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Research Article

An Optimization Scheduling Model for Wind Power and Thermal Power with Energy Storage System considering Carbon Emission Trading

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Wind power has the characteristics of randomness and intermittence, which influences power system safety and stable operation. To alleviate the effect of wind power grid connection and improve power system's wind power consumptive capability, this paper took emission trading and energy storage system into consideration and built an optimization model for thermal-wind power system and energy storage systems collaborative scheduling. A simulation based on 10 thermal units and wind farms with 2800 MW installed capacity verified the correctness of the models put forward by this paper. According to the simulation results, the introduction of carbon emission trading can improve wind power consumptive capability and cut down the average coal consumption per unit of power. The introduction of energy storage system can smooth wind power output curve and suppress power fluctuations. The optimization effects achieve the best when both of carbon emission trading and energy storage system work at the same time.

1. Introduction

Carbon emission trading can promote large-scale wind power development and help power industry achieve energy-saving. Wind power output has the characteristics of randomness and intermittence, which puts impact on power system safety and stable operation and makes consumptive problem become the major factor that hinders large-scale wind power development. Power charging and discharging function of energy storage system can smooth wind power output curve, restrain power fluctuation, and provide backup services for wind power grid integration. Therefore, analysis optimization model for thermal-wind power system and energy storage system collaboration scheduling considering carbon emission trading has important sense in improving power system's wind power consumptive capability.

Literature [1] regarded carbon emission as virtual network flow that attached to the power flow. Based on the analysis results of carbon emission trading and power industry developing trend, a theoretical framework for power system carbon emission was built. Literature [2–4] studied carbon emission right definition problems in cross-regional power trading. An emission right allocation principle was obtained according to the carbon flow tracking mathematical model put forward by those literatures. Literature [5–8] discussed the effects of carbon emission trading. While meeting load demand, CO_2 emission can be effectively controlled when carbon trading and energy storage systems are both considered.

Wind power output is random and intermittent, which makes its output hard to be accurately predicted [9]. This factor makes wind power consumptive problem hard to be solved. The most effective solution is to control wind power output characteristics [10, 11]. Wind-thermal power system and energy storage system collaborative scheduling provides an effective way to solve this problem [12–14]. Literature [15, 16] put forward an operation model for multiple-time-scale hybrid system collaborative scheduling, which can arrange wind power and energy storage online and provide the specific scheduling information for system operators. Literature [17, 18] studied specific energy storage measures and built a planning model for hybrid system joint scheduling model that combined wind power and pumped storage.

The rest of this paper is structured as follows. Section 2 introduces the optimization models of wind-thermal system in different scenarios, including the basic optimization model, the model considering carbon emission trading, the model considering energy storage system, and the model considering both of carbon emission trading and energy storage system. To verify the correctness of the models put forward by this paper and analyze the influence of carbon emission trading and energy storage system on power system's wind power consumptive capability, Section 3 demonstrates a numerical example analysis based on 10 thermal power units and wind farms with 2800 MW installed capacity. Section 4 concludes this paper.

2. Optimization for Wind-Thermal System in Different Conditions

2.1. Optimization Model for Wind-Thermal System Collaborative Scheduling. Wind-thermal system optimization collaborative scheduling is aimed at improving wind power consumptive capability. However, wind power grid connection needs thermal power providing backup service to meet demand load. Therefore, overemphasizing the improvement of wind power consumptive capacity would require higher backup service level, which makes related thermal units start up and shut down more frequently and brings more coal consumption and pollutant emission. To improve wind power consumptive capacity and control thermal units' startup and shutdown, this paper builds a scheduling optimization model of wind power and thermal power. Maximizing the total profit is the optimization objective as follows:

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

wherein π_w is the total profit of wind farms; π_c is the total profit of thermal power units. π_w and π_c could be, respectively, calculated by

$$\begin{aligned} \pi_w &= p_w \sum_{t=1}^{T} Q_{w,t}\left(1-\theta_w\right) - \mathrm{OM}_w - D_w, \\ \pi_c &= p_c \sum_{i=1}^{I}\sum_{t=1}^{T} Q_{i,t}\left(1-\theta_{c,i}\right) - C_{\text{fuel}} - \sum_{i=1}^{I}\mathrm{OM}_{c,i} - \sum_{i=1}^{I} D_{c,i}, \end{aligned} \tag{2}$$

wherein p_c is the benchmark price of thermal power in power output area; $Q_{i,t}$ is the real-time output of thermal unit i at time t; $\theta_{c,i}$ is power consumption rate of thermal unit i; C_{fuel} is fuel cost; $\mathrm{OM}_{c,i}$ is maintenance cost of thermal unit i; $D_{c,i}$ is depreciation cost of thermal unit i.

Fuel cost mainly consists of coal cost and oil cost as follows:

$$\begin{aligned} C_{\text{fuel}} = \sum_{i=1}^{I}\sum_{t=1}^{T} &\left[p_{\text{coal}} u_{i,t} f_i\left(Q_{i,t}\right) + u_{i,t}\left(1-u_{i,t-1}\right)\mathrm{SU}_i \right. \\ &\left. + u_{i,t-1}\left(1-u_{i,t}\right)\mathrm{SD}_i\right], \end{aligned} \tag{3}$$

wherein p_{coal} is the procurement price of standard coal; $Q_{i,t}$ is the real-time output of thermal unit i at time t; $u_{i,t} f_i(Q_{i,t})$ is standard coal consumption of thermal unit i with real-time output $Q_{i,t}$; $u_{i,t}$ is an operation or stop status variable of thermal unit i at time t, if the unit stop $u_{i,t} = 0$ and coal consumption is 0; else $u_{i,t} = 1$ and coal consumption could be calculated by the consumption characteristic function $f_i(\cdot)$ and real-time generation output $Q_{i,t}$. The consumption characteristic function is

$$f_i\left(Q_{i,t}\right) = a_i + b_i Q_{i,t} + c_i Q_{i,t}^2, \tag{4}$$

wherein a_i, b_i, and c_i are parameters of coal consumption function and all greater than 0; $u_{i,t}(1-u_{i,t-1})\mathrm{SU}_i$ is startup cost of thermal power unit i at time t, if and only if $u_{i,t} = 1$ and $u_{i,t-1} = 0$, and $u_{i,t}(1-u_{i,t-1})\mathrm{SU}_i$ does not equal zero; SU_i is the cost of a single startup of thermal unit i, including coal and oil costs; $u_{i,t-1}(1-u_{i,t})\mathrm{SD}_i$ is shutdown cost of thermal unit i at time t, if and only if $u_{i,t-1} = 1$ and $u_{i,t} = 0$, and $u_{i,t-1}(1-u_{i,t})\mathrm{SD}_i$ does not equal zero; SD_i is the cost of a single shutdown of thermal unit i, including coal and oil costs.

The constraints mainly consist of three aspects, namely, demand side, wind power, and thermal output constraints.

(1) Equilibrium Constraint of Power Supply and Demand. Consider

$$\sum_{i=1}^{I} u_{i,t} Q_{i,t}\left(1-\theta_i\right) + Q_{w,t}\left(1-\theta_w\right) = \frac{G_t}{(1-l)}, \tag{5}$$

wherein G_t is the demand load at time t; l is the line losses rate of power system.

(2) Backup Service Constraints. When power system operates, generation side may be inconsistent with demand side. To ensure real-time equilibrium between supply and demand, thermal units should adjust their outputs to coordinate wind power output to meet load demand. The adjustments should meet some constraints, which are depending on thermal units' characteristics:

$$\begin{aligned} &\sum_{i=1}^{I} u_{i,t}\left(Q_{i,t}^{\max} - Q_{i,t}\right)\left(1-\theta_i\right) \geq R_t^{\text{usr}}, \\ &Q_{i,t}^{\max} = \min\left(u_{i,t-1}\overline{Q_i}, Q_{i,t-1} + \Delta Q_i^{+}\right)\cdot u_{i,t-1}, \\ &R_t^{\text{usr}} = \beta_c \sum_{i=1}^{I} Q_{i,t} + \beta_w Q_{w,t}. \end{aligned} \tag{6}$$

Equations (6) are upper spinning reserve constraints, wherein $Q_{i,t}^{\max}$ is the maximum possible output of unit i at time t; R_t^{usr} is upper spinning reserve demand, depending on thermal and wind power output in corresponding periods; $\overline{Q_i}$ is the maximum possible output of unit i in unit period, which is determined by installed capacity; ΔQ_i^{+} is the upper limit of power climbing speed, namely, the biggest power increment of unit i in unit period; β_c is thermal power units' power reserve coefficient; β_w is power reserve coefficient of wind turbine. Consider

$$\begin{gathered}\sum_{i=1}^{I} Q_{i,t}\left(Q_{i,t}-Q_{i,t}^{\min}\right)\left(1-\theta_i\right) \geq R_t^{\mathrm{dsr}},\\ Q_{i,t+1}^{\min}=\max\left(u_{i,t}\underline{Q_i}, Q_{i,t}-\Delta Q_i^{-}\right)\cdot u_{i,t},\\ R_t^{\mathrm{dsr}}=\beta_w Q_{w,t}.\end{gathered} \tag{7}$$

Equations (7) are lower spinning reserve constraints. $Q_{i,t}^{\min}$ is the minimum output of unit i at time t, which is determined by two factors: one is the minimum output of unit i at the starting state and the other is output-decreasing constraint of unit i in unit period; R_t^{dsr} is the lower spinning reserve demand, depending on wind power output in corresponding period; $\underline{Q_i}$ is the minimum output of unit i at the starting state in unit time, which is the same as the minimum real-time power output; ΔQ_i^{-} is output-decreasing speed of unit i, namely, the maximum output decrement in unit time.

(3) Thermal Unit Real-Time Output Power Constraint. Real-time output of a thermal power unit is limited by its installed capacity and minimum power output as follows:

$$u_{i,t}\underline{Q_i} \leq Q_{i,t} \leq u_{i,t}\overline{Q_i}. \tag{8}$$

(4) Output Climbing Speed Constraints. Influenced by technical level, thermal power output changes in a unit period are limited. Real-time output power increment and decrement should meet

$$\Delta Q_i^{-} \leq Q_{i,t}-Q_{i,t-1} \leq \Delta Q_i^{+}. \tag{9}$$

(5) Unit Startup and Shutdown Time Constraints. Frequently startup and shutdown are harmful to unit's performance and cause more fuel cost. Therefore, constraints for the continuous startup and shutdown time are necessary, as shown in the following equations:

$$\left(T_{i,t-1}^{\mathrm{on}}-M_i^{\mathrm{on}}\right)\left(u_{i,t-1}-u_{i,t}\right) \geq 0, \tag{10}$$

$$\left(T_{i,t-1}^{\mathrm{off}}-M_i^{\mathrm{off}}\right)\left(u_{i,t}-u_{i,t-1}\right) \geq 0. \tag{11}$$

Equation (10) is the minimum startup time constraint; $T_{i,t-1}^{\mathrm{on}}$ is continuous running time of unit i at time $t-1$; M_i^{on} is the minimum continuous running time. Equation (11) is the minimum downtime constraint; $T_{i,t-1}^{\mathrm{off}}$ is continuous downtime of unit i at moment $t-1$; M_i^{off} is the minimum continuous downtime.

(6) Wind Power Output Constraint. Wind turbine real-time power output is determined by income air velocity:

$$Q_{w,t} \leq \delta_t P_w, \tag{12}$$

wherein δ_t is the equivalent efficiency of wind farms at time t; P_w is the total installed capacity of wind farms.

2.2. Optimization Model for Wind-Thermal System with Carbon Emission Trading.

The introduction of carbon emission trading would redefine thermal power marginal cost, which consists of power generation cost and carbon emission cost. Pollutant emission coefficients of different units are not the same. Therefore, the introduction of carbon emission trading would change the original scheduling plan. To maximize system profit under carbon trading mechanism, this paper built an optimization model with the objective of maximizing the total profit of thermal power and wind power as follows:

$$\max z_2=\pi_c+\pi_w. \tag{13}$$

The profit of thermal power π_c can be calculated by

$$\pi_c=p_c\sum_{i=1}^{I}\sum_{t=1}^{T} Q_{i,t}\left(1-\theta_{c,i}\right)-C_c-\sum_{i=1}^{I}\mathrm{OM}_{c,i}-\sum_{i=1}^{I} D_{c,i}, \tag{14}$$

wherein p_c is the benchmark price of thermal power in power output area; $\theta_{c,i}$ is self-power-consumption rate of thermal unit i; $\mathrm{OM}_{c,i}$ is the maintenance cost of thermal unit i; $D_{c,i}$ is the depreciation cost of thermal power unit i.

Carbon emission trading mechanism uses emission cost to measure the environmental value of power generation plans. Without carbon emission trading, the variable cost of thermal units mainly consists of coal cost, oil cost, and water cost. But while carbon emission trading is considered, the thermal unit must buy CO_2 emission right when its emission exceeds the initial allocated quota level. Therefore, the variable cost of thermal power could be calculated by

$$C_c=C_{\mathrm{fuel}}+C_{\mathrm{CO}_2}, \tag{15}$$

wherein C_{fuel} is the fuel cost that includes coal cost and oil cost; C_{CO_2} is carbon emission cost, which could be calculated by

$$C_{\mathrm{CO}_2}=\left(E_{\mathrm{CO}_2}-E_0\right) p_{\mathrm{CO}_2}, \tag{16}$$

wherein E_{CO_2} is actual carbon emission amount of thermal power; E_0 is the initial allocated carbon emission right, namely, the allowed CO_2 emission amount; p_{CO_2} is carbon emission trading price, determined by the supply and demand relationship in the carbon emission trading market. To simplify the optimization model, this paper hypothesized the price to be a constant value in a short period.

Thermal units' carbon emission amount is related to its power load rate. Generally speaking, carbon emission of unit electricity production can be integrated as a quadratic function as follows:

$$E_i\left(Q_{i,t}\right)=a_{\mathrm{CO}_2,i}+b_{\mathrm{CO}_2,i}Q_{i,t}+c_{\mathrm{CO}_2,i}Q_{i,t}^2, \tag{17}$$

wherein $a_{\mathrm{CO}_2,i}$, $b_{\mathrm{CO}_2,i}$, and $c_{\mathrm{CO}_2,i}$ are parameters of the carbon emission function.

Total carbon emission of the system can be calculated by

$$E_{\mathrm{CO}_2}=\sum_{t=1}^{T}\sum_{i=1}^{I} E_i\left(Q_{i,t}\right). \tag{18}$$

Other constraints are the same as the basic model in Section 1, from (6) to (12).

2.3. Optimization Model for Wind-Thermal System with Energy Storage System.

While energy storage system is considered, the stakeholders would change from two to three parties. To maximize the total profit, the objective should be changed into (23). Consider

$$\max z_3 = \pi_c + \pi_w + \pi_s, \tag{19}$$

wherein π_s is the profit of energy storage system, determined by charge-discharge price, charge-discharge electric quantity, and fixed cost. Consider

$$\pi_s = p_{s,\mathrm{char}}\sum_{t=1}^{T} Q_{s,t}^{+} - p_{s,\mathrm{disc}}\sum_{t=1}^{T} Q_{s,t}^{-} - F_s, \tag{20}$$

wherein $Q_{s,t}^{+}$ is energy storage system's charging power at time t; $Q_{s,t}^{-}$ is energy storage system's discharging power at time t; F_s is the fixed cost of energy storage system; $p_{s,\mathrm{char}}$ and $p_{s,\mathrm{disc}}$ are, respectively, charging and discharging price.

Energy storage system can control power charging and discharging, which make it have the characteristics of both power and load. Wind power output opposite distributed with demand load. In daytime, wind power is not sufficient to satisfy demand load and the energy storage system would act as power to meet the demand load. In night wind power output is far exceeding demand load and energy storage system would act as load to transform the extra wind power into potential energy.

The charge and discharge process of energy storage system is determined by real-time load equilibrium and the charging-discharging capability of the energy storage system. Assuming the power that energy storage stored in system s at time t is $Q_{s,t}$, charge-discharge power balance should meet (21). Consider

$$Q_{s,t} = Q_{s,t-1} + Q_{s,t}^{+} - \frac{Q_{s,t}^{-}}{(1-\theta_s)}, \tag{21}$$

wherein θ_s is discharging power at time t; θ_s is charge-discharge power loss coefficient that is reflecting the power loss during power transforming.

Charge-discharge capability in unit time is limited by technical level of the energy storage system, as shown in (22) and (23). Consider

$$Q_{s,t}^{+} \le \overline{Q_s}, \tag{22}$$

$$Q_{s,t}^{-} \le \overline{Q_s}, \tag{23}$$

wherein $\overline{Q_s}$ is the upper limit of energy storage system charge-discharge power in unit time.

Energy storage system power storage capability also has its upper limit.

Consider

$$Q_{s,t} < Q_s^{\max}, \tag{24}$$

wherein $Q_s^{\max}$ is the maximum storage capacity of storage system.

For the entire study period, the charged power should be equal to the discharged power as follows:

$$\sum_{t=1}^{T} Q_{s,t}^{+}\left(1-\theta_s\right) = \sum_{t=1}^{T} Q_{s,t}^{-}. \tag{25}$$

Based on (25), to ensure energy storage system positive profit, charge and discharge price should meet

$$p_{s,\mathrm{char}} > \frac{p_{s,\mathrm{disc}}}{(1-\theta_s)}. \tag{26}$$

At any moment power output should equal demand load as follows:

$$\begin{aligned}\sum_{i=1}^{I} u_{i,t}Q_{i,t}\left(1-\theta_i\right) + Q_{w,t}\left(1-\theta_w\right) + Q_{s,t}^{-} \\ = \frac{G_t}{(1-l)} + Q_{s,t}^{+}.\end{aligned} \tag{27}$$

Other constraints are the same as the basic model in Section 1, namely, from (6) to (12).

2.4. Optimization Model for Wind-Thermal System with Carbon Emission Trading and Energy Storage System.

The same with Section 3, in this optimization model the optimization objective is still consisting of three parts as follows:

$$\max z_4 = \pi_c + \pi_w + \pi_s, \tag{28}$$

wherein thermal power unit profit π_c is influenced by coal consumption, coal price, carbon emission, and carbon emission price. π_c could be calculated by

$$\begin{aligned}\pi_c = \Bigg[& p_c\sum_{i=1}^{I}\sum_{t=1}^{T} Q_{i,t}\left(1-\theta_{c,i}\right) - C_{\mathrm{fuel}} - C_{\mathrm{CO}_2} \\ & - \sum_{i=1}^{I}\mathrm{OM}_{c,i} - \sum_{i=1}^{I} D_{c,i}\Bigg],\end{aligned} \tag{29}$$

wherein carbon emission cost is determined by the initial allocated carbon emission right and carbon emission price.

Wind power and thermal power real-time output, energy storage system charge-discharge power, and system load should comply with

$$\begin{aligned}\sum_{i=1}^{I} u_{i,t}Q_{i,t}\left(1-\theta_i\right) + Q_{w,t}\left(1-\theta_w\right) + Q_{s,t}^{-} \\ = \frac{G_t}{(1-l)} + Q_{s,t}^{+}.\end{aligned} \tag{30}$$

Other constraints are the same as the basic model in Section 1, from (6) to (12).

Table 1: Equivalent utilization of wind power units (MW).

Period	Load	Utilization ratio	Period	Load	Utilization rate	Period	Load	Utilization rate
1	1100	0.33	9	2300	0.28	17	1700	0.32
2	1200	0.55	10	2500	0.11	18	1900	0.29
3	1400	0.68	11	2600	0.26	19	2100	0.17
4	1600	0.76	12	2500	0.23	20	2500	0.13
5	1700	0.67	13	2400	0.12	21	2300	0.23
6	1900	0.51	14	2300	0.20	22	1900	0.38
7	2000	0.36	15	2100	0.09	23	1500	0.33
8	2100	0.32	16	1800	0.21	24	1300	0.38

Table 2: Dispatching optimization result of power system under different scenarios.

Scenario	Wind power			Thermal power			Profit (10^4 Yuan)
	Output (MW·h)	Grid accessed rate (%)	Abandoned rate (%)	Output (MW·h)	Grid accessed rate (%)	Coal consumption (kg/MW·h)	
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

3. Numerical Example Analysis

3.1. Basic Data. This paper did a simulation based on 10 thermal power units and wind power farms with 2800 MW installed capacity. Thermal power units' operating parameters are referred to in literature [19]. A typical day's system load and wind load output data is shown in Table 1. Assume wind power tariff to be 540 Yuan/MW·h, maintenance and depreciation costs to be 600 million, and thermal power tariff to be 380 Yuan/MW·h, equivalent to 800 Yuan/t of standard coal price.

3.2. Numerical Example Results. With the optimization objective of maximizing total profit, this paper solved the scheduling optimization model of wind and thermal power with or without carbon trading and energy storage system by the mean of GAMS.

3.2.1. Carbon Emission Trading's Impact on Wind Power Consumption. To study different carbon emission prices' impact on wind power consumption, three carbon emission mechanisms scenarios are set. Carbon emission trading is not considered in scenario 1; namely, the carbon trading is not levied. In other two parts the part where carbon emission quantity exceeds initial carbon emission right should levy emission fee. The fee is 80 Yuan/t in scenario 2 and 100 Yuan/t in scenario 3.

In scenario 1, total carbon emission is 29079.7 t. Assume the allocated carbon emission right is 98% of the total emission; the initial carbon emission right that thermal power gains would be 28498.1 t. Wind power consumptive optimization results under different carbon emission mechanisms are listed in Table 2.

According to Table 2, price increasing of carbon emission trading would increase wind power output and decrease abandoned wind. In scenario 1, wind power generation is 18407.1 MW·h. When carbon emission trading price is 80 Yuan/t, wind power output is increased to 18413.6 MW·h. When carbon emission trading price is 100 Yuan/t, wind power output is 18896.9 MW·h and abandoned wind rate would decrease to 14.7%. Thermal power outputs with different carbon emission trading prices are shown in Figure 1.

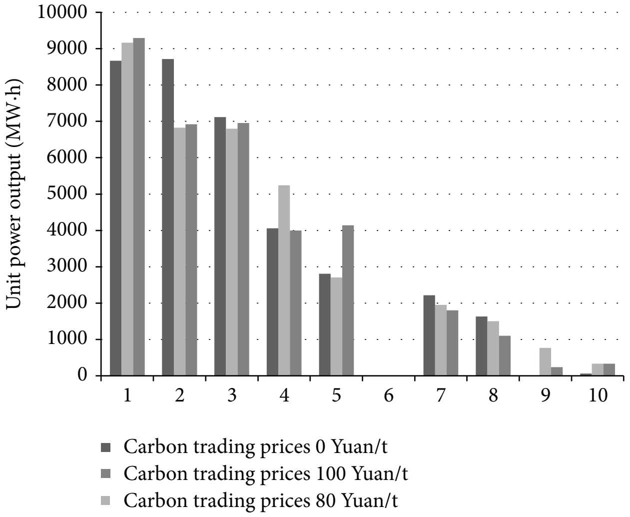

Figure 1: Thermal power output with different carbon emission trading prices.

The introduction of carbon emission trading mechanism makes thermal power market structure change with the margin output cost. For example, units 2# and 3# are with big carbon emission coefficients; the increasing of carbon trading price would decrease their output. Contrarily, unit 5# has small carbon emission coefficients; then the increasing of carbon emission trading would increase its power output. To meet system supply and demand balance constraints,

Table 3: Dispatching optimization result of power system under different scenarios.

Scenario	Wind power			Thermal power			Profit (10^4 Yuan)
	Generation (MW·h)	Electricity grid accessed rate (%)	Wind abandon rate (%)	Generation	Electricity grid accessed rate (%)	Coal consumption (kg/MW·h)	
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

Table 4: Dispatching optimization result of power system under different scenarios.

Scenario	Wind power			Thermal power			Profit (10^4 Yuan)
	Generation (MW·h)	Electricity grid accessed rate (%)	Wind abandon rate (%)	Generation (MW·h)	Electricity grid accessed rate (%)	Coal consumption (kg/MW·h)	
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

unit backup constraints, and unit output constraints, thermal power generation structure does not show obvious change regulation.

3.2.2. Energy Storage System's Impact on Wind Power Consumption. To study energy storage system impact on wind consumption, this paper sets three scenarios according to the energy storage capacity. And optimization results are shown in Table 3.

With the access and scale-expansion of energy storage system, abandoned wind rate showed a downward trend and unit utilization efficiency increased gradually. Without energy storage system, abandoned wind rate is 16.9%. With 20 MW energy storage system connected to the system, abandoned wind rate decreased to 16.3% and electric quantity increased by 135.0 MW. With 40 MW energy storage system connected to the system, abandoned wind rate decreased to 15.9%, and electric quantity increased by 213.5 MW.

When decreasing the abandoned wind rate, thermal power output decreased and its net coal consumption rate increased to some extent. Without energy storage system, unit output coal consumption quantity is 343.5 kg/MW·h. And when the connected energy storage system is with 20 MW power storage capacity, the unit coal consumption quantity changes to be 344.3 kg/MW·h and 344.6 kg/MW·h, separately increased by 0.8 kg/MW·h and 1.1 kg/MW·h.

From the aspect of system profit, system profit decreased with the increasing power storage capacity, which is because of energy storage system's high investment cost and lack of commercial promotion in large scale. From the aspect of policy, China's policies gradually concentrate on large-scale energy storage system development but still lack industrial planning, industrial standards and financial subsidy, and other substantive supports. From the aspect of economic benefits, only pumped storage power plants can gain good economic benefit; other storage techniques are constrained by the high investment cost and unsound energy storage electricity price mechanism.

The development of China's large-scale energy storage system means both opportunities and challenges. Currently, challenges that are brought by price mechanism and investment cost are much more than opportunities. But in the long run, with the establishment of price mechanism and mature energy storage technology, China's large-scale energy storage system has a huge potential market.

3.2.3. Carbon Trading and Energy Storage System's Impact on Wind Consumption. To compare wind power consumption of different combinations, 4 scenarios were set according to wind consumption combination with assistance of generation side. Scenario 1 is wind and thermal power joint scheduling optimization. Scenario 2 is wind and thermal power, energy storage system integrated scheduling optimization. Scenario 3 is wind and thermal power integrated scheduling optimization under carbon trading mechanism. Scenario 4 is wind power, thermal power, and energy storage system joint scheduling optimization with carbon trading mechanism. This paper uses GAMS to optimize. The optimization results are listed in Table 4.

From the aspect of wind power output, when there are only thermal power and wind power joint scheduled, the abandoned wind rate is 16.9%. With the introduction of carbon emission trading or energy storage system, abandoned wind rate decreased. And when both of carbon emission trading and energy storage system are considered, abandoned wind rate decreased to 14.4%, which achieves the minimum in 4 scenarios. From the aspect of thermal power, its power output and grid accessed rate decreased from scenario 1 to scenario 4.

From the aspect of system total profits, due to the high fixed cost of energy storage system, the profits will be higher without energy storage system. For energy storage system, its real-time charge and discharge power in scenario 4 and system power storage are shown in Figure 2. In scenario 4, energy storage system total charged power quantity is 488.1 MW·h, discharged power quantity is 346.9 MW·h, and

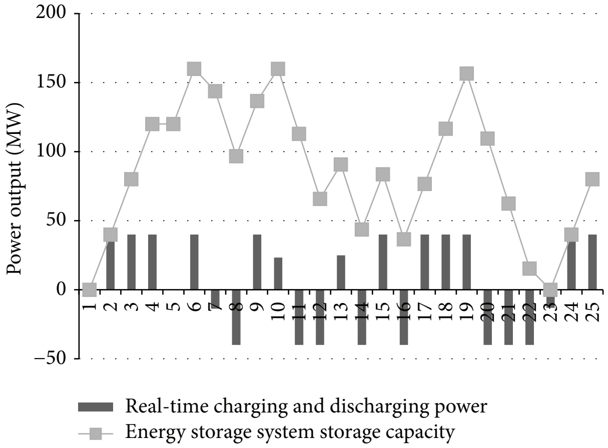

Figure 2: Charge and discharge optimization result of energy storage system.

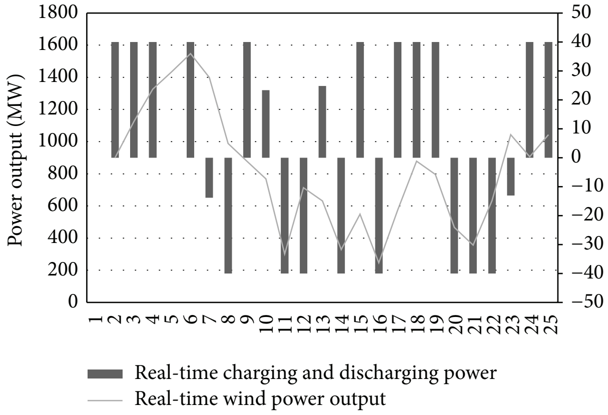

Figure 3: Comparison of wind power output and charge-discharge power of energy storage system.

final power storage is 80 MW·h. According to (22), total profit of energy storage system is −348000 Yuan. Wherein profit in charge-discharge process is 12000 Yuan, fixed cost is 360000 Yuan.

For energy storage system, it should release all the power in the final time to gain more economic benefits by selling the stored power. However, to reduce wind power output fluctuation's impact on system, charge and discharge decisions are determined by wind power output, which can reduce the pressure on thermal power peak shaving.

Figure 3 shows the change curves of real-time wind power output and energy storage charge-discharge power. In Figure 3, most of the charging time is in the wind power output-increasing period and most of the discharging time is in the wind power output-decreasing period.

From the aspect of system carbon emission level, thermal power's carbon emission is 28765.3 t in scenario 3, which is 267.2 t more than the initial allocated quota, and 26700 Yuan should be levied as the carbon emission cost. Thermal power's carbon emission is 28685.4 t in scenario 4, which is 187.3 t, and is more than the initial allocation quota, and 187000 Yuan should be levied as the carbon emission cost.

Based on the above analysis, the introduction of carbon emission trading and energy storage systems can improve wind power consumptive capacity, improve wind power generation efficiency, and reduce thermal power output as well as coal consumption. However, due to the high fixed costs of energy storage system, power profits will be reduced by the access of energy storage system. For the examples in this paper, total charge quantity of the energy storage system is 488.1 MW·h, and total profit is −348000 Yuan.

4. Conclusion

To promote large-scale wind power grid connection and achieve energy-saving, this paper introduced carbon emission trading, which can bring economic benefits for wind power. To alleviate randomness and intermittence of wind power output and its impact on wind power consumptive capacity, this paper introduced energy storage system to provide backup services for wind power and built wind power energy storage collaborative scheduling optimization model with carbon emission trading and made a numerical example; the conclusions are as follows:

(1) Carbon emission trading can bring economic benefits for wind power and transform its cleaning feature into economic value, improve wind power grid connection, and reduce average coal consumption if there is power generation. The introduction of energy storage system can smooth wind power output, suppress fluctuation, and provide backup services for wind power that accessed the grid; electric quantity of wind power paralleling in the grid increased with the increasing capacity of energy storage system access.

(2) Energy storage system and carbon emission trading's introduction can achieve security and stability while running to maximize wind power capacity and increase economic benefits of wind power. However, due to the high fixed cost of energy storage systems, the above measures would reduce system total profit. Therefore, to maximize wind power utilization, related subsidies for the energy storage system need to be formulated.

Conflict of Interests

The authors declare that there is no conflict of interests.

Authors' Contribution

Huan-huan Li, Qing-kun Tan, and Li-wei Ju have built the demand response model, energy storage model, and power generation scheduling optimization model and He Xin and Zhong-fu Tan have improved the models and built the scenario simulation and reduction strategy and done the simulation analysis.

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