The Frontiers of Society, Science and Technology
ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

Low Carbon-based Scheduling Optimization Model for Wind Power and Thermal Power Considering Energy Storage Systems

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Abstract: *In order to reduce the randomness of wind power and improve system consumption capacity, a jointly scheduling optimization model with energy storage systems (ESSs) and carbon emission trade (CET) is introduced. Firstly, the basic scheduling model for wind power and thermal power is established with the objective function of the maximum system benefit considering system operation constraints. Secondly, the carbon emission cost model for thermal power generation and the ESSs' operation profit model are established, respectively. System comprehensive scheduling objective function considering CET and ESSs is also presented. Thirdly, the jointly scheduling model for wind power and thermal power considering ESSs' operation condition, CET condition and newly system reserve condition are taken into consideration. Finally, the simulation system with 10 thermal power units and 2800MW wind power turbines is proposed. The results show the large-scale wind power grid connection relies on thermal power to provide reserve service, which could reduce unit utilization efficiency and the overall coal consumption rate. The cleaning characteristics of wind power could be transformed into economic benefits by CET, which will promote wind power consumption and reduce abandoned wind power. The charge-discharge characteristics of ESSs could smooth load curve and enlarge the grid-connected space of wind power. However, the overall benefit reduces due to ESS's high fixed costs. The system overall benefit reaches the maximum when ESSs and CET are simultaneously introduced, which indicates ESS and CET have synergistic optimization effect.*

Keywords: *Wind power; ESSs; CET; optimization;*

1 Introduction

In recent years, greenhouse effect and energy-saving emission

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

reduction pressure drive wind power develop more rapidly. However, subjected to the natural wind uncertainty, wind power generation has strong volatility and intermittency. The grid-connection of large-scale wind power relies on sound peak shaving and reserve service [1]. Thermal power units often provide reserve power supply for wind power, but thermal power units will also produce pollutant emissions. Therefore, an alternative reserve power supply for wind power is necessary [2]. The charge-discharge characteristics of energy storage systems (ESSs) can smooth wind power output, suppress power fluctuation and provide reserve service [3]. Subjected to excessive initial investment cost, ESSs has not hit scale. As an important environmental policy for controlling carbon emissions, carbon emission trade (CET) can quantify environmentally friendly features and enhance the grid-connected advantages of clean energy power generation [4], which play an important role in promoting wind power. Therefore, based on the present combination situation of wind power and thermal power, the jointly scheduling optimization model for wind power and thermal power considering ESSs and CET has great practical significance to improve system operation capacity.

In order to increase wind power grid-connection, scholars at home and abroad carried out much researches. Main achievements can be summarized into three aspects, namely constructing optimization model, selecting better reserve service and formulating relevant incentive policies. Firstly, in terms of constructing optimization model, the economic scheduling model established considered wind speed and power demand in literature [5]. Based on analysis of wind power output randomness, literature [6] calculated the possible extra costs to maintain system stability caused by unstable wind power incorporation, and proposed the stochastic optimization model for wind power and thermal power. Considering power distribution coordination, literature [7] established the economic dispatching model for thermal power and wind power to reduce the atmospheric pollutant emission level. The fuel cost, emission level and operation cost of wind power and thermal power units are considered synthetically. Literature [8] proposed a new robust model by integrating two-phase optimization theory and robust stochastic optimization theory. The new robust model was used to avoid the risk management uncertainty in day-ahead scheduling phrase. In order to

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

reduce wind power uncertainty in electric power system operation, literature [9] introduced demand response and robust stochastic theory to establish a stochastic scheduling model. The paper proved that the robust stochastic optimization theory can overcome wind output uncertainty and demand response can improve system wind power consumption.

In terms of selecting superior reserve service, literature [10] found the energy storage systems with more effective control and coordination can not only increase wind power output, but also reduce the operation cost significantly. Aiming at wind power fluctuating characteristics, literature [11] proposed a new control strategy for controlling the smoothing time constant segmentally, which maximize the ability of energy storage systems to translate fluctuation. A jointly short-term scheduling model for wind power and ESS system was built in literature [12]. The adverse effects of wind prediction error on power grid scheduling operation were corrected by the short-term operation strategy. Literature [13] took the minimum wind prediction error as objective to optimize ESSs capacity. The optimal storage capacity under different conditions was analyzed by building function relationship between ESS capacity and wind prediction error. Literature [14] took the maximum grid-connected energy storage profit as the optimal objective. Literature [15] implemented segmented optimization for wind power and ESS system. Peak shaving was carried out according to energy storage capacity in day-ahead period and plan tracking implemented by energy storage operation limits in real-time scheduling period.

Finally, in terms of relevant incentive policies, especially the carbon emission trade policy study, literature [16] explored the policy process and development state of China's carbon trading market to understand the market emergence and development and barriers. Literature [17] analyzed the economic impact of carbon emission trade on four energy-intensive industries in Guangdong province. The generation trading replacement model with and without carbon emission trade were compared in literature [18], which proved the proposed model can well improve the emission reduction initiative and generation replacement efficiency. For green certificate transaction study, literature [19] proposed the cost-effectiveness analysis of the international green-certificate trade market and analyzes the positive effect of carbon emissions. Literature [20] pointed out that establishing transaction was beneficial to achieving the renewable energy consumption goal and reducing the emission reduction cost in the green certificate transaction market. Literature [21] showed the green certificate transaction, as a renewable energy quota system complementary mechanism, may not reach the expected economic-cost effectiveness. Based on the researches, CET has more market characteristics, which has more advantages in improving cost effectiveness and environmental effectiveness.

The existing research results have been involved in many wind power optimization scheduling aspects. However, after analyzing different literatures research contents, there are still three deficiencies: 1) Existing researches on wind power generation scheduling mainly focus on prediction and scheduling model. Few researches have been done to improve the applicability and economics of wind power scheduling model. The intermittence, uncertainty and anti-peak-shaving characteristics of wind power restrict the economic operation [22]. Therefore, in order to improve the economy of wind power and thermal power, jointly scheduling should become an important optimal objective. 2) Although the jointly optimization problem for wind power and ESSs is mentioned in many literatures, the established optimization models fail to consider ESSs excessive initial investment cost, which has an important impact on the economy of wind power and ESSs operation. 3) Few existing literatures analyzed the optimization and promotion effect of carbon emission trade on wind power consumption. In fact, CET can quantify the wind power economic characteristics, transform the environmental benefits into economic benefits, and play an important role in system optimization operation. Based on the studies above, the main contribution of the paper could be shown as following:

- The basic scheduling optimization model for wind power and thermal power is built. The model takes the maximum system operation profit as the objective and considers condition constraints like load demand and supply balance, unit operation and system reserve, which provides the basis for analyzing influence of CET and ESSs on system scheduling.
- The jointly scheduling optimization model for wind power and thermal power with ESSs and CET is proposed. The operation

efficiency and carbon emission cost are calculated. Based on the basic scheduling model, the maximum system profit is taken as objective function considering ESSs operation revenue and carbon emission cost of thermal power units. System scheduling model considering CET constraints, ESSs constraints and system reserve constraints is established.

- Four simulation scenarios are constructed according to ESSs and CET, namely basic scenario, ESSs scenario, CET scenario and comprehensive scenario. The simulation scenarios could comparatively analyze the optimization effects of ESSs and CET on jointly scheduling for wind power and thermal power. 10 thermal power units and 2800MW wind power are selected to form the simulation system.

The remainder of this paper is organized as follows: Section 1 constructs the basic scheduling optimization model for wind power and thermal power, which takes the maximum system power generation revenue as the objective function. The jointly scheduling optimization model for wind power and thermal power with ESSs and CET is constructed in Section 2. Four simulation cases are set up to demonstrate the validity of the proposed model in Section 3. Section 4 highlights the main conclusions of this study.

2 Basic scheduling optimization model

The reasonable scheduling optimization model for wind power and thermal power can effectively improve the utilization efficiency of clean energy, enhance the scheduling decision level and promote system safety economy operation [23]. In this section, a joint scheduling optimization model for wind power and thermal power is established with the objective function of the maximum system benefits and mainly condition constraints.

2.1 Objective function

More wind power consumed by system will bring better economic benefits. However, for power system, excessive wind power consumption level pursuit may lead to more thermal units to provide peak shaving service and increase the start-stop time of thermal power

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

units [24], which could also increase coal consumption. In order to achieve the optimal energy efficiency, the section takes the maximum system power generation revenue as objective function as shown in Eq.(1):

$$\max z_1 = \pi_w + \pi_c \tag{1}$$

Wherein, π_w is the profit of wind farm. π_c is the total profit of thermal power units. The profits of wind power and thermal power units are shown in Eq.(2) and Eq.(3):

$$\pi_w = p_w \sum_{t=1}^{T} Q_{w,t}(1-\theta_w) - OM_w - D_w \tag{2}$$

$$\pi_c = p_c \sum_{i=1}^{I} \sum_{t=1}^{T} Q_{i,t}(1-\theta_{c,i}) - C_{fuel} - \sum_{i=1}^{I} OM_{c,i} - \sum_{i=1}^{I} D_{c,i} \tag{3}$$

Wherein, p_w is the benchmark price of wind power in transmission area. p_c is the benchmark price of thermal power in transmission area. $Q_{w,t}$ is the real-time output of wind power at time t. $Q_{i,t}$ is the real-time output of unit i at time t. θ_w is power consumption rate of wind power. $\theta_{c,i}$ is power consumption rate of unit i. C_{fuel} is the fuel cost. OM_w is operation and maintenance cost of wind power. $OM_{c,i}$ is operation and maintenance cost of unit i. D_w is the depreciation cost of wind power. $D_{c,i}$ is the depreciation cost of r unit i.

The power generation cost of thermal power mainly includes generation fuel costs and start-stop cost as calculated in Eq.(4):

$$C_{fuel} = \sum_{i=1}^{I} \sum_{t=1}^{T} [p_{coal} u_{i,t} f_i(Q_{i,t}) + u_{i,t}(1-u_{i,t-1})SU_i + u_{i,t-1}(1-u_{i,t})SD_i] \tag{4}$$

Wherein, p_{coal} is standard coal price. $u_{i,t} f_i(Q_{i,t})$ is standard generation coal consumption of unit *i*. $u_{i,t}$ is the start-stop status variable, when $u_{i,t} = 0$, unit is not in operation, power generation coal consumption is 0. When $u_{i,t} = 1$, the coal consumption is

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

determined by both unit consumption characteristic function $f_i(\bullet)$ and unit real-time power generation output $Q_{i,t}$. The relationship between coal consumption and power output is shown as follow:

$$f_i(Q_{i,t}) = a_i + b_i Q_{i,t} + c_i Q_{i,t}^2 \quad (5)$$

Wherein, a_i , b_i , c_i are relevant parameters of coal consumption function. $u_{i,t}(1-u_{i,t-1})SU_i$ is start cost of unit i at time t . SU_i is one-time start-up cost. $u_{i,t-1}(1-u_{i,t})SD_i$ is shutdown cost of unit i at time t , $u_{i,t-1}(1-u_{i,t})SD_i \neq 0$. SD_i is one-time shutdown cost.

2.2 Constraint conditions

In order to ensure system security and stability, the coordinated scheduling of wind power and thermal power should meet the conditions constraints of load supply and demand, system reserve, thermal power unit operation and wind power output.

2.2.1 Load supply and demand constraints

In order to ensure the real-time balance between electricity demand and power output, system power supply and demand should meet:

$$\sum_{i=1}^{I} u_{i,t} Q_{i,t}(1-\theta_i) + Q_{w,t}(1-\theta_w) = G_t / (1-l) \quad (6)$$

Wherein, $u_{i,t}$ is the start-stop state variable of unit i at time t, if unit i is in start state, $u_{i,t}$=1, if not, $u_{i,t}$=0. $Q_{i,t}$ is the generating capacity of unit i at time t. θ_i is the power consumption rate of unit i. G_t is the real time power demand for system load. l is line loss rate.

2.2.2 System reserve constraints

In order to ensure the real-time balance of power supply and demand, power generation output of thermal power units should meet a certain adjustment margin as follows [25]:

$$\sum_{i=1}^{I} u_{i,t}(Q_{i,t}^{\max} - Q_{i,t})(1-\theta_i) \geq R_t^{usr} \tag{7}$$

$$Q_{i,t}^{\max} = \min(u_{i,t-1}\overline{Q_i}, Q_{i,t-1} + \Delta Q_i^{+}) \cdot u_{i,t-1} \tag{8}$$

$$R_t^{usr} = \beta_c \sum_{i=1}^{I} Q_{i,t} + \beta_w Q_{w,t} \tag{9}$$

Wherein, $Q_{i,t}^{\max}$ is the maximum possible output of unit i at time *t*. R_t^{usr} is system upper reserve demand. $\overline{Q_i}$ is installed capacity of unit i. ΔQ_i^{+} is power ramp up rate of unit i. β_c is reserve factor of thermal power units. β_w is reserve factor of wind power units.

$$\sum_{i=1}^{I} Q_{i,t}(Q_{i,t} - Q_{i,t}^{\min})(1-\theta_i) \geq R_t^{dsr} \tag{10}$$

$$Q_{i,t+1}^{\min} = \max(u_{i,t}\underline{Q_i}, Q_{i,t} - \Delta Q_i^{-}) \cdot u_{i,t} \tag{11}$$

$$R_t^{dsr} = \beta_w Q_{w,t} \tag{12}$$

Wherein, $Q_{i,t}^{\min}$ is the minimum possible output of unit i at time *t*. R_t^{dsr} is system lower reserve demand. $\underline{Q_i}$ is the minimum power output of unit i. ΔQ_i^{-} is power ramp down rate of unit i.

2.2.3 Thermal power unit operation constraints

（1）Unit power generation constraints

The real-time power output of thermal power units are limited by unit installed capacity and the minimum power output [26]:

$$u_{i,t}\underline{Q_i} \leq Q_{i,t} \leq u_{i,t}\overline{Q_i} \tag{13}$$

（2）Unit ramp rate constraints

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

In adjacent period, it has constraint for power output variation of the unit:

$$\Delta Q_i^- \le Q_{i,t} - Q_{i,t-1} \le \Delta Q_i^+ \tag{14}$$

（3）Unit start-stop time constraints

The continuous unit start-up and shut-down time can be described as follows:

$$(T_{i,t-1}^{\text{on}} - M_i^{\text{on}})(u_{i,t-1} - u_{i,t}) \ge 0 \tag{15}$$

$$(T_{i,t-1}^{\text{off}} - M_i^{\text{off}})(u_{i,t} - u_{i,t-1}) \ge 0 \tag{16}$$

Wherein, $T_{i,t-1}^{\text{on}}$ is continuous running time of unit i at time $t-1$. M_i^{on} is the minimum running time of unit i. $T_{i,t-1}^{\text{off}}$ is continuous downtime of unit i at time $t-1$. M_i^{off} is the minimum downtime of unit i.

2.2.4 Wind power output constraints

The real-time output of wind power is restricted by the actually available output of wind power at time *t*, set wind power output coefficient δ_t, then the output of wind power could be calculated in Eq. (17):

$$Q_{w,t} \le \delta_t P_w \tag{17}$$

3 Jointly scheduling model with ESSs and CET

This chapter establishes a jointly scheduling optimization model for wind power and thermal power based on the basic scheduling optimization mode considering ESSs and CET under the objective function of the maximum system benefit.

3.1 Objective function

3.1.1 Objective function with ESSs

If considering ESSs, ESSs' benefit should be taken into

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

consideration. In order to maximize the overall benefit, the optimized objective function is constructed.

$$\max\ z_2 = \pi_c + \pi_w + \pi_s \tag{18}$$

Wherein, π_s is the profit of ESSs related to the price and capacity of charging and discharging power.

$$\pi_s = p_{s,char}\sum_{t=1}^{T} Q_{s,t}^{+} - p_{s,disc}\sum_{t=1}^{T} Q_{s,t}^{-} - F_s \tag{19}$$

Wherein, $p_{s,char}$ and $p_{s,disc}$ are charge price and discharge price of ESSs. F_s is fixed cost.

3.1.2 Objective function with CET

When CET is considered, thermal power unit needs purchase carbon emission from CET market if the carbon dioxide emission of thermal power unit is higher than the initial allocated quota level [27]. Therefore, thermal power scheduling plan will change after CET. In order to maximize system overall benefit with CET, the maximum profits after CET is taken as the objective function as following:

$$\max\ z_3 = \pi_c + \pi_w \tag{20}$$

Wherein, thermal power unit profit π_c satisfies Eq. (21):

$$\pi_c = p_c\sum_{i=1}^{I}\sum_{t=1}^{T} Q_{i,t}(1-\theta_{c,i}) - \left(C_{fuel} + C_{co_2}\right) - \sum_{i=1}^{I} OM_{c,i} - \sum_{i=1}^{I} D_{c,i} \tag{21}$$

Wherein, C_{fuel} is fuel cost calculated by Eq. (4). C_{co_2} is carbon emission cost of thermal power unit calculated as following:

$$C_{co_2} = (E_{co_2} - E_0)\, p_{co_2} \tag{22}$$

Wherein, E_{co_2} is the actual carbon emission quantity during operation period. E_0 is the total initial carbon emission right of thermal power unit. p_{co_2} is CET price. The actual carbon emission quantity of thermal power unit is related to unit power output in each time period. The real-time carbon emission is calculated as following:

$$E_i(Q_{i,t}) = a_{co_2,i} + b_{co_2,i}Q_{i,t} + c_{co_2,i}Q_{i,t}^2 \tag{23}$$

Wherein, $a_{co_2,i}, b_{co_2,i}, c_{co_2,i}$ are relevant parameters in carbon emission function, the total system emission quantity is calculated as follows:

$$E_{co_2} = \sum_{t=1}^{T} \sum_{i=1}^{I} E_i(Q_{i,t}) \tag{24}$$

3.1.3 Objective function with ESSs and CET

If considering ESSs and CET, system could consume more wind power. In order to obtain more profits, the maximum overall profit is taken as objective function.

$$\max \ z_4 = \pi_c + \pi_w + \pi_s \tag{25}$$

3.2 Constraint conditions

The jointly scheduling model should also meet the condition constraints of system reserve, thermal power unit operation and wind power output, as Eq. (6)-Eq. (17). Besides, load supply and demand constraints, capacity constraints of ESSs charge-discharge power should also be considered.

3.2.1 Power balance constraints

Eq. (26) is satisfied by real-time output of wind power, thermal power, ESSs charge-discharge power and system load.

$$\sum_{i=1}^{I} u_{i,t} Q_{i,t} (1-\theta_i) + Q_{w,t}(1-\theta_w) + Q_{s,t}^{-} = G_t / (1-l) + Q_{s,t}^{+} \tag{26}$$

3.2.2 ESSs charge-discharge power constraints

ESSs have dual characteristics of power supply and demand load. Wind power output is high at night, and ESS can be used as load to convert electricity energy into other energy forms for storage. Then in peak load, ESS releases electricity energy as power supply to meet load demand. ESSs can ease the volatility of thermal equivalent output curve and promote system to consume wind power [28]. ESSs charge-discharge processes are restricted by power and capacity. Assuming the storage electricity capacity of ESSs is $Q_{s,t}$ at time t, ESSs charge-discharge power balance is calculated as follows:

$$Q_{s,t} = Q_{s,t-1} + Q_{s,t}^{+} - Q_{s,t}^{-} / (1-\theta_s) \tag{27}$$

Wherein, $Q_{s,t}^{+}$ is charge capacity of ESSs at time t. $Q_{s,t}^{-}$ is discharge capacity of ESSs at time t. θ_s is charge and discharge power loss coefficient. The charge and discharge capacity of ESSs is limited by system technology, which is calculated as follows:

$$Q_{s,t}^{+} \le \overline{Q_s} \tag{28}$$

$$Q_{s,t}^{+} \le \overline{Q_s} \tag{29}$$

Wherein, $\overline{Q_s}$ is upper limitation of ESSs charge-discharge power. In addition, the storage electricity capacity of ESSs is also limited by capacity calculated as following:

$$Q_{s,t} < Q_s^{\max} \tag{30}$$

Wherein, $Q_s^{\max}$ is the maximum storage electricity capacity. For ESSs, the cumulative charge capacity and cumulative discharge capacity meet Eq.(31):

$$\sum_{t=1}^{T} Q_{s,t}^{+}(1-\theta_s) = \sum_{t=1}^{T} Q_{s,t}^{-} \tag{31}$$

In order to make profits, system charge-discharge prices can be calculated as follow:

$$p_{s,char} > p_{s,disc} / (1-\theta_s) \tag{32}$$

4 Case simulation

4.1 Basic data

To verify the feasibility of the proposed model, 10 thermal power generator units and 2800MW wind power are chosen as simulation system. The benchmarking price of thermal power is 380 ¥/MWh (800 ¥/tce). The operation, maintenance and depreciation cost is ¥6,000,000.

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

The benchmarking price of wind power is 540 ¥ /MWh. The charge-discharge power of ESSs is 20 MW/h. The highest charge capacity is 80 MWh. The conversion loss coefficient is 15%. The charge price and discharge price of ESSs are 330 ¥/MWh and 500 ¥/MWh. ESSs' fixed cost is ¥180,000 [29]. Table 1 is available wind power output and load demand in typical load daily. Table 2 and Table 3 are the coefficients and cost of thermal power units, respectively.

Table 1 The available wind power output and load demand in typical load daily (unit: MW)

Time	Wind power	Load	Time	Wind power	Load	Time	Wind power	Load
1	924	1100	9	784	2300	17	896	1700
2	1540	1200	10	308	2500	18	812	1900
3	1904	1400	11	728	2600	19	476	2100
4	2128	1600	12	644	2500	20	364	2500
5	1876	1700	13	336	2400	21	644	2300
6	1428	1900	14	560	2300	22	1064	1900
7	1008	2000	15	252	2100	23	924	1500
8	896	2100	16	588	1800	24	1064	1300

Table 2 Coefficients of thermal power units

Unit	$\overline{Q}_i$ (MW)	$\underline{Q}_i$ (MW)	ΔQ_i^+ (MW/h)	ΔQ_i^- (MW/h)	M_i^{on} (h)	M_i^{off} (h)	θ_i (%)
1#	250	600	280	-280	8	8	4.9
2#	200	500	240	-240	8	8	5.3
3#	200	450	210	-210	7	7	5.2
4#	180	400	180	-180	7	7	5.7
5#	150	350	150	-150	6	6	6.1
6#	150	300	150	-150	5	5	6.8
7#	120	300	120	-120	4	4	6.9
8#	100	250	100	-100	4	4	7.3
9#	70	150	70	-70	3	3	8.3

10#	30	100	50	-50	2	2	8.7

Table 3 Cost of thermal power units

Unit	a_i	b_i	$c_i/10^{-5}$	SU_i	SD_i	$OM_{c,i}+D_{c,i}$	$a_{co_2,i}$	$b_{co_2,i}$	$c_{co_2,i}$ $/10^{-5}$
1#	11.71	0.274	0.644	38.4	38.4	80	29.04	0.680	1.60
2#	9.79	0.282	0.808	34.7	34.7	64	24.77	0.713	2.04
3#	8.88	0.293	1.12	35.0	35.0	60	22.64	0.747	2.86
4#	8.48	0.297	1.84	29.4	29.4	57	21.54	0.754	4.67
5#	7.27	0.304	2.40	24.3	24.3	53	18.97	0.793	6.26
6#	6.17	0.308	3.66	23.1	23.1	45	15.80	0.788	9.37
7#	5.26	0.317	3.74	18.5	18.5	44	13.57	0.818	9.65
8#	4.65	0.328	4.59	12.2	12.2	39	12.18	0.859	12.03
9#	3.54	0.332	4.15	6.5	6.5	30	9.35	0.876	10.96
10#	1.43	0.337	9.01	3.2	3.2	25	3.82	0.900	24.06

4.2 Case setting

To analyze the effects of ESSs and CET on wind power consumption, four cases are set as following:

Case 1: Basic scenario, self-scheduling of system without ESSs and CET. This case is classified into two scenes. One only considers thermal power units and the other one both consider thermal power and wind power.

Case 2: ESSs scenario, self-scheduling of system only with ESSs. The optimizing effects of ESSs on wind power consumption are analyzed. The scheduling model of wind power, thermal power and ESSs is proposed. To study the facilitating effects of ESSs, three scenes are classified by ESSs number, namely with 0 ESS, 1 ESS and 2 ESSs.

Case 3: CET scenario, self-scheduling of system only with CET. The optimizing effects of CET on wind power consumption are mainly analyzed. The scheduling model of wind power and thermal power in CET is construct. The case is classified into three scenes, namely, no CET, 80¥/tce and 100¥/tce for carbon emission if initial carbon emission permit is out.

Case 4: Comprehensive scenario, self-scheduling of system with

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

ESSs and CET. The optimizing effects of CET and ESSs collaboration are analyzed.

4.3 Simulation result

4.3.1 Results in Case 1

Case 1 is the basic scenario and discusses the jointly scheduling optimization of wind power and thermal power without considering ESSs and CET. The carbon emission cost is not considered in this case. Since wind power output has the characteristic of inverse load distribution. Wind power output is higher when load demand is lower at nighttime, whereas, wind power output is lower when load demand is higher at daytime. This characteristic increases the peak-shaving pressure for thermal power. Fig.1 is the output distribution of wind power and thermal power.

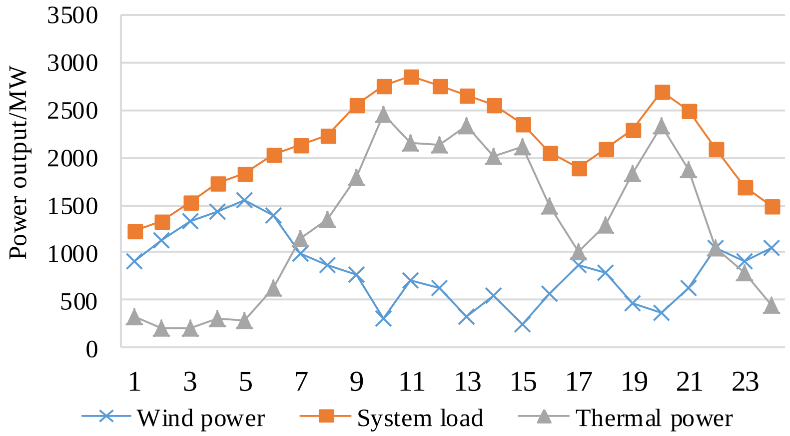

Fig. 1 Output distribution of wind power, thermal power and system load

As Fig.1 shows, the maximum load and minimum load are 2860 MW and 1230 MW, respectively. The difference is 1630 MW and load peak-to-valley ratio is 2.33. If wind power is not covered in system, thermal power units will be scheduled by this load level. However, after considering wind power, the share of wind power generation

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

growing more at valley period, the output equivalence curve of thermal power declines more sharply in the valley and peak periods. As Fig.1 shows, the maximum load and minimum load of equivalent thermal power output curve are 2458 MW and 204 MW. The difference is 2254 MW, and load peak-to-valley ratio is 12.07. By comparison, it is known that the peak pressure of thermal power units increased if considering wind power. Table 4 is the startup and shutdown status of thermal units with and without wind power.

Tab. 4 Startup and shutdown status of thermal units with and without wind power scenes

time	with wind power										without wind power									
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
1	0	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	0	0
2	0	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0
3	0	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0
4	0	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0
5	0	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0
6	0	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0
7	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0
8	1	1	1	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	0	0
9	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	0	0
10	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	0	1
11	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1

As Table 4 shows, if considering wind power, thermal power units encounter an increase in peak pressure and the start-stop counts increased. Most thermal power units have changes in start-stop times. Considering start and stop cost, the start-stop cost of thermal power

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

units is ¥1,292,000 with wind power. However, the starts-stop cost is only ¥282,000 without wind power. The start-stop frequency of thermal power unit increases and the start-stop cost also increases. Table 5 is utilization efficiency of thermal power units under different scenarios.

Tab.5 Utilization efficiency of thermal power units under different scenes

Scene	Unit (%)									
	1	2	3	4	5	6	7	8	9	10
With wind power	60.2	72.7	65.9	42.3	33.4	-	30.7	27.2	-	2.5
Without wind power	93.7	85.3	76.3	66.6	60.4	58.1	41.3	41.0	27.2	18.8

Note: "-" means the unit is not called

Since wind power need more reserve capacity, system reserve demand increases, which means more thermal power units are required to reduce power output to provide reserve. As shown in Table 5, in the scene with wind power, all thermal power units are less efficient than the scene without wind power. Given the less efficient utilization, the coal consumption is higher. In view of the whole system, the average coal consumption of thermal power units is 324.6 kg/kWh，326.0 kg/kWh in the scene with wind power. The average coal consumption of thermal power units is 326.0 kg/kWh in the scene without wind power. That is because small capacity units with lower energy consumption level have higher utilization level. However, concerning the coal consumption level of all units, the coal consumption level in the scene with wind power is higher than that in the scene without wind power.

4.3.2 Results in Case 2

Case 2 is self-scheduling of system only with ESSs, which could analyze the optimization effects of ESSs on wind power consumption. Case 2 is classified into three scenes, namely, 0 ESS, 1 ESSs, and 2 ESSs. Table 6 is system scheduling result under different scenes.

Table 6 system scheduling result under different scenes in Case 2

Scenes	Wind power			Thermal power			Profit/ (10^4¥)
	Power (MWh)	On-grid ratio (%)	Abandoned energy rate(%)	Power (MWh)	On-grid ratio (%)	coal consumption (kg/MWh)	
1	18407.1	35.1	16.9	35274.8	64.9	343.5	327.8
2	18542.1	35.3	16.3	35237.2	64.7	344.3	301.1
3	18620.6	35.4	15.9	35252.5	64.6	344.6	290.0

As Table 6 shows, after considering ESSs, the abandoned wind power decreases and the unit utilization efficiency gradually rises. In the scene of no ESSs, the abandoned wind power rate is 16.9%. If 20 MW ESSs is accessed to system, the rate reduces to 16.3% and on-grid power increases 135.0 MW. If 40 MW ESS is accessed to system, the abandoned wind power rate reduces to 15.9% and on-grid power increases 213.5 MW. As the abandoned wind power rate falls, on-grid power proportion of thermal power units show a downward trend and the coal consumption rate in power supply rises. In the scene without ESSs, the coal consumption rate is 343.5 kg/MWh. If 20 MW ESS is accessed to system, the rate rises to 344.3 kg/MWh, 0.8 kg/MWh more than that in the scene without ESSs. If 40 MW ESS is accessed to system, the rate rises to 344.6 kg/MWh. Considering system profits, the overall profit shows downward trend when ESSs are accessed.

4.3.3 Results in Case 3

Case 3 is self-scheduling of system only with CET and mainly analyzes the optimization effects of CET on wind power consumption. The case is classified into three scenes: no CET, 80¥/tce and 100¥/tce for carbon emission if initial carbon emission permit is out. In scene 1, the total carbon emission of thermal power units is 29079.7 ton. Assuming that carbon emission permit is distributed by 98%, the initial carbon emission of thermal power is 28498.1 ton. In Case 3, the total carbon emission of thermal power is 28765.3 ton, which is 267.2 ton higher than the initial allocation limitation and ¥26,700 is charged for this. Table 8 is the dispatching optimization result of power system under different scenarios.

Table 8 System scheduling result under different scenes in Case 3

Scene	Wind power			Thermal power			Profit/ (10^4 ¥)
	Power (MWh)	On-grid ratio (%)	Abandoned energy rate(%)	Power (MWh)	On-grid ratio (%)	coal consumption (kg/MWh)	
1	18407.1	35.1	16.9	35274.8	64.9	343.5	327.8
2	18413.6	35.1	16.9	35294.8	64.9	346.8	295.9
3	18896.9	36.0	14.7	34772.9	64.0	344.4	305.6

As Table 8 shows, if considering CET, wind power shows upward trend while the abandoned wind t rate falls gradually with the rise of CET prices. Before CET, wind power output is 18407.1 MWh. After CET, the cost for out-of-tolerance emission is charged in standard of 80 ¥/tce. Wind power output reached 18413.6 MWh, showing a small increase. When cost for out-of-tolerance emission is 100 ¥/tce, wind power output is 18896.9 MWh, and the abandoned wind rate falls to 14.7%. Fig.2 is the comparison of thermal power under different carbon prices.

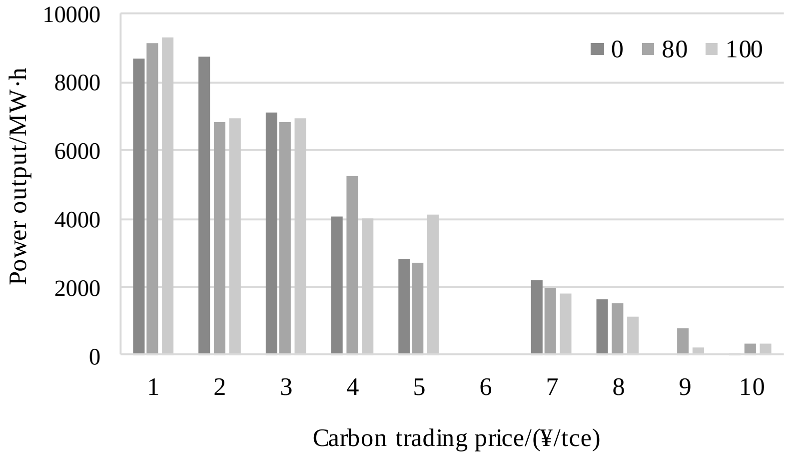

Fig.2 Comparison of thermal power under different carbon prices

As Fig.2 shows, with the rises of CET price, the structure of power generation units shows no remarkable change restricted by reserve capacity and the maximum output.

4.3.4 Results in Case 4

Case 4 is a comprehensive scenario of self-scheduling of system

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

with ESSs and CET and mainly analyzes the synergic optimization effects of CET and ESSs. Case 4 is classified into four scenes: the jointly scheduling of wind power and thermal power scene without ESSs and CET (scene 1), the jointly scheduling of wind power and thermal power scene with ESSs (scene 2), the jointly scheduling of wind power and thermal power scene with CET(scene 3, 100¥/tce for carbon emission if initial carbon emission permit is out) and the jointly scheduling of wind power and thermal power scene with ESSs and CET(scene 4). The carbon emission of thermal power units in Case 4 is 28685.4 ton, which is 187.3 ton higher than the initial allocation limitation, and ¥18,700 is charged for carbon emission. Table 8 is the dispatching optimization result of power system under different scenarios。

Tab.8 System scheduling result under different scenes in Case 4

Scene	Wind power			Thermal power			Profit/ (10^4 ¥)
	Power (MWh)	On-grid ratio (%)	Abandoned energy rate(%)	Power (MWh)	On-grid ratio (%)	coal consumption (kg/MWh)	
1	18407.1	35.1	16.9	35274.8	64.9	343.5	327.8
2	18620.6	35.4	15.9	35252.5	64.6	344.6	290.0
3	18896.9	36.0	14.7	34772.9	64.0	344.4	305.6
4	18963.2	36.1	14.4	34837.5	63.9	342.6	296.4

As Table 8 shows, in terms of wind power, when it is in only combined with thermal power units, the abandoned wind rate is 16.9%. When ESSs or CET is introduced, the rate reduces. When both ESS and CET are introduced, the abandoned wind rate is down to 14.4%. As for thermal power, units' power output decreases with the increase of wind power output, and the proportion of on-grid electricity consumption decreases synchronously. Concerning the overall profit, since fixed cost of ESSs is higher, so the profit is lower than that without ESSs. Fig.3 is the charge-discharge optimization result of energy storage system.

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

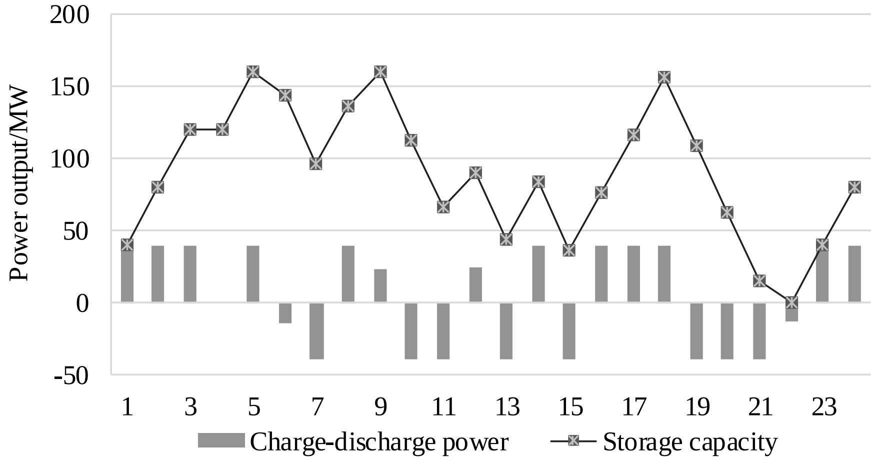

Fig.3 Charge-discharge optimization result of ESS

Fig.3 shows that the charge power and discharge power of ESSs are 488.1 MWh and 346.9 MWh. The final system storage energy is 80 MWh. The gross profit of ESSs is -¥348,000. The charge-discharge revenue of ESSs is ¥12,000. Fig.4 is the comparison of wind power output and charge-discharge power of ESSs.

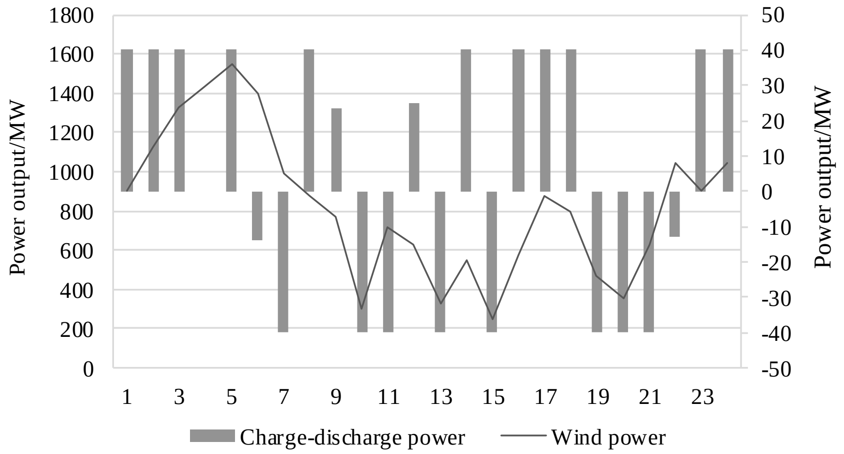

Fig.4 Comparison of wind power output and charge-discharge power of ESS

As Fig.4 shows, in terms of ESSs, it needs to fully release all electric energy and gain economic benefit by selling storage electric energy to maximize the profits at the end of scheduling period. However, to reduce the fluctuation effects of wind power output and reduce the peak pressure of thermal power, ESSs make charge-discharge decisions generally based on output fluctuation of wind power. ESSs charged while wind output rises, and discharged while wind output falls.

5 Conclusion

Due to the volatility and intermittency of wind power, the abandoned wind problem is more serious, which make the optimize wind power consumption has important practical significance. The paper establishes a jointly scheduling model for wind power and thermal power with ESSs and CET and studies the wind power consumption level under different cooperation optimization. The results are as follow:

(1) The large-scale grid connection of wind power need thermal units to provide reserve, thermal power unit utilization efficiency decreased and coal consumption increased. With four cases analyzed, the model can effectively make the scheduling arrangement of the wind power and thermal power and reduce the overall coal consumption rate.

(2) CET can convert the cleaning characteristics of wind power into economic benefits. After considering CET, the carbon emission of thermal power units shows a downward trend, and wind power consumption increases gradually with carbon emission price increasing, which effectively promotes wind power consumption and reduces abandoned wind power. ESSs can improve wind power consumption level, reduce the abandoned wind power rate, improve unit utilization efficiency and enhance the grid-connected space.

(3) The overall system efficiency reach maximum after introducing ESSs and CET. ESSs and CET have synergistic optimization effect, which could optimize the wind power consumption and improve economic benefit of wind power and thermal power.

Conflict of Interests

The authors declare that there is no conflict of interests regarding

ISSN 2616-7433 Vol. 1, Issue 4: 299-323, DOI: 10.25236/FSST.20190347

the publication of this paper.

Acknowledgement

This paper is supported by the National Science Foundation of China (Grant No: 71271081).

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