The Open Fuels & Energy Science Journal, 2015, *8*, 189-196

The Synergistic Scheduling Optimization Model for Wind Power and Thermal Power with Energy Storage System Under the Carbon Emission Trade

Liu Hai-Bo*[,1], Xin He[1], Wu Hongliang[2], Zhou Bao-Rong[2], Dong Nan[2] and Pan Ge[1]

[1]*North China Electric Power University, Beijing, China*

[2]*Electric Power Research Institute, CSG, Guangzhou 510080, China*

Abstract: In order to alleviate the effect of randomness and intermittent of wind power output on safe and stable operation of the power grid and improve system consumptive wind power capacity, the paper introduce carbon emissions trading and energy storage systems to construct the collaborative scheduling optimization model of wind power and energy storage system based on the energy generation scheduling optimization model of wind power and thermal power. Then, 10 thermal power and 2800MW wind farms constitute simulation systems to analyze the impact of carbon trading and energy storage systems on system wind power consumptive capacity. Numerical example shows: The introduction of carbon trading can increase wind power capacity and reduce coal consumption systems; the introduction of the energy storage system can gentle wind power output, suppress power fluctuations; While, system optimization results achieve the best when carbon trading and energy storage systems are introduced at the same time.

Keywords: Carbon trade emission, energy storage system, model, scheduling, wind power.

1. INTRODUCTION

Carbon emissions trading introduction can promote large-scale development of wind power with clean characteristics, realize energy conservation and emissions reduction. However, subjected to randomness and intermittence of wind power output, large-scale wind power grid integration will bring impact on stable operation of power grid. The charge -discharge properties of energy storage system can smooth wind power output, restrain power fluctuation and provide back-up services for wind power grid integration. So study cooperative scheduling optimization of wind energy storage system with carbon emission trading has an important effect on improving wind power consumption

Literature [1] considered carbon emissions as virtual network flow attached to the trend. With analysis of carbon emissions and power trend, theoretical framework of power system carbon emissions was built. Literature [2-3] studied carbon emissions property's definition of power interregional transportation. Based on the construction of carbon flow tracking mathematical model, a fair allocation principle was proposed. Literature [4-7] discussed the carbon emissions trading. On the premise of guaranteeing load demand, CO2 emission can be effectively controlled with the consideration of carbon emissions trading cost, wind energy storage system can effectively reduce carbon emissions.

Wind energy resource is random, intermittent and have the low accuracy of prediction [8], wind power 's characteristics run counter to reliable demand of the power system, the key to solve this problem is how to control power characteristic of the wind power when it access system [9]. In recent years, combined operation of wind power energy storage hybrid system [10-11] provided an efficient way to this issue. Literature [12] established the hybrid system combined operation model under multiple time scales for wind power storage hybrid system, which can arrange wind power output and energy storage online and has actual operability, it can provide the specific scheduling output information for the system operators. Literature [13-14] considered specific energy storage measures, two phase dynamic programming model of the hybrid system combined operation was set up through combination of wind power and pumped storage power.

In summary, this paper introduced carbon emissions trading and energy storage systems based on the collaborative scheduling optimization model of wind and thermal power. Wind power consumption optimization models are built with carbon trading, energy storage system, and both of them. Then, the paper made 10 thermal power units and wind farm of 2800MW into a simulation system to analyze the impact of carbon trading and energy storage system on wind power consumption.

2. SCHEDULING OPTIMIZATION MODEL OF WIND AND THERMAL POWER

The purpose of wind and thermal power's optimal scheduling is to promote wind power consumption, but if

*Address correspondence to this author at the North China Electric Power University, Beijing, China

1876-973X/15

wind power consumption is over -pursued, more frequent peak shavings and more start-stop of thermal power units may be required. So, although the electricity to access grid for wind power is assured, the coal consumption may increase. To achieve optimal energy efficiency of system generation, this paper built a scheduling optimization model of wind and thermal power with the goal of maximizing the profit, the specific objective function is shown as follows,

$\max z_1 = \pi_w + \pi_c$ (1) Wherein, π_w is wind farms 'profit, π_c is total profits of thermal power units.

Profit of the wind farms is shown as follows:

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

Profit of thermal power units is shown as follows,

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

Wherein, p_c is thermal power's stake electrovalence of sending area. $Q_{i,t}$ is real-time generation power of thermal power unit i at moment t ; $\theta_{c,i}$ is power consumption rate of thermal power unit i , C_{fuel} is fuel cost ; $OM_{c,i}$ is maintenance cost of thermal power unit i ; $D_{c,i}$ is depreciation cost of thermal power unit i .

Fuel cost of the thermal power units mainly consists of the coal cost and oil cost, which is shown as follows:

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

Wherein, p_{coal} is procurement price of standard coal ; $u_{i,t}f_i(Q_{i,t})$ is standard coal consumption during the thermal power units' operation; $u_{i,t}$ is start-stop factor, when the thermal power unit shutdown, namely $u_{i,t} = 0$, coal consumption of the generation is 0; When thermal power units operate, namely $u_{i,t} = 1$, coal consumption is decided by the consumption characteristic function $f_i(\cdot)$ and real-time generation output $Q_{i,t}$ .The relationship between coal consumption and generation output is often shown as a quadratic function, which is

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

Wherein, a_i □ b_i □ c_i are related parameters of coal consumption function and they are all greater than 0; $u_{i,t}(1-u_{i,t-1})SU_i$ is start-up cost of thermal power units at moment t , if and only if $u_{i,t} = 1$, $u_{i,t-1} = 0$, it does not equal to zero; SU_i is the cost of single start-up, including coal and fuel costs. $u_{i,t-1}(1-u_{i,t})SD_i$ is shutdown cost at moment t , if and only if $u_{i,t-1} = 1$, $u_{i,t} = 0$, it does not equal to zero SD_i .is single shutdown cost of the unit, including coal and fuel costs.

(1) Supply and demand balance constraints

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

Wherein, G_t is system load demand, l is grid losses.

(2) System generation reserve constraints

When power system operate, generation side and demand side may fluctuate. In order to ensure real-time balance, the adjustment of power output is necessary to meet certain margin, through increasing or reducing the power output.

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

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

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

Equation (7) - (9) is maximum spinning reserve constraint of system, $Q_{i,t}^{\max}$ is maximum possible output of unit i in period t ; R_t^{usr} is upper rotation reserve constraint demand, depending on thermal and wind power generation of corresponding period;

$\overline{Q_i}$ is maximum possible generation of unit i in unit time, adapted to the installed capacity; ΔQ_i^{+} is upper generate climbing speed, namely the biggest power increment of unit i in adjacent period; β_c is thermal power units' power reserve coefficient β_w is wind turbines 'power reserve coefficient.

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

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

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

Equation (10) - (12) is minimum spinning reserve constraints. $Q_{i,t}^{\min}$ is minimum possible output of unit i in period t , it is restricted by two factors, one is the minimum possible generation in unit time at starting state, one is downward generate climbing constraint in adjacent time; R_t^{dsr} is downward spinning reserve requirements, depending on the wind power of corresponding period; $\underline{Q_i}$ is the minimum possible output of unit i at starting state in unit time, which is suitable to real-time minimum power output; ΔQ_i^{-} is downward generate climbing speed of unit i , namely the maximum unit generation decrement in adjacent time.

(3) Real-time power constraint of thermal power units

Real-time output of thermal power units is limited by installed capacity and minimum power output, which is shown as follows (13)

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

(4) Unit climbing speed constraints

Influenced by the technology, output change in adjacent period have constraints to some extent, increment and decrement of real-time output should meet:

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

(5) Unit start-stop time constraints

Frequent start-stop of generators will damage the performance and cause huge fuel consumption at the same time, so constraints for the continuous start-stop time of the unit are shown as follows;

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

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

Equation (15) is minimum start time constraints; $T_{i,t-1}^{\text{on}}$ is running time of unit i at moment $t-1$; M_i^{on} is minimum running time. Formula (16) is minimum downtime constraint; $T_{i,t-1}^{\text{off}}$ is downtime of unit i at moment $t-1$; M_i^{off} is minimum downtime.

(6) Wind power output constraints

Wind turbines 'real-time power output is restrained by the air income, and it meet: $Q_{w,t} \le \delta_t P_w$ (17)

Wherein, δ_t is equivalent efficiency of wind farms in period t; P_w is wind farms' total installed capacity.

3. WIND CONSUMPTION OPTIMIZATION MODEL WITH CARBON TRADING ASSISTANCE

With the introduction of carbon trading, thermal power generation marginal cost will consist of power generation cost and carbon emissions cost. Due to different carbon emissions coefficients, the introduction of carbon trading mechanism will change original generation scheduling plan. To maximize whole system profit under the carbon trading mechanism, this paper built an optimization model with the objective of maximizing thermal and wind power profits (18).

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

The profits π_c of thermal power should meet

$$\pi_c = p_c \sum_{i=1}^{I}\sum_{t=1}^{T} Q_{i,t}(1-\theta_{c,i}) - C_c - \sum_{i=1}^{I} OM_{c,i} - \sum_{i=1}^{I} D_{c,i} \tag{19}$$

Thermal power profit π_c should meet the following conditions

Wherein: p_c is thermal power stake electrovalence in sending area; $\theta_{c,i}$ is thermal unit service-power consumption rate; $OM_{c,i}$ is maintenance cost of thermal unit i, $D_{c,i}$ is depreciation cost of thermal power unit i.

Carbon trading mechanism transforms environmental value into emission cost. Then, environmental value could be considered in electricity production. Without considering carbon trading mechanism,

Thermal power variable cost includes coal cost, oil cost and water cost, etc. However, under the carbon trading mechanisms, if power generation CO2 emission is higher than the initial allocated quota level, thermal power unit will buy carbon emission right from carbon trading market to satisfy the production, under the mechanism of carbon trading, thermal power variable cost is:

$$C_c = C_{fuel} + C_{co_2} \tag{20}$$

Wherein, C_{fuel} is the fuel cost, C_{co_2} is the carbon emission cost

Thermal unit carbon emission cost is as follows

$$C_{co_2} = (E_{co_2} - E_0)p_{co_2} \tag{21}$$

Wherein, E_{co_2} is actual carbon emission of thermal unit during the operation period, E_0 is total initial carbon emission right, p_{co_2} is carbon trading price, which is related to carbon trading demand, to simplify the optimization model, this paper hypothesized the price would not change by the carbon trading demand.

Actual thermal units' carbon emission is related to power load rate. Generally speaking, actual carbon emission of unit electricity production can be integrated as a quadratic function.

Wherein, $a_{co_2,i}$ □ $b_{co_2,i}$ □ $c_{co_2,i}$ are parameters of carbon emission function.

Then, total system emissions is

$$E_{co_2} = \sum_{t=1}^{T}\sum_{i=1}^{I} E_i(Q_{i,t}) \tag{23}$$

System power back-up service constraint, real-time thermal power constraint, unit climbing speed constraint, unit start-up time constraint are shown in formula (7) to (17).

4 WIND POWER CONSUMPTION OPTIMIZATION MODEL WITH ENERGY STORAGE SYSTEM

4.1. Energy Storage System Charge - Discharge Model

Energy storage system has characteristics of both power and load. When wind power output is at high level during the night, energy storage system will act as load to transform electrical energy into other forms of energy. When load is at high level during the day, energy storage system will act as the power to meet the load demand.

Charge-discharge process of the energy storage system is constrained by charge-discharge power and system capacity. Assuming the power that energy storage stored at moment t is $Q_{s,t}$, charge-discharge power balance should meet:

$$Q_{s,t} = Q_{s,t-1} + Q_{s,t}^{+} - Q_{s,t}^{-} / (1-\theta_s) \tag{24}$$

Wherein, $Q_{s,t}^{+}$ is energy storage system's charging quantity at moment t , θ_s is discharging quantity at moment t , θ_s is charge-discharge power loss coefficient, namely the energy consumption level.

Charge-discharge capacity in unit time is constrained by technical level, it should meet:

$$Q_{s,t}^{+} \le \overline{Q_s} \tag{25}$$

$$Q_{s,t}^{-} \le \overline{Q_s} \tag{26}$$

Wherein, $\overline{Q_s}$ is charge-discharge power upper limit of energy storage system in unit time, the capacity of energy storage system is constrained by the upper storage limit, the capacity should meet:

$$Q_{s,t} < Q_s^{\max} \tag{27}$$

Wherein, $Q_s^{\max}$ is storage system maximum storage capacity.

4.2. Wind Power Consumption Model with Energy Storage System

Considering the energy storage system, system' stakeholders should include energy storage system besides thermal and wind power. To realize total profit maximization of three aspects, this paper built the optimization objective function.

$$\max\ z_3 = \pi_c + \pi_w + \pi_s \tag{28}$$

Wherein, π_s is energy storage system profit, which is related to charge-discharge price, charge –discharge electric quantity and fixed cost.

$$\pi_s = p_{s,char} \sum_{t=1}^{T} Q_{s,t}^{+} - p_{s,disc} \sum_{t=1}^{T} Q_{s,t}^{-} - F_s \tag{29}$$

For the energy storage system, accumulation of charged capacity and discharged capacity should meet

$$\sum_{t=1}^{T} Q_{s,t}^{+} (1-\theta_s) = \sum_{t=1}^{T} Q_{s,t}^{-} \tag{30}$$

If the energy storage system want to gain profit, charge and discharge price of energy storage system should meet

$$p_{s,char} > p_{s,disc} / (1-\theta_s) \tag{31}$$

Wind and thermal power output, charge-discharge power and system load should meet

$$\sum_{i=1}^{I} u_{i,t} Q_{i,t} (1-\theta_i) + Q_{w,t}(1-\theta_w) + Q_{s,t}^{-} = G_t / (1-l) + Q_{s,t}^{+} \tag{32}$$

System power back-up service constraint, real-time thermal power constraint, unit climbing speed constraint, unit start-up time constraint are shown in formula (7) to (17).

5. WIND POWER CONSUMPTION OPTIMIZATION MODEL WITH CARBON TRADING ANDENERGY STORAGE

The way that generation side prompt wind power consumption are wind power, thermal power and energy storage system. To gain more economic value, an optimization function is built:

$$\max\ z_6 = \pi_c + \pi_w + \pi_s \tag{33}$$

Wherein, thermal power unit profit π_c is influenced by coal consumption, coal price, carbon emission and carbon emission price, the expression is as follows,

$$\pi_c = [p_c \sum_{i=1}^{I} \sum_{t=1}^{T} Q_{i,t} (1-\theta_{c,i}) - C_{\text{fuel}} - C_{co_2} - \sum_{i=1}^{I} OM_{c,i} - \sum_{i=1}^{I} D_{c,i}] \tag{34}$$

Wherein, carbon emission cost is constrained by e initial allocation of carbon emission right and carbon emission price.

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

$$\sum_{i=1}^{I} u_{i,t} Q_{i,t} (1-\theta_i) + Q_{w,t}(1-\theta_w) + Q_{s,t}^{-} = G_t / (1-l) + Q_{s,t}^{+} \tag{35}$$

System power back-up service constraint, real-time thermal power constraint, unit climbing speed constraint, unit start-up time constraint are shown in formula (7) to (17).

6 NUMERICAL EXAMPLE ANALYSIS

6.1. Basic Data

To make simulation system for the model, this paper selected 10 set thermal power units and wind power of 2800MW installed capacity, thermal power units' operating parameters should refer to literature [15]. Choose a typical day's system load and wind load output data, which is shown in Table **1**. This paper set wind power tariff as 540 yuan / MW • h, maintenance and depreciation costs as 600 million; thermal power tariff as 380 yuan / MW • h, equivalent to 800 yuan / t of standard coal price.

6.2. Numerical Example Results

With the goal of maximizing profit, we solved the scheduling optimization model of wind and thermal power with or without carbon trading and energy storage system by the mean of GAMs.

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

6.2.1. Carbon Trading's Impact on Wind Power Consumption

To study different carbon emission price's impact on wind power consumption, three carbon emission mechanisms scenarios are set. Carbon trading is not considered in scenario 1, namely the carbon trading cost should not be levied.

The part that carbon emission exceed initial carbon emission right should levy emission fee for 80 yuan/t in scenario2, 100yuan/t of emission fee should be levied in senario3.

In scenario 1, total unit carbon emission is 29079.7 t, if the carbon emission right is allocated according to 98% emission, initial carbon emission right that thermal power unit gain is 28498.1 t; the wind power consumption model of different carbon emission mechanism is optimized based on above conditions, optimization result is shown in Table 2.

Compared three scenarios, gradual increasing of carbon trading price will enhance wind power integration electric quantity, reduce abandon wind. In scenario1, wind power generation is 18407.1 MWh. When the carbon trading price is 80 yuan /t, wind power generation will enhance to 18413.6 MWh; when the carbon trading price is 100yuan/t, wind power generation is 18896.9 MWh and wind abandon rate will reduce to 14.7%. Comparative results of different carbon price thermal power generation is shown in Fig. (**1**).

With the introduction of carbon trading mechanism, Thermal power market structure will change with the margin generation cost. For example, number 2 and number 3 units' carbon emission coefficients are high, so carbon trading will reduce their power generation, while number 5 unit's carbon emission coefficient is low, the power generation will be enhanced with the introduction of carbon trading.

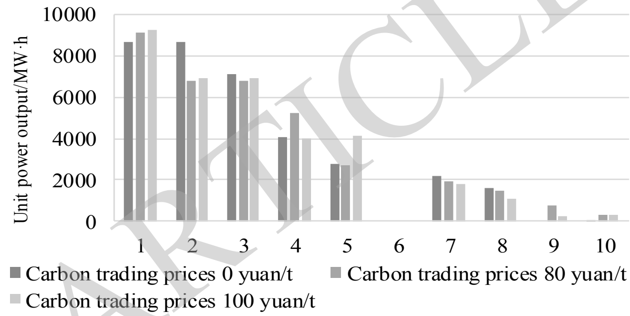

Fig. (1). Conparison of thermal power generation under different carbon prices.

On the whole, to meet system supply and demand balance constraints, unit back-up constraints, and unit output constraints, thermal power generation structure does not have obvious change law.

6.2.2. Energy Storage System's Impact on Wind Power Consumption

To study energy storage system' promotion on wind consumption, this paper divided 3 scenario according to the amount of the energy storage system. Different scenarios' optimization results are shown in Table **3**.

With the access and expansion of energy storage system, abandon wind rate showed a downward trend and unit utilization efficiency increased gradually. Without energy storage system, wind abandon rate is 16.9%, when energy storage system of 20 MW accessed the system, wind abandon rate reduced to 16.3%, , electric quantity increased 135.0 MW, when energy storage system of 40 MW accessed the system, wind abandon rate reduced to 15.9%, electric quantity increased 213.5 MW.

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

Scenario	Wind Power			Thermal Power			Profit (10 Thousands Yuan)
	Generation (MWh)	Electricity Grid Accessed Rate (%)	Wind Abandon Rate (%)	Generation (MWh)	Electricity Grid Accessed Rate (%)	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

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

Scenario	Wind Power			Thermal Power			Profit (10 Thousands Yuan)
	Generation (MWh)	Electricity Grid Accessed Rate (%)	Wind Abandon Rate (%)	Generation	Electricity Grid Accessed Rate (%)	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

With the reduction of wind abandon rate, thermal power unit that access the grid showed a downward trend, while the coal consumption enhanced to some extent. Without the energy storage system, coal consumption of thermal power supply is 343.5 kg/MWh. When energy storage system of 20 MW accessed system, coal consumption of thermal power supply was 344.3 kg/MWh and0.8 kg/MWh increased, when energy storage system with 40 MW accessed the system, coal consumption of thermal power supply was 344.6 kg/MWh and 1.1 kg/MWh increased.

From the view of system profit, it showed a downward trend with the access of energy storage system, because energy storage system's high investment cost and lack of commercial promotion in large scale. From the view of policy, China's policies have concentrated on large-scale energy storage system development gradually, but still lack of industry planning, industry standard and financial subsidy and other substantive supports. From the view of economic benefits, except pumped storage power plants can achieve 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 is both opportunity and challenge, from the current situation, challenges that brought by price mechanism and investment cost are 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.

6.2.3. Carbon Trading and Energy Storage System's Impact on Wind Consumption

To compare wind power consumption of different combination, 4 scenarios were divided according to the wind consumption combination with assistant of generation side. Scenario 1 is wind and thermal power integrated 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 and thermal power, energy storage system integrated scheduling optimization under carbon trading mechanism. We use GAMS to optimize, the optimization result is shown in Table **4**.

For the wind power, wind abandon rate was 16.9%; the wind abandon rate reduced when the energy storage system or carbon trading mechanism access the system, when both of them access the system, the abandon wind rate will reduce to 14.4%. For the thermal power, the generation showed a downward trend with the increase of wind power generation.

From the view of system total profits, due to the high fixed cost, the profits will be higher without energy storage system. For the energy storage system, real-time charge and discharge power in scenario 4 and system power storage are shown in Fig. (**2**), total charge quantity of energy storage system is 488.1 MWh, total discharge is346.9 MWh, final system storage is 80 MWh, According to formula (27), total profits of energy storage system is -348000yuan, profit in charge-discharge process is 12000yuan, fixed cost is 360000yuan.

For the energy storage system, to realize the profit maximization in optimized time, energy storage system should release all the power in the final of optimization, 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 made based on the wind power output, thus reducing the pressure of thermal power peak shaving. In Fig. (**3**) most of the charging time is in the wind power output increasing period and most of the discharging time is in the decreasing period.

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

Scenario	Wind Power			Thermal Power			Profit (10 Thousands Yuan)
	Generation (MWh)	Electricity Grid Accessed Rate (%)	Wind Abandon Rate (%)	Generation (MWh)	Electricity Grid Accessed Rate (%)	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

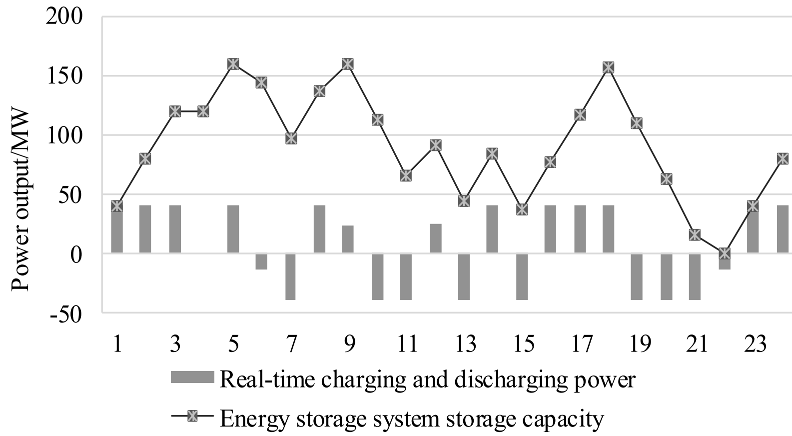

Fig. (2). Charge and discharge optimization result of energy storage system.

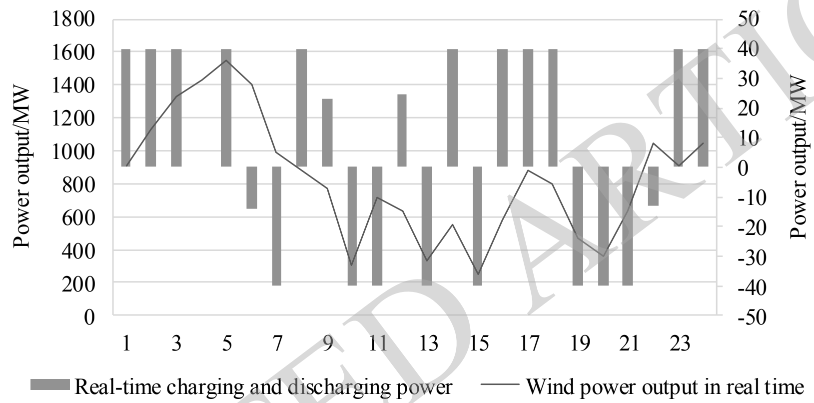

Fig. (3). Comparison of wind power output and charge-discharge power of energy storage system.

For the carbon emission of system generation, thermal power's carbon emission is 28765.3 t in scenario 3, 267.2 t is increased compared to the initial allocation quota, 26700 yuan should be levied as the carbon emission cost. Thermal power's carbon emission is 28685.4 in scenario 4, 187.3 t is increased compared to the initial allocation quota, 187000 yuan should be levied as the carbon emission cost.

Based on the above analysis, introduction of carbon trading and energy storage systems can enhance wind power consumption and wind power generation efficiency, reduce thermal power generation and coal consumption. However, due to the high costs, power profits will be reduced by the access of energy storage system. Considering the examples in this article, total charge quantity of the energy storage system is 488.1 MWh, and total profit is -348000 yuan.

CONCLUSION

To promote large-scale wind power paralleling in the grid and achieve the goal of energy conservation, this paper introduced carbon emissions trading, which can enhance the economic advantages of wind power. To alleviate randomness and intermittence of wind power output 's impact on wind power consumption, this paper introduced the energy storage system network to provide backup services for the wind power and built wind power energy storage collaborative scheduling optimization model with carbon emission trading and made a numerical example, the results are shown as follows:

(1) Carbon trading can enhance economic advantages of wind power and transform its cleaning feature into economic value, increase wind power generation to access the grid and reduce average coal consumption. The introduction of energy storage system can smooth wind power output, suppress fluctuation and provide back-up services for wind power 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, increase economic benefits of wind power. However, due to the high cost of energy storage systems, above measures will reduce the generation profit. Therefore, to maximize wind power utilization, related subsidies for the energy storage system need to be formulated.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

Declared none.

REFERENCES

[1] Wang Qingran, Xie Guohui, Zhang Lizi. An integrated generation consumption dispatch model with wind power [J]. Automation of Electric Power Systems, 2011, 35(5): 15-18,30

[2] ZHOU Tianrui, KANU Chongqing, XU Qianyao, CHEN Qixinl.Preliminary Investigation on a Method for Carbon Emission Flow Calculation of Power System[J]. Automation of Electric Power Systems, 2012, 36(11):44-49.

[3] Chen chong. Research on the Dynamic Relations Among Carbon Emissions, Economic and Energy Development in China: Based on the VAR Model Analysis of Time Series Data from 1978 to 2012[J]. Journal of North China Electric Power University (Social Sciences), 2014, 4:15-23.

[4] LI Ying, YAN Xingzhi. The Legal Consideration on EU Suspending the Levy of Aviation Carbon Tax[J]. Journal of North China Electric Power University (Social Sciences), 2014, 1: 20-25.

[5] 邓舒仁. 现阶段我国低碳经济发展路径[J]. 华北电力大学学报 (社会科学版), 2011, 6: 1-5.

[6] ZHOU Tianrui, KANU Chongqing, XU Qianyao, *et al*.Preliminary theoretical investigation on powersystemcarbon emission flow[J].Automation of ElectricPowerSystems, 2012, 36(7):1-7.

[7] 崔和瑞, 尤丽君. 河北省碳排放的环境库兹涅茨曲线实证研究[J]. 华北电力大学学报 (社会科学版), 2014, 1: 11-14.

[8] ZHENG Jing, WEN Fu-shuan, ZHOU Ming-lei, etal. Transmission system planning for power systems with wind generators considering demand side responses[J]. Journal of North China Electric Power University,2014,41(03): 42-48

[9] CHAI Da-peng, LI Yu-long, MA Ming-juan, etal. Research on comprehensive and coordinated planning of wind power and transmissions investment model based on mixed-integer linear programming[J]. Journal of North China Electric Power University,2014,41(04): 107-112

[10] Yu Peng, Zhao Yu, Zhou Wei, etal. Research on themethod based on hybrid energy storage system for balancing fluctuant wind power[J]. PowerSystem Protection and Control, 2011, 39(24): 35-40(in Chinese).

[11] HE Yong-qi, ZHANG Jian-chen, BAO Xue-na. Optimization of storage capacity in grid-connected wind / PV / storage hybrid system[J]. Journal of North China Electric Power University, 2012, 39(4): 1-5.

[12] YAN Yue-hao, BAO Wei, LI Guang-hui, SUN Yanxia. Control strategy of dispatchable distributed generation based on hybrid energy storage[J]. Journal of North China Electric Power University,2014,41(1):28-35.

[13] Dicorato M, Forte G, Pisani M, etal. Planning and operating combined wind-storage system in electricity market[J]. IEEE Transactions on Sustainable Energy, 2012, 3(2): 209-217.

[14] Garcia-Gonzalez J, dela Muela RMR, Santos LM, etal. Stochastic joint optimization of wind generation and pumped-storage units in an electricity market[J]. IEEE Transactions on Power Systems, 2008, 23(2): 460-468.

[15] 董安有. 我国解决风电充风的组合途径及优化模型研究[D].华北电力大学,2014

Received: January 6, 2015 Revised: May 20, 2015 Accepted: June 19, 2015