. Some scholars have also constructed a multi-objective power planning model from the perspective of energy-efficient power plants[7]. A multi-objective optimization method based on a genetic algorithm to determine the scale and location of distributed power generation planning based on performance indicators[8]. Propose a cross-border power optimization planning method considering carbon emission constraints based on the requirements of clean and low-carbon power planning [9]. In addition, predict and evolve the optimal path to address low-carbon evolution in the power supply structure [10]. In terms of practical applications, scholars have conducted research on economically feasible solutions to improve grid flexibility and reduce losses[11]. In terms of algorithm innovation, some scholars have proposed the Honey Badger algorithm to solve power expansion planning problems[12].

Based on the above analysis, this article establishes a power structure optimization model that considers flexibility and carbon emissions. Taking a certain region in China as an example, the power structure planning solution that meets the minimum carbon emissions and the lowest total cost of electricity production in the whole society is solved.

2 A Power Supply Structure Optimization Model Considering Flexibility and Carbon Emissions

2.1. Flexibility Resource Modeling

2.1.1. Modeling Method for Power Flexibility

Set the time scale to τ and establish a functional relationship between the flexibility of controllable power

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supply regulation and output level:

$$x^{+}_{g,\pi,t}\left(P_g,\tau\right)=\min\left[R^{+}_{g}\tau, P^{\max}_{g}-P_{g,t}\right] \quad (1)$$

Similarly, the relationship between downward flexibility and output level function is:

$$x^{-}_{g,\pi,t}\left(P_g,\tau\right)=\min\left[R^{-}_{g}\tau, P_{g,t}-P^{\min}_{g}\right] \quad (2)$$

In the formula, $x^{+}_{g,\pi,t}$ and $x^{-}_{g,\pi,t}$ represent the flexibility of controllable power supply up and down adjustment; R^{+}_{g} and R^{-}_{g} are the ramp rates for controllable power supply up and down; $P_{g,t}$ and $P^{\max}_{g}$ are the current output and maximum output of the controllable power supply at time t.

Renewable energy sources such as semi-controlled wind and solar power are composed of two parts: controllable and uncontrollable output. When the flexibility of the system is insufficient, it can be provided through methods such as abandoning wind/light to become a flexibility provider. The calculation formula is as follows:

$$y^{+,-}_{RE,\pi,t}\left(P_{RE},\tau\right)=P_{RE,t+\tau}-P_{RE,t} \quad (3)$$

$$y^{+,-}_{RE,\pi,t}\left(P_{RE},\tau\right)=y_{RE,\pi}\left(P_{RE},\tau\right)+P^{cu\gamma}_{RE,t}-P^{cu\gamma}_{RE,t+\tau} \quad (4)$$

If the impact of prediction error is considered, the flexibility requirement becomes as follows:

$$\tilde{y}^{+,-}_{RE,\pi,t}\left(P_{RE},\tau\right)=\tilde{y}^{+,-}_{RE,\pi}\left(P_{RE},\tau\right)+P^{e\gamma\gamma o\gamma}_{RE,t+\tau} \quad (5)$$

In the formula, $y^{+,-}_{RE,\pi,t}$ and $\tilde{y}^{+,-}_{RE,\pi,t}$ represent the flexibility requirements of semi controlled renewable energy in different directions before and after power limit; $P_{RE,t}$, $P^{cu\gamma}_{RE,t}$, $P^{cu\gamma}_{RE,t+\tau}$, and $P^{e\gamma\gamma o\gamma}_{RE,t+\tau}$ are the original output, limited power output, and prediction error at time t and time $t+\tau$, respectively.

2.1.2. Modeling Method for Energy Storage Flexibility

Establish a model as shown in the following formula: Set the time scale to τ, and establish a functional relationship between the flexibility of energy storage upregulation and output level:

$$x^{+}_{st,\pi,t}\left(P_{st},\tau\right)=\min\left[P^{\max}_{st}-P_{st,t},\frac{E_{st,t}-E^{\min}_{st}}{\tau}-P_{st,t}\right] \quad (6)$$

Similarly, the relationship between flexibility and output level is as follows:

$$x^{-}_{st,\pi,t}\left(P_{st},\tau\right)=\min\left[P^{\max}_{st}-P_{st,t},\frac{E^{\max}_{st}-E_{st,t}}{\tau}+P_{st,t}\right] \quad (7)$$

In the formula, $x^{+}_{st,\pi,t}$ and $x^{-}_{st,\pi,t}$ represent the flexibility of energy storage up and down respectively; $E^{\max}_{st}$, $E^{\min}_{st}$ and $E_{st,t}$ represent the maximum and minimum storage energy limits and t storage energy, respectively; $P^{\max}_{st}$ and $P_{st,t}$ are the maximum charging and discharging power of energy storage and the charging and discharging power at time t.

2.2. Objective Function of Power Supply Structure Optimization Model

2.2.1. Design of Objective Function Based on the Lowest Total Cost of Electricity Production in the Whole Society

$$\min f=\sum_{t=1}^{T}\left[\sum_{i=1}^{I}\left[\left(F_{ti}+S^{F}_{ti}\right)C_{ti}-S^{F}_{ti}C_{t-1,i}+\left(V_{ti}+S^{V}_{ti}\right)C_{ti}H_{ti}\right]\right]\frac{1}{\left(1+r\right)^{t}} \quad (8)$$

In the formula, f is the total economic cost during the planning period; T is the planning year; I is the planning period; I represents the corresponding serial number for different unit types; F_{ti} represents the total number of all unit types; F_{ti} represents the annual value converted from the unit capacity cost of the i-th unit in year t; S^{F}_{ti} represents the subsidy or additional cost corresponding to the newly added installed capacity of the i-class unit in year t; C_{ti} represents the total installed capacity of type i units in year t. Considering the different roles of different types of units in ensuring power balance, the capacity of virtual power plants on the demand side specifically refers to peak shaving capacity, while the capacity of renewable energy generation is the output during peak load periods, which is the product of power supply installation and peak output contribution factors; V_{ti} represents the operating cost of the i-type unit in year t for producing unit electricity; S^{V}_{ti} represents the subsidy or additional cost corresponding to the production unit electricity of the i-type unit in year t; H_{ti} represents the utilization hours of unit type i in year t; R is the discount rate.

2.2.2. Design of objective function for optimizing power supply structure based on minimizing carbon emissions

The construction idea of the power structure optimization model is shown in Figure 1.

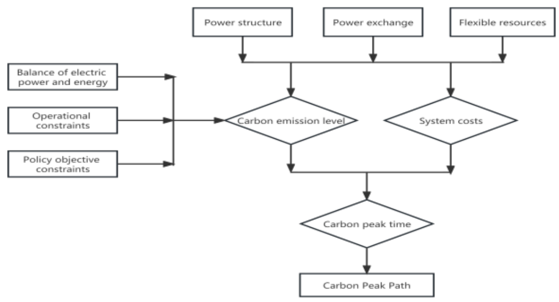

Fig.1. Power Supply Structure Optimization Model Based on Minimal Carbon Emissions

The optimization objective of this model is to minimize the cumulative carbon emissions of the regional system during the calculation period, and the objective function is as follows:

$$\min P=\min_{t=1}^{T}\left\{\sum_{t=1}^{T}\left[\sum_{i=1}^{m}\left(E_{fi}\times Q_{fi}\right)+\sum_{j=1}^{n}\left(E_{sj}\times Q_{sj}\right)\right]\right\} \quad (9)$$

In the formula: P is the regional carbon emissions, E_{fi} is the i-class power generation, Q_{fi} is the i-class power carbon emission coefficient, m is the number of power sources that generate carbon emissions, E_{si} is the electricity transmitted through the transmission channel, Q_{si} is the transmission channel carbon emission coefficient, n is the number of transmission channels that generate carbon emissions, and T is the calculation year.

2.2.3. Dual objective processing method

Due to the different dimensions of the two objectives, the carbon trading price is used to convert the carbon emissions target into cost, resulting in the following objective function.

$$\min(f+P\times p_c)=\left(\sum_{t=1}^{T}\left[\sum_{i=1}^{I}\left[\left(F_{ti}+S_{ti}^{F}\right)C_{ti}-S_{ti}^{F}C_{t-1,i}+\left(V_{ti}+S_{ti}^{V}\right)C_{ti}H_{ti}\right]\right]\frac{1}{(1+r)^t}\right) \\ +\left(\sum_{t=1}^{T}\left[\sum_{i=1}^{m}\left(E_{fi}\times Q_{fi}\right)+\sum_{j=1}^{n}\left(E_{sj}\times Q_{sj}\right)\right]\times p_{ct}\right) \quad (10)$$

In the formula, p_{ct} represents the carbon trading price for period t.

2.3 Constraints of Power Supply Structure Optimization Model

(1) Carbon Peak Target Constraints

According to China's carbon peak target, the carbon peak year of the regional electricity system should not be later than 2030. The model study takes 2020 as the base year, and the carbon peak target constraint can be expressed as $1 \le t \le 10$.

(2) Balance of electric power and energy

Adopting a production simulation calculation method based on typical days to meet the balance of electricity and energy.

$$\sum_{k=1}^{l}\left[\sum_{i=1}^{m}\left(P_{fi,t}\right)+\sum_{j=1}^{n}\left(P_{sj,t}\right)+P_{c,t}+P_{x,t}\right]\times K \ge F_{Pt} \quad (11)$$

In the formula: $P_{fi,t}$ is the power output coefficient in year t, $P_{si,t}$ is the transmission channel output coefficient in year t, $P_{c,t}$ is the energy storage equipment output coefficient in year t, $P_{x,t}$ is the pumped storage power plant output coefficient in year t, K is the expansion coefficient, $F_{p,t}$ is the predicted maximum load demand in year t.

(3) Power output constraint

Wind power and photovoltaic systems need to be constrained by the highest national electricity abandonment rate, namely:

$$\frac{E_{W,t}+E_{S,t}}{E_{WM,t}+E_{SM,t}} \le L \quad (12)$$

In the formula: $E_{W,t}$ is the wind power generation in year t, $E_{S,t}$ is the photovoltaic power generation in year t, $E_{WM,t}$ is the full wind power generation in year t, $E_{SM,t}$ is the full photovoltaic power generation in year t, L is the maximum abandonment rate specified by the policy.

For thermal power units, the upper and lower limits of regulation are set according to the regulation capacity, namely:

Coal electric unit: $45\% \le P_m \le 100\%$

Gas electric unit: $10\% \le P_q \le 100\%$

The regulation capacity of pumped storage and electrochemical energy storage is calculated based on power and capacity.

(4) Carbon emission level of power supply

Establish a relationship curve between output and coal consumption based on the unit classification in power constraints, considering the coal consumption levels under different output states.

(5) Cross regional power exchange

Consider the cross-regional exchange of electricity and the proportion of non-converted electricity to other electricity structures.

(6) Power demand and load characteristics

Consider the impact of electricity substitution, electric vehicles, and other factors on electricity demand and load characteristics.

(7) Demand side responsiveness

As a sensitive factor, the demand side capability gradually improves and participates in system response during peak and low periods.

(8) Flexible supply-demand upward balance constraints

The upward balance constraint formula is as follows:

$$\min\left[(C\_a)_{t,coal}-P_{t,coal}^{ave}, R_{coal}^{up}\cdot\Delta t\right]+ \\ \left[(C\_a)_{t,gas}-P_{t,gas}^{force}\right]+\sum_{i\in(ps,es,dr)}(C\_a)_{ti} \\ \ge A_{UP}\times\sum_{i\in wind,solar}(C\_a)_{ti}/\sum_{i\in I}(C\_a)_{ti}+B_{UP},\ \ t\in T \quad (13)$$

$$P_{t,coal}^{ave}=(C\_a)_{t,coal}\cdot\frac{H_{t,coal}}{8760}$$

In the formula, $P_{t,coal}^{ave}$ represents the average output of coal-fired power in the year t; Δt is the flexible time scale; $P_{t,gas}^{force}$ represents the total forced output of the pneumatic motor unit in year t; A_{UP} and B_{UP} are historical data parameters, while E represents the maximum continuous net load climbing demand corresponding to different percentages of wind and solar total installed capacity.

(9) Flexible supply-demand downward balance constraints

$$\min\left[P_{t,coal}^{ave}\left(1-\frac{1}{\varphi}\times 50\%\right)+(C\_a)_{t,fle}\times(50\%-30\%),\ \ R_{coal}^{down}\cdot\Delta t\right] \\ +\left[(C\_a)_{t,gas}-P_{t,gas}^{force}\right]+\sum_{i\in(ps,es,dr)}(C\_a)_{ti} \\ \ge A_{DO}\times\sum_{i\in wind,solar}(C\_a)_{ti}/\sum_{i\in I}(C\_a)_{ti}+B_{DO},\ \ \ t\in T \quad (14)$$

In the formula, φ is the proportion of the average minimum output to the rated output of coal-fired power units without flexibility modification; A_{DO} and B_{DO} are historical numbers.

3 Example analysis

3.1 Basic data

According to the research results of the "14th Five Year Plan" and medium to long-term power planning in the calculation area, the predicted results are shown in Table 1.

Table 1. Forecast results of electricity consumption in the whole society

Example region	2019	2020	2025	2030	2035

Total electricity consumption	6696	6900	8800	9600	10100
Growth rate		5.4%	5.0%	1.8%	1.0%

Note: The corresponding five-year growth rates for 2020, 2025, 2030, and 2035.

The maximum social load of the region during the period from the 14th Five-Year Plan to the 16th Five-Year Plan is predicted as shown in Table 2.

Table 2. Maximum load prediction for the entire society

Unit: 10MW

Project	Time				Annual growth rate			
	2020	2025	2030	2035	The 13th Five-Year Plan	The 14th Five-Year Plan	The 15th Five-Year Plan	The 16th Five-Year Plan
The maximum load of the whole society	147290	197770	228090	247130	6.03%	6.21%	2.94%	1.64%

3.2 Calculation results

Table 3 Example Regional Power Balance Table

Unit: 10MW

Serial Number	Indicator		2025	2030	2035
1	Load demand		19777	22809	24713
(1)	Electricity load		17300	20000	21700
(2)	Spare capacity		2076	2400	2604
(3)	External power transmission		401	409	409
2	West to East Power Transmission (Transmission End)		4508	6508	7008
3	Installed capacity		23700	27731	31102
(1)	Coal electricity		7570	7084	7084
(2)	Gas electricity		6438	6438	6438
(3)	Nuclear power		1854	2344	2844
(4)	hydropower	Conventional hydropower	848	848	848
(5)		Pumped storage energy nuclear power	1058	2218	3178
(6)	Wind power	Offshore wind power	1774	3506	4200
(7)		Onshore wind power	777	984	1390
(8)	Photovoltaic		2797	3600	4100
(9)	Biomass and others		485	508	519
(10)	Energy storage		100	201	501
4	Utilization scale		16358	17622	19158
(1)	Coal electricity		7318	6848	6848
(2)	Gas electricity		5300	5300	5300
(3)	Nuclear power		1854	2344	2844
(4)	hydropower	Conventional hydropower	402	402	402
(5)		Pumped storage energy nuclear power	1058	2218	3178
(6)	Wind power	Offshore wind power	18	35	42
(7)		Onshore wind power	16	20	28
(8)	Photovoltaic		140	180	205
(9)	Biomass and others		243	254	260
(10)	Energy storage		10	20	50
5	Power balance		864	805	864

The electricity balance situation in the example region is shown in Table 3. Based on the maximum load prediction plan for the entire society, while considering the potential for pumping and energy storage construction in the example region. The channel utilization hours are set to be 3400 hours, with an additional supply of 20 million kilowatts/68 billion kilowatt hours, and a clean channel accounting for 100%. During the "16th Five Year Plan", we are considering adding another ultra-high voltage direct current channel, with an estimated utilization time of 3400 hours and an additional supply of 5 million kilowatts/17 billion kilowatt hours. The clean channel accounts for 100% of the total. The utilization hours of coal-fired power during the 14th Five Year Plan period gradually decreased to below 3000 hours. The overall electricity and quantity in the area are surplus, and by the end of the "16th Five Year Plan", the utilization hours of coal power will be maintained at around 2500 hours, while the utilization hours of gas and electricity will be maintained at around 3400 hours.

4 Conclusion

This article proposes a power structure optimization model that considers flexibility and carbon emissions. In response to the parameter setting requirements of the medium to long-term power planning model, it analyzes the balance of electricity and electricity in a certain region of China and replaces it with the power structure optimization model to obtain a flexible power planning solution that meets the principle of low-carbon sustainability. The results indicate that the power structure optimization model proposed in this article can meet the goals of minimizing the total production cost and carbon emissions of the entire society.

This article does not consider the impact of uncertainty on power planning. In subsequent research, a distributed robust optimization model can be introduced to address the volatility of new energy generation, and various factors of thermal power units and new energy units can be comprehensively considered, taking into account the environmental and economic benefits of power planning.

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