 https://doi.org/10.1051/e3sconf/20183804023

Study on the optimization allocation of wind-solar in power system based on multi-region production simulation

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Abstract. In this paper, a power supply optimization model is proposed. The model takes the minimum fossil energy consumption as the target, considering the output characteristics of the conventional power supply and the renewable power supply. The optimal capacity ratio of wind-solar in the power supply under various constraints is calculated, and the interrelation between conventional power supply and renewable energy is analyzed in the system of high proportion renewable energy integration. Using the model, we can provide scientific guidance for the coordinated and orderly development of renewable energy and conventional power sources.

1 Introduction

Power planning plays an important role in the development of power system. The traditional mixing configuration refers to the simple combination, in which the system lacks the detailed calculation model so that the guarantee rate is low, and the service life is short. The real meaning of the renewable energy system configuration is to maximize the use of resources such as wind and solar energy. When designing the system, we should choose the appropriate capacity configuration according to the local meteorological conditions. The target of hybrid system configuration is to determine the rated power, solar battery power and battery capacity of wind turbines in hybrid power system according to local meteorological data and load demand design algorithm, so that the configuration results match each other, and the system cost is lowest while satisfying the requirements of power balance and minimum boot capacity. The paper [1] uses the method of production simulation to calculate the optimal configuration of scenery, and the document [2,3] introduces the power programming modeling and solving method considering the minimum target cost. The influence of uncertain factors on power supply planning is considered in the literature [4], and the influence of uncertainty and electricity price on the load forecasting is taken into account in the objective function. The paper [5,6] considers the environmental protection benefit in the planning, analyzes the harm of various kinds of units emissions to the environment and establishes the multi-objective power supply optimization model with the minimum current value of total cost and the least CO_2 emission. The paper [7] proposes a power supply planning model which pursues the profit maximization of each generation company under the market environment.

The power supply planning problem is a high dimensional non-convex nonlinear optimization problem, so that the solution is more complex. Heuristic algorithms, mathematical optimization methods and artificial intelligence methods are used to solve the algorithm. However, the existing methods are based on the total cost value and profit, take the benefit cost as the center, and seldom take into account the influence of renewable energy on the power grid, and the interrelated mechanism of various power sources in the system of high proportion renewable energy integration is not clear enough. Therefore, it is necessary to study the new programming algorithm for the multi area power supply planning.

2 Multi-region renewable energy accommodation assessment model

2.1 Model framework

In this paper, a novel multi-region renewable energy accomodation capacity assessment model is proposed. In this model, the installed capacity of renewable energy is not given in advance, but is regarded as a decision variable in the optimization process. It means that the model is a joint optimization one, and it also takes into account the characteristics of renewable energy output, the characteristics of different types of generating units, the transmission channels, and the maximum capacity of the installed renewable energy.

2.2 Decision variables

The decision variables mainly include the following parts, and the key variables are shown in table 1:

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1) the accomodation capacity of wind and solar power;

$C_{Wind,k}$--maximum wind-installed capacity located in k-region;

$C_{Solar,k}$-- maximum solar-installed capacity located in k-region.

2) operation simulation decision variables, which are shown in table 1.

Table 1. Key variable definition and its description.

Variable	Type	Comments
$P^t_{\text{unittype},i}$	Continuous type variable	The output of i-unit at time t
$U^t_{\text{thermal},i}$	0-1Variable	The state of i-thermal power unit at time t, 0 for shutdown, 1 for startup
$U^t_{pump,i}$	0-1Variable	The state of i-pump power unit at time t, 0 for pumping, 1 for generating

2.3 Objective function

The model is aimed at the optimal economy, and the objective function includes the following parts: 1) fuel cost and variable operating cost, 2) unit starting and shutdown cost for the thermal power, 3) fixed operating cost, 4) electricity outage cost, 5) pollutant emission cost, namely

$$C = \sum_t \sum_i C_i^{SU}(1-U^{t\text{-}1}_{\text{thermal},i})U^t_{\text{thermal},i} + \sum_t \sum_i F(P^t_{\text{thermal},i}) + C_{fix} + C_{eens} + C_{emission} \quad (1)$$

The first right part of the equal sign is the start/shutdown cost of the thermal power unit, C_i^{SU} for startup charges, in the following notation:

$$C_i^{SU} = \begin{cases} C_i^h, T_{i,off} \le t_{i,off} \le t_{i,h} \\ C_i^c, t_{i,off} \ge t_{i,h} \end{cases} \quad (2)$$

which, C_i^h for hot start-up costs, C_i^c for cold start-up costs, $T_{i,off}$ for minimum continuous shutdown time, $t_{i,\ off}$ for the actual continuous shutdown time, t_{iH} is the hot start decision time.

The second part is the fuel cost of thermal power unit, $F(\cdot)$ for the thermal power unit operating cost function, can be expressed by linear or piecewise linear function, if divided into k segments, namely

$$F = \begin{cases} a_{i,1}P^t_{\text{thermal},i}, P^t_{\text{thermal},i} \in [0, P_{\text{thermal},i,1}] \\ a_{i,2}P^t_{\text{thermal},i}, P^t_{\text{thermal},i} \in (P_{\text{thermal},i,1}, P_{\text{thermal},i,2}] \\ \cdots \\ a_{i,k}P^t_{\text{thermal},i}, P^t_{\text{thermal},i} \in (P_{\text{thermal},i,k-1}, P_{\text{thermal},i,k}] \end{cases} \quad (3)$$

The third, fourth and fifth parts are fixed operating cost, electricity outage cost and pollutant discharge cost respectively. It is noted that the unit power operation cost of wind power plant / solar power station is set to zero. The amount of curtailement wind and solar power is minimized, and priority scheduling of renewable energy power generation is ensured.

2.4 Constraint conditions

(1) Power balance constraint:

All types of units and line output and equal to the load.

$$\forall t, \sum_{s \in unittype} \sum_i P^t_{s,i} + \sum_i P^t_{\text{line},i} = L_t \quad (4)$$

Which L_t denotes the load demand at moment t.

(2) Upper and lower limit constraint of unit output:

$$\forall t, \forall i, \forall s \in \text{unittype}, \quad P_{s,i,\min} \le P^t_{s,i} \le P_{s,i,\max} \quad (5)$$

Among them, $P_{S,i,\text{Min}}$ and $P_{S,i,\text{Max}}$ represent the minimum and maximum output of the first S class i units. For wind power and solar power generation, the maximum output of each moment is the product of the predicted output value and the decision variable of the installation capacity.

(3) Constraint of starting and shutdown of thermal power unit:

For thermal power units, especially coal and nuclear units, the minimum continuous opening and minimum continuous shutdown time constraints need to be met.

$$\sum_{l=t}^{t+T_{i,on}-1} U^l_{s,i} \ge T_{i,on}(U^l_{s,i} - U^{l-1}_{s,i}) \quad (6)$$

$$\sum_{l=t}^{t+T_{i,off}-1} (1-U^l_{s,i}) \ge T_{i,on}(U^{l-1}_{s,i} - U^l_{s,i})\,) \quad (7)$$

which, $T_{I,on}$, $T_{I,off}$ represents minimum continuous opening and minimum continuous shutdown time for the unit.

(4) Unit ramp rate constraint:

It is necessary to meet the ramp up constraints for the thermal power unit, that is, the normal operation state can not exceed the speed of the ramp rate.

$$P^t_{s,i} \ge P^{t-1}_{s,i} - RD_{s,i} - (1-U^t_{s,i})P_{s,i.\max} \quad (8)$$

$$P^t_{s,i} \le P^{t-1}_{s,i} + RU_{s,i} + (1-U^{t-1}_{s,i})P_{s,i.\max} \quad (9)$$

which, $RD_{S,I}$ and $RU_{S,I}$ denote the unit's lower ramp and upper rate.

(5) Constraint of pumped storage power station:

When the pumped storage unit is running, it is necessary to maintain the water level between the top and bottom of the reservoir between the highest and the dead water level:

$$W_{u,\min} \le W_u \le W_{u,\max} \quad (10)$$

$$W_{d,\min} \le W_d \le W_{d,\max} \quad (11)$$

Which W_u and W_d represent the water content of the upper reservoir and the lower reservoir respectively; $W_{u,\text{ Max}}$ and $W_{u,\text{ min}}$ are the maximum and minimum allowable water content of the upper reservoir respectively; $W_{d,\text{ Max}}$ and $W_{d,\text{ min}}$ represent the maximum and minimum allowable water quantity of the lower reservoir respectively. There is a dynamic coupling relationship between the upper and lower reservoir water at different time, namely:

$$W^t_u = W^{t-1}_u - \lambda_g P^t_g + \lambda_p P^t_p \quad (12)$$

$$W^t_d = W^{t-1}_d + \lambda_g P^t_g - \lambda_p P^t_p \quad (13)$$

For the day/week cycle type unit, if one day/week is divided into S time, then the initial and final period of the upper reservoir water level should be consistent, that is:

$$W_u^s = W_u^0 \tag{14}$$

which W_u^0 and W_u^s represent the water level at the start period and the final period.

(6) Transmission lines constraints:

$$C_{line,\min} \le P_{\text{line},i}^t \le C_{line,\max} \tag{15}$$

(7) Spinning reserve constraints:

Spinning reserve generally includes the reserve required by the load and the reserve to cope with the uncertainty of renewable energy sources.

$$\sum_s \sum_i R_{s,i}^t \ge L_t(1 + R_L) \tag{16}$$

$$\sum_s \sum_i R_{s,i}^t \le L_t(1 + R_{VG}) \tag{17}$$

(8) Curtailment ratio constraints:

Curtailment ratio must be less than the given value:

$$\frac{\sum_i \sum_t Cur_{wind,i}^t + \sum_i \sum_t Cur_{solar,i}^t}{\sum_i \sum_t P_{wind,i}^t + \sum_i \sum_t P_{solar,i}^t} \le \alpha \tag{18}$$

After the construction of the evaluation model of the renewable energy accomodation capacity of the multi-area, the CPLEX commercial solver is invoked to optimize the calculation of the model, and the renewable energy accomodation capacity and the simulation results of the system can be obtained.

3 Scenario Design

The following are the important constraints, such as load demand, power supply capacity, renewable energy output characteristics and the scale of transmission channels.

3.1. Load demand

According to the medium and long term energy demand forecast model in the literature [8], it is estimated that in 2050, the whole society electricity consumption, the maximum load is 11.7×10^6 GWh, 18.7×10^6 GW respectively, other characteristic parameters as shown in table 2.

Table 2. National electricity consumption and maximum load forecast in 2050.

Regional	Category	2050 (GWh, GW)
National	Power consumption	11.7×10^6
	Maximum Load	18.7×10^6
	Average load factor	64.37%
	Average peak and valley ratio	25.84%

3.2. Power supply development (except for renewable energy)

Combining the assessment of resource potential and the technical progress of various types of power sources (except renewable energy sources) and the foreseeable national planning and prediction, the general situation of the installation of various types of power sources is obtained. The results are illusrtrated in table 3 and figures 1, 2, and the specific prediction model can be referred to [9]. The overall situation of the development of power sources is described from the total amount, structure and layout of power supply units in three aspects.

Table 3. Installation capacity of various power supply in China in 2050.

Power type	Capacity /(GW)
Coal power	671
Gas and electricity	201
Nuclear power	340
Hydropower	519
Pumped storage	138
Biomass	160
Total	**1358**

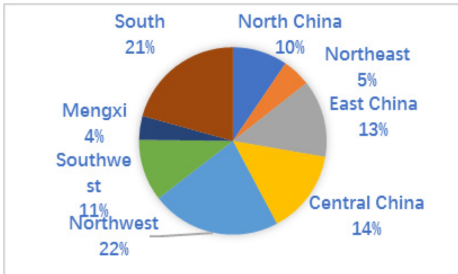

Fig. 1. Regional distribution of power capacity in China in 2050 (except RE power generation).

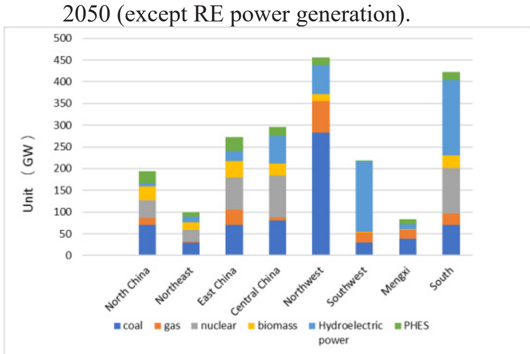

Fig. 2. National power supply structures in China in 2050 (except RE power generation).

3.3. Inter-regional channel power flow direction and scale

With the accelerated development of renewable energy in the northern part of the western region, the scale of power flow is gradually expanding. Considering the capacity of the transmission channels, and the coordination of inter-district and inter-provincial transmission corridors and routes, the power flow from the "sending end" in the northern part of the western region to the receiving provinces (cities) is expected to reach 553 GW in 2050, as shown in the graph below.

Fig. 3. Inter-regional channel power flow direction and scale in 2050.

4 Case Study

This section studies the renewable energy accomodation capacity in all regions of China in 2050, that is, the optimal installation capacity of wind and solar power generation that can be friendly integrated by all provinces and regions when the overall renewable energy curtaiment rate in each area is controlled below 5%. The process is conducted based on the multi-region renewable energy accomodation assessment model proposed in Section 2, and the various constraints proposed in Section 3. The renewable energy construction and its distribution are listed in table 4 and illustrated in figure 4.

Table 4. Renewable energy allocation in different regions in China in 2050 (Unit: GW).

	Renewable energy	Wind	Solar
Total	2367.23	1432.02	935.21
North	149.841	89	60.841
Northeast	165.542	77.157	88.385
East	132	48	84
Central	259.55	35	224.55
Northwest	1286.87	906.44	380.43
Southwest	37.423	19.423	18
Inner mongolia	227	201	26
South	109	56	53

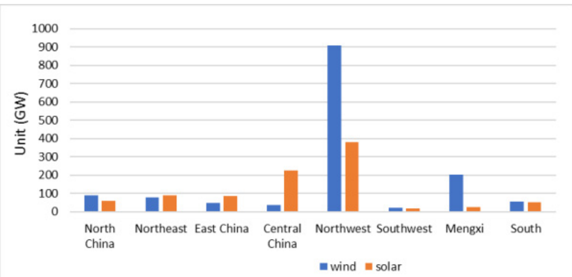

Fig. 4. Comparison of wind/solar accomodation capacity in different regions of China in 2050.

In order to evaluate the operation condition, the proposed production simulation is conducted to calculate the renewable energy curtailment rate and some important performance indicators such as the utilization hour of wind and solar power generation under the given renewable energy planning.

Table 5. Analysis of RE accomodation capacity in different regions of China in 2050.

	Curtailment rate			Utilization hours		
	Average curtailment rate	Wind curtailement	Solar curtailement	Average utilization hour	Wind utilization hour	Solar utilization hour
Total	**11.36%**	**11.39%**	**11.27%**	1796	3759	2184
North	5.53%	3.79%	9.72%	1551	3623	1877
Northeast	10.29%	8.23%	13.20%	1556	3252	2003
East	8.25%	8.60%	7.90%	1548	3914	2099
Central	5.78%	3.54%	6.40%	1154	3391	1890
Northwest	12.85%	12.49%	14.27%	1964	3532	2232
Southwest	11.93%	11.70%	12.30%	1537	4037	1850
Inner mongolia	12.14%	12.53%	5.80%	2166	3548	2295
South	8.32%	7.80%	9.30%	1659	3759	2130

5 Conclusions and Recommendations

The renewable energy accommodation is the key factor that affects the healthy development of renewable energy. This paper puts forward an innovative assessment model to evaluate the optimal wind-solar hosting capacity. What is more, we also quantifies and analyzes the scale of renewable energy installed in different regions of China in 2050. The cross-provincial transmission capacity for renewable energy bases and the corresponding optimization power flow schemes are of important significance for the healthy development of renewable energy in China. An optimal allocation of wind-solar in power system is meaningful for the decision-maker for system's planning and manegement.

As to China's medium and long term power supply planning, the reverse distribution of energy production and load center will be more obvious, and the scale of energy trans-regional transportation, especially the amount of renewable energy transmission, will be further enlarged. In order to meet the large-scale renewable energy integration, the following suggestions are put forward to ensure the healthy and sustainable development of power system. The specific suggestions are as follows: (1) Carry out special research on renewable energy integration, and the renewable energy planning plan should be optimized and updated by rolling. (2) Speed up the construction of HVDC transmission projects to increase the transmission capability of renewable energy. (3) Motivate the enthusiasm of power generation enterprises to participate in peak shaving and power plant flexibility transformation, and to accelerate the transformation of thermal energy flexibility, and to implement the transformation target proposed by the national "Thirteen-Five" electricity planning. (4) Establish a mature market mechanism to break the renewable energy accomodation barriers between provinces so that the renewable energy can be accomodated in a larger region.

Acknowledgements

This work is supported by Science and Technology Project of State Grid Corporation of China (B3670116A005): Study on the evaluation model and application of peak shaving technology, economy and policy for power system wiht large-scale renewable energy integration.

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