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Environmental implications of China's wind-coal combined power generation system

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ABSTRACT

China's power supply structure is dominated by coal-fired power. As China's renewable power expands, coal-fired power units are required to improve flexibility to balance power system. However, more flexible operation of coal power units increases energy consumption and pollutant emissions. This paper examines the energy efficiency, CO_2 and pollutant emissions characteristics of China's generic wind-coal combined power generation system, and discusses pollution-minimizing dispatch strategies by modeling three hypothetical scenarios of wind-coal combined power generation systems. For day-scale analyses, we find expected displacement rates of coal consumption and CO_2 emission decrease by wind fraction rate, indicating reduced energy savings from wind power per unit of increase in wind capacity. For NO_x emission, we find that expected displacement rate reaches maximum value of 112% when wind fraction rate is equal to 0.27.For week-scale analysis, we simulate the coal consumption rate and emission factors with and without an operation of shutdown and startup of coal power units in the system. We suggest future study on dispatch decisions of startup/shutdown of coal power units to optimize power generation economically and environmentally.

1. Introduction

China has proposed an ambitious development plan for renewable energy (NDRC and SERC, 2011; NDRC and NEA, 2016; NEA and NDRC, 2017; Yuan, 2016a, b. The goal is to achieve 15% non-fossil energy supply by 2020 and 20% non-fossil energy supply by 2030, and the goal will mainly be achieved via expansion of wind and solar energy (Yuan et al., 2007, Yuan and Xu 2014a,b; Yuan, 2016a, b; Yuan and Na, 2016; Yuan and Lei, 2016; among others).With strong support of national policies, renewable power generation has experienced rapid development in the past decade (CEC, 2018). By the end of 2016, China has become the world's largest investor of wind and solar power capacity. Due to intermittency of wind and solar power generation, large-scale wind and solar integration onto power grid inevitably requires other generation sources to balance demand load (Denny and O'Malley, 2006; Valentino and Valenzuela, 2012; Lu et al., 2011; Lu et al., 2014; Liu et al., 2015; Na et al., 2018).

China's power supply structure is still dominated by coal-fired power, and the more flexible power sources such as gas turbine power generation and pumped-storage power generation account for only a small share. Many existing studies have studied the CO_2 emissions scenarios in China's energy and power system, but few works have addressed the impact of renewable integration on CO_2emissions in the power system (Chen and Cai, 2017; Su and Fang, 2016; Liu et al., 2017; Peng and Xie, 2018; Zhou and Wang, 2018; Ye and Ren, 2018; Tang et al., 2018). In the three northern regions of China (North China, Northwest China, Northeast China), wind and solar power generation account for a larger proportion, and the system load is mainly balanced by coal-fired power units. Although wind and solar power can be considered to produce zero emissions, their intermittent and uncertainties can impose negative impacts on economics and emissions of peaking units in the system. As wind fraction increases, the thermal power units in the network need to operate in a more flexible manner (including frequent deep cycling, frequent start-up and shutdown),

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increasing energy consumption and emissions(Katzenstein and Apt, 2009; Oates and Jaramillo, 2013; Lu et al., 2014; Gonzalez-Salazara et al., 2018).

Studies have investigated how integration of renewable power would impact economics and emissions of thermal power generation, but most of them are based on power systems in the U.S. (NREL, 2013). For China's specific situation, Dong and Jiang (2018) used historical operation data of typical 300 MW and 600 MW coal-fired power units to study their energy efficiency and emission factors (cycling, low output, and start-up and shut-down), providing basis for further studies of power systems consisting of coal-fired power and high penetration of renewable power generation. Existing studies on energy efficiency, CO_2 and pollutant emission characteristics of generation systems with high penetration of renewable energy are mostly case studies of specific regions (Valentino and Valenzuela (2012); Oates and Jaramillo, 2013).

This paper examines the energy efficiency, CO_2 and pollutant emissions characteristics of China's generic wind-coal combined power generation system, and discusses pollution-minimizing dispatch strategies. Based on Dong and Jiang (2018) that provides data support for emission factors of typical peak-shaving units in China, 300 MW subcritical and 600 MW subcritical coal power units[1], this paper builds on the literature by simulating different hypothetical combinations of wind and coal power units for system coal consumption rates (China's equivalent concept for heat rate) and emission factors. Since the wind-coal combined power generation system is very common in China, especially in Northern, Northeast and Northwest China, this paper showcases environmental impacts of such a generation system. The main difference between this paper and existing literature (Katzenstein and Apt, 2009) is that the latter considers gas turbines to accommodate wind power in the system. While natural gas is abundant and gas generators are common in the United States, China still and will rely on coal power units to accommodate intermittent renewable power in the foreseeable future. Because emission factors for gas and coal power generation units differ significantly, conclusions drawn from Katzenstein and Apt (2009) may not necessarily apply to China, which incentivizes China-specific studies.

The paper is organized as follows: Section 2 describes three representative scenarios of wind-coal combined power generation system and introduces methods used to analyze energy efficiency and emissions of the system. Section 3 uses actual regional wind power data to simulate system generation and emissions in the three scenarios, and discusses dispatch strategies to minimize CO_2 and pollutant emissions. Section 4 concludes.

2. Wind-coal combined power generation system

2.1. Three representative scenarios

Assume the power system consists of two types of power sources: wind power and coal power. The wind power includes several wind farms and the installed capacity of a single wind farm is 49.5 MW (1.5 MW * 33 units). The coal power units include sub-critical 300 MW and sub-critical 600 MW units that are responsible for most peak-shaving tasks in China. Peak-shaving refers to the process that coal power unit must adjust its output level to accommodate variable wind power to serve the load, which is assumed to be constant here. We use short-term forecasted (theoretical) wind power at 15-minute interval as wind output, and cycle coal power units to balance loads. With the two typical sizes of peak-shaving coal power units, we consider the following three hypothetical scenarios of wind-coal combined power generation systems. In Scenario 1 and 2, the load only needs to be balanced by a single-sized coal power unit – 300 MW or 600 MW unit. In Scenario 3, because of increased load and wind power output, two coal power units are needed to balance load, and the question arises as to which unit to cycle first. For each scenario, we establish a day-scale analysis in which we calculate the wind power generation as a fraction of constant load, and simulate the system coal consumption rate and atmospheric emissions from coal power generation. We then plot the wind power generation (as a fraction of constant load) and system atmospheric emission factors (g/kWh) for 366 days in 2016, obtaining a statistical relationship between them. For Scenario 3, we further conduct a week-scale analysis to simulate system emissions with and without an operation of shutdown of a coal power unit, and we discuss the need to conduct future study on the decision-making strategy of shut-down and start-up of coal power units to accommodate more wind power.

Scenario 1: load of 300 MWserved by wind power and a 300 MW coal power unit

The system consists of 6 wind farms and a 300 MW coal power unit. Wind power is preferentially dispatched and the coal-fired power unit serves the remaining load. The 300 MW coal power unit serves maximum output of 300 MW and minimum stable output (lower operational limit) of105MW.

Scenario 2: load of 600 MWserved by wind power and a 600 MW coal power unit

The system consists of 12 wind farms and a 600 MW coal power unit. Wind power is preferentially dispatched and the coal-fired power unit serves the remaining load. The 600 MW coal power unit serves maximum output of 600 MW and minimum stable output (lower operational limit) of210MW.

Scenario 3: load of 840 MWserved by wind power and two coal power units (300 MW and 600 MW)

The system consists of 17 wind farms, a 300 MWcoal power unit, and a 600 MW coal power unit. Wind power is preferentially dispatched and the coal-fired power units serve the remaining load. The two coal power units together serve maximum output of 840 MW and minimum stable output (lower operational limit) of105MW when the 600 MW is shut down.

2.2. Day-scale analysis of energy efficiency and emissions

Because it can take coal power units 3 h for a hot startup and 9–10 h for a cold startup, we do not consider the option of startup and shutdown to shave peak in the day-scale analysis. We consider coal power units not subject to operation constraints so that load can be balanced at all times. For this part, we attempt to estimate the CO_2 and pollutant emissions of such wind-coal combined power systems as wind penetration increases.

Let the regional power load be $P_{b,i}$, the theoretical wind power output be $P_{w,i}$, which is the 15-minute interval forecast data, and the coal power output be $P_{c,i}$

$$P_{c,i} = P_{b,i} - P_{w,i} \tag{1}$$

Coal consumption and total emissions during a day can be calculated as:

$$M_{day} = \sum_{i=1}^{96} \frac{dM_t}{dt} \bullet P_{ci} \bullet \Delta t \tag{2}$$

where $\frac{dM_t}{dt} = a \times P_{c,i}^3 + b \times P_{c,i}^2 + c \times P_{c,i} + d$, is the coal consumption rate or emission factors, measured bygce/kWh, the coefficients a, b, c, d are reported in Table 1; Δt is the time interval, which is 15 min in this dataset.

Daily wind fraction can be calculated as

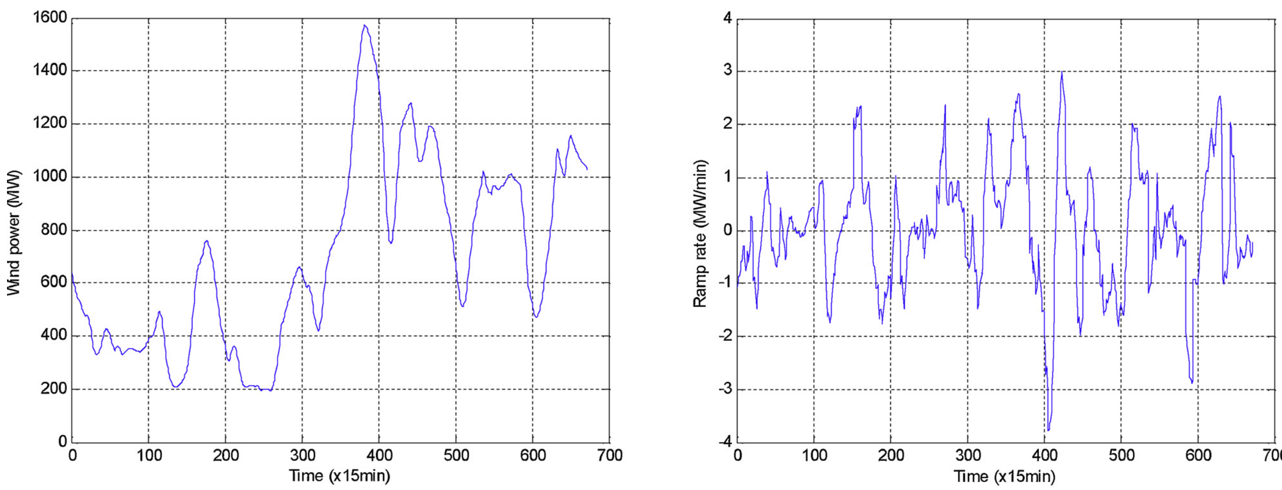
$$\alpha_{day} = \frac{\sum_{i=1}^{96} P_{w,i}}{\sum_{i=1}^{96} P_{b,i}} \tag{3}$$

Expected coal consumption rate and expected emission factors can be calculated as:

[1] Section 3.2 describes coal power data used in this paper in detail.

Table 1
The coefficients of coal consumption and different emission function for selected units.

Items	300 MW unit				600 MW unit			
Coefficients	a	b(◊10^{-8})	c(◊10^{-5})	d	a(◊10^{-9})	b(◊10^{-8})	c(◊10^{-5})	d
Coal cons.(g/kWh)	0	140000	−85620	470.8261	0	50000	−46500	443.7786
CO_2 emission g/kWh)	0	320000	200010	1099.9	0	110000	−108620	1036.8
NO_xemission(g/kWh)	0	60.324	−30.840	0.1602	−5.2333	760.06	−360	0.6360
SO_2mission(g/kWh)	0	−42.636	19.342	0.0267	0	8.9567	−3.1219	0.0550
Dust mission(g/kWh)	0	3.3502	−2.994	0.0136	0	12.003	−11.465	0.0407



(a) Wind Profile (b) Rate of Change in Wind Output

Fig. 1. Regional wind power profile and rate of change in wind output.

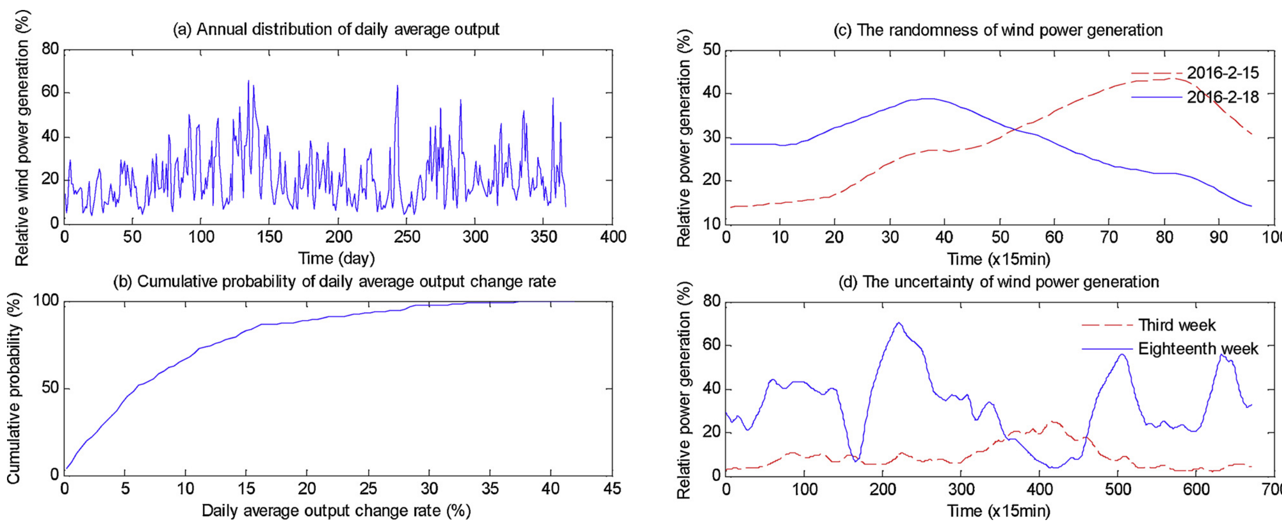


Fig. 2. The characteristics of wind power generation.

Table 2
The cumulative emissions volume of three pollutants in a cold start-up in case units.

Unit	NOx(kg)	SO2 (kg)	Dust(kg)
300 MW	296/264*	24.5/530*	16.8
600 MW	587/528*	53/1060*	63.7

Note: the figures marked with * are theoretical calculation values based on (NREL, 2013).

$$\gamma_e = M_c(1-\alpha_{day})/\sum_{i=1}^{96} P_{b,i}\bullet\Delta t \tag{4}$$

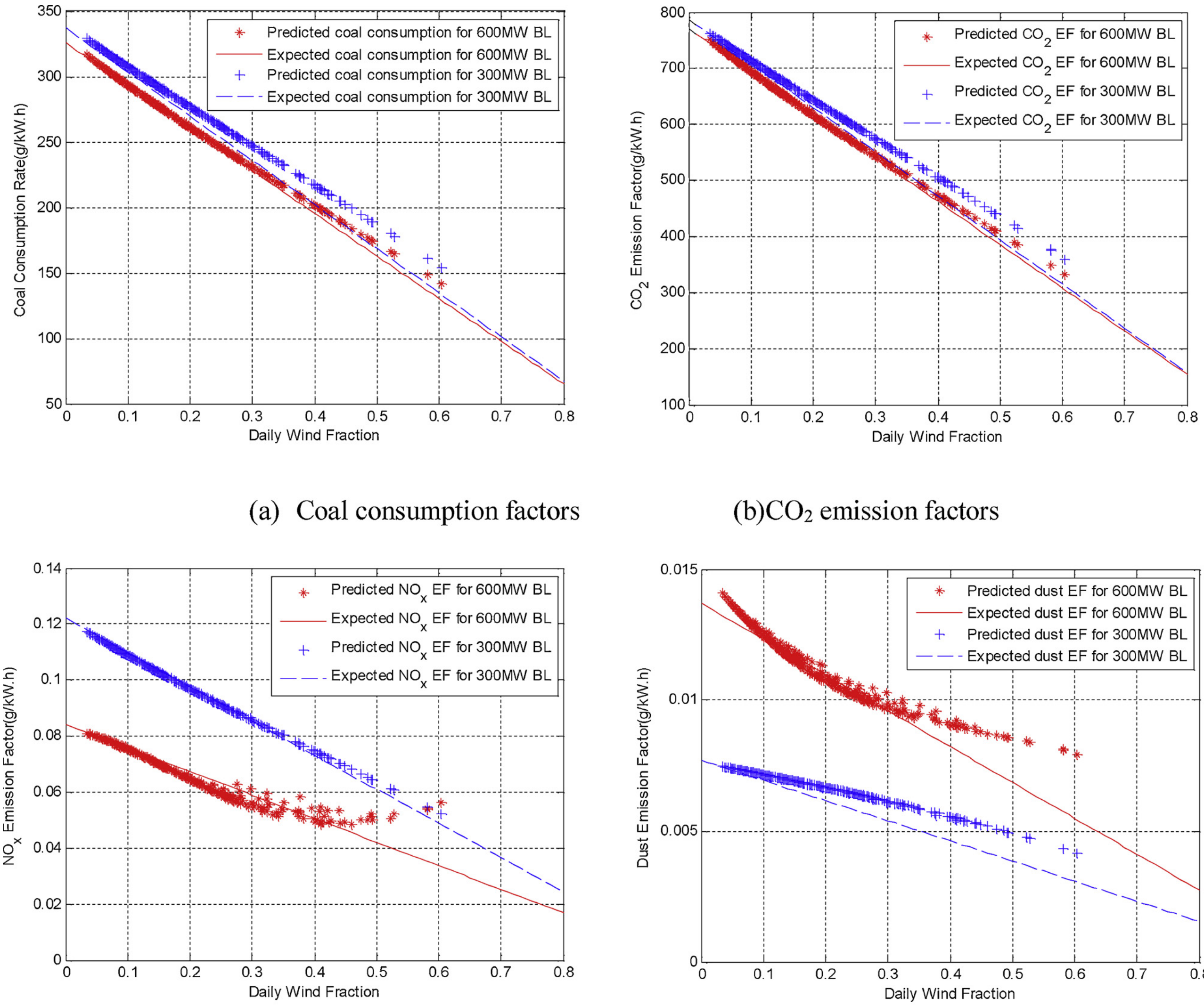
where *Mc* is the coal consumption (or emissions) during a day with no wind power in the system.

Predicted (simulated) coal consumption rate and emission factors are:

$$\gamma_p = M_{day}/\sum_{i=1}^{96} P_{b,i}\bullet\Delta t \tag{5}$$

where M_{day} is the coal consumption (or emissions) during a day with wind power in the system.

Expected displacement rates of coal consumption and emissions can



(a) Coal consumption factors (b) CO_2 emission factors

(c) NO_x emission factors (d) Dust emission factors

Fig. 3. The relationship between energy consumption, air emission factors and daily wind fraction.

therefore be calculated as:

$$\eta = (M_c - M_{day})/(M_c \times \alpha_{day}) \tag{6}$$

2.3. Week-scale analysis of energy efficiency and emissions

Week-scale analysis differs from day-scale analysis in that shutdown and startup of one or both coal power units can be employed to shave peaks during the time window of a week. Calculation methods for coal consumption and emissions follow above. For example, coal consumption and total emissions during a week can be calculated as:

$$M_{week} = \sum_{i=1}^{672} \frac{dM_t}{dt} \bullet P_{ci} \bullet \Delta t \tag{7}$$

3. Data and results

3.1. Wind power output characteristics

The wind power data in this paper are forecasted theoretical wind power output in a provincial power system in Northeast China. The wind power capacity of the province is 4950 MW, which consists of 100 wind farms, each installed at 49.5 (1.5 MW*33 turbines). The output data are proportionally scaled down for scenario analyses. In this paper, we prioritize the dispatch of wind power and fulfill the remaining load with coal power by adjusting its output level. Figure 1shows the region's theoretical wind power profile during a typical week(a) and associatedrate of change in wind output(b).

It can be seen from Fig. 1 that wind power output varies significantly between 200 MW and 1600 MW, but the rate of change is rather small, ranging from −4 MW/min to 4 MW/min, which allows coal power units to follow the variation. The small rate of change is mainly because of the "complementary" effect of wind turbines within a wind farm and "complementary" effect of different wind farms (Xiao et al., 2010).

The total wind power output is highly volatile and uncertain (Xiao et al., 2010). Fig. 2(a) shows the annual distribution of the average daily output of wind power in the region. It can be seen that the daily average output fluctuates significantly from about 5% to about 65%. Fig. 2(b) shows the cumulative probability distribution of the daily average output change rate ($\varphi = (P_{i+1} - P_i) \times 100\%/P_0$, where P_i and P_{i+1} are the average daily outputs of i^{th} and $(i+1)^{th}$ days, respectively, and P_0 is the installed capacity of the wind farm). The maximum rate of change in wind output during a day is 42%, and the days with rate of change greater than 20% account for about 11% of the year. Fig. 2(c)

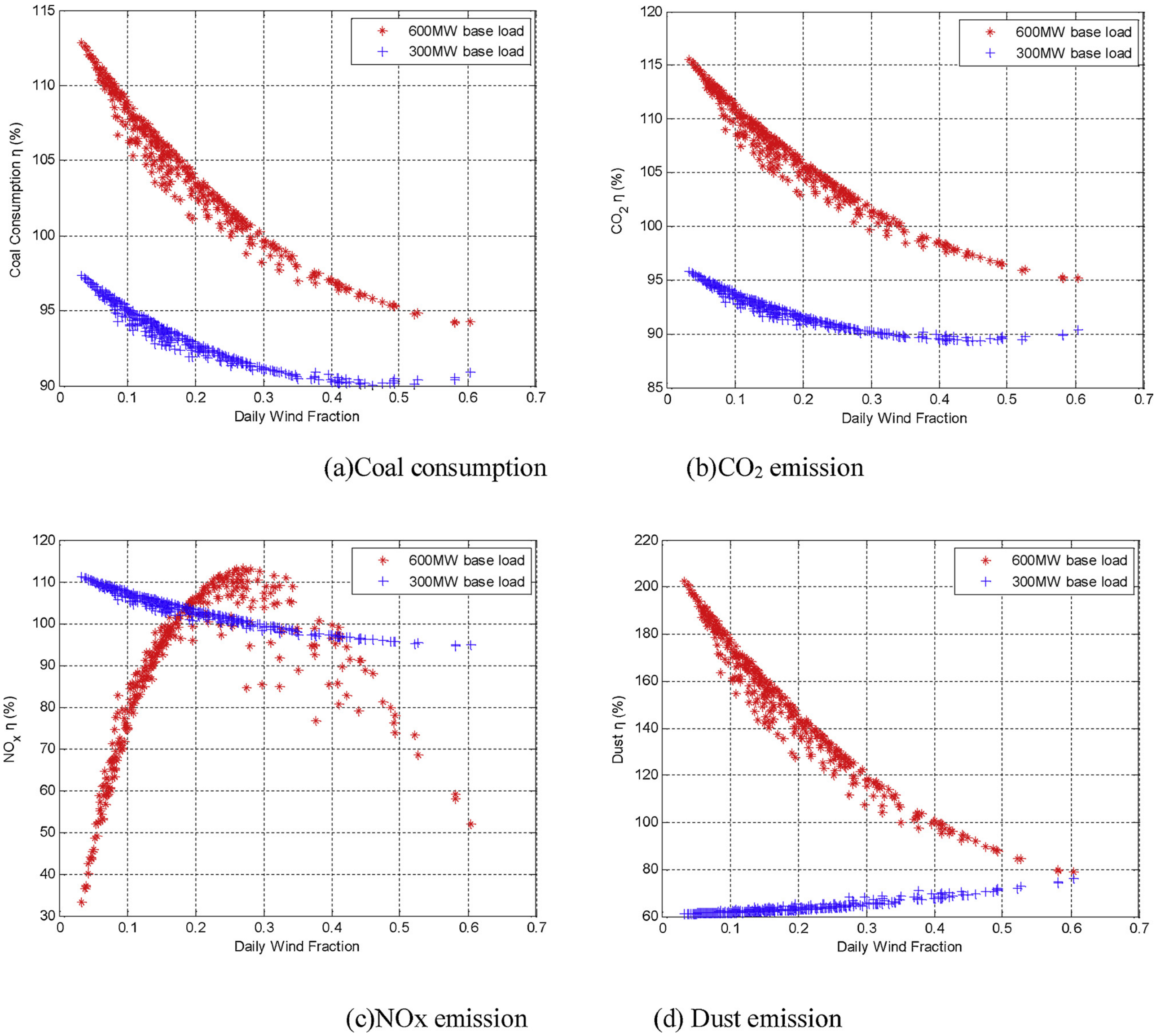


Fig. 4. Expected displacement rates of coal consumption and air emissions by wind fractions.

shows wind profiles of two different days with similar total wind generation, and one can see that even with similar generation, wind output profiles can be very different. Fig. 2(d) shows wind profiles of two different weeks, and one can see wind output can be very random.

3.2. Coal power units data

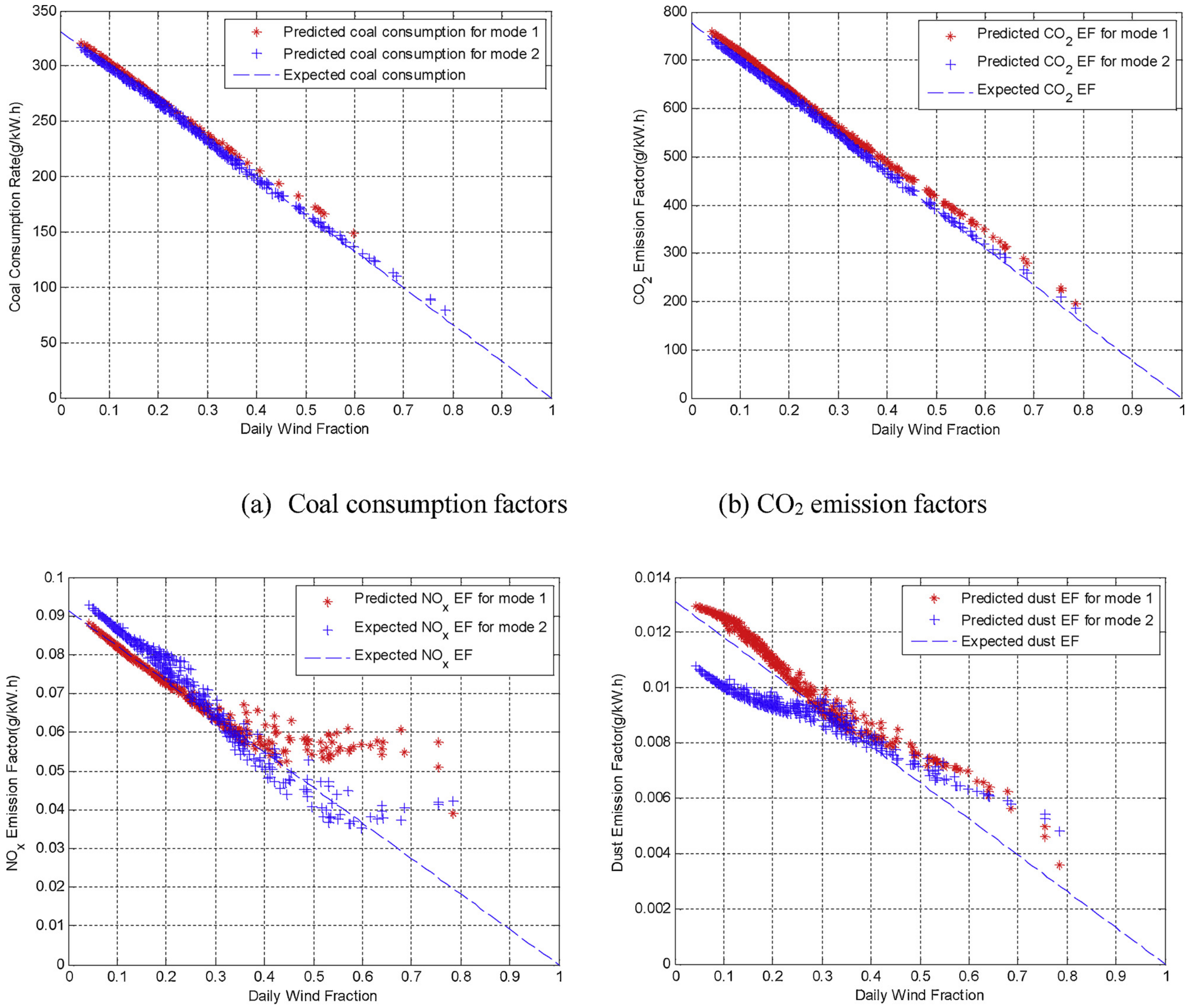
As unit size of coal power and peak-valley load differences increase, coal units of 300 MW and 600 MW have become the main fleets to perform flexible operation by regulation. In this paper, we use a long-term high resolution operation dataset (1-min interval data sourced from Supervisor Information System) of typical 300 MW and 600 MW units to estimate the economic and environmental implications of wind-coal combined power generation system.

The 300 MW steam turbine is a sub-critical, intermediate reheating double-cylinder with double exhaust steam extraction condensing steam turbine made by DongFang Turbine Co., Ltd. The boiler is a subcritical natural circulation drum boiler with tangential combustion, steam temperature control by tilting burner, dry-ash furnace and bituminous coal as the fuel. The 300 MW unit was put into operation in 2010.

The 600 MW steam turbine is a sub-critical, intermediate reheating three-cylinder with four exhaust steam extraction condensing steam turbine, with main steam pressure at 16.67 MPa and temperature at 538 °C, made by Harbin Turbine Co., Ltd. The boiler is a tangential firing, sub-critical, single reheat, controlled circulation, dry ash furnace and pulverized coal fired boiler, with bituminous coal as the fuel. Both units are equipped with SCR denitrification facility, limestone-gypsum flue gas desulfurization (FGD) device, and wet electrostatic precipitator (WESP). The 600 MW unit was put into operation in 2002.

Note that 300 MW-class units and 600 MW-class units account for 39% (365 G W with heat rate ranging between 312gce/kWh and 360gce/kWh) and 36% (337 G W with heat rate ranging between 287gce/kWh and 320gce/kWh) of China's existing coal fleet by the end of 2016 (CEC, 2017b). Because sub-critical technology is poorer in energy efficiency compared with super-critical technology, sub-critical units represent the most promising candidate for flexibility retrofit in China. Hence the selection of case units in our study is typical and can reflect the general situations in China. Also, though the heat rates or pollutant emissions vary in diff ;erent coal plants, the basic pattern revealed by two case units also has generality in China.

The general function for the coal consumption rate and different emissions types can be expressed as follow:



(a) Coal consumption factors (b) CO_2 emission factors

(c)NOx emission factors (d) Dust emission factors

Fig. 5. The relationship between energy consumption, air emission factors and wind fractions.

$$y= ax^3 + bx^2 + cx + d \tag{8}$$

For coal consumption and different emission types function, the regressed coefficients are listed in Table 1.

The pollutant emissions of the two units during cold startups are shown in Table 2, which can also be found in Dong and Jiang (2018). The additional pollutant emissions during the shutdown process are trivial and ignored here.

3.3. Day-scale analysis and results

3.3.1. Wind power accommodated by single-sized coal power units

In Scenario 1, the system consists of 6 wind farms and a 300 MW coal power unit, and in Scenario 2, 12 wind farms and a600 MW coal power unit. We prioritize the dispatch of wind power and fulfill the remaining load with coal power by adjusting its output level. Using energy consumption rates and emission factors of coal-fired power units in Dong and Jiang (2018), we plot the relationship between energy consumption rates and system emission factors by wind fractions at a day scale. We use forecasted theoretical wind output data at 15-min interval, energy consumption rates and emission factors of coal power units during 366 days to conduct the analysis. Results are shown in Fig. 3.

Fig. 3(a) and (b) shows that the average daily coal consumption rate and CO_2 emission factor are lower when the system is balanced by 600 MW coal power unit, because coal consumption rate of 600 MW units is smaller than 300 MW units at the same level of power output. As wind fraction increases, system coal consumption rates and emission factors of CO_2decrease linearly.

Fig. 3(c) shows that for the 300 MW system, the predicted emission factor of NO_x still maintain a rather linear relationship with wind fraction; the 600 MW system, though, exhibits an obvious nonlinear relationship with wind fraction. When the daily wind fraction is larger than 0.4, the predicted NO_x emission factor increases by wind fraction. That means when we have 40% or more wind penetration capacity, more wind power leads to higher NO_x emission per kilowatt hour of electricity produced by the system (600 MW). Fig. 3(d) shows that the predicted Dust emission factors of the both systems are reduced non-linearly by wind fraction.

In order to better show the differences between the predicted and expected values of coal consumption rates and emission factors, we calculate the expected displacement rates of coal consumption and

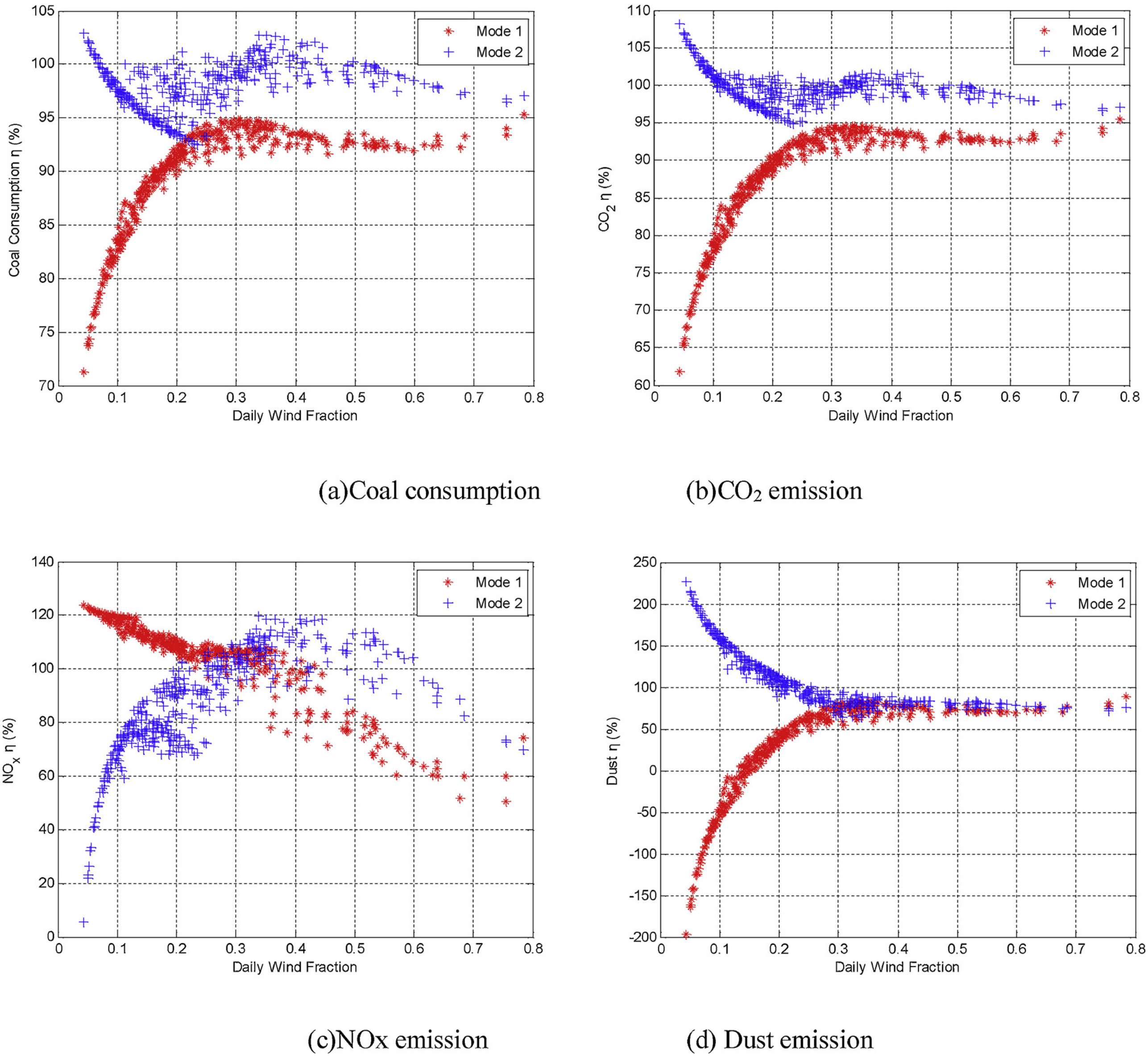


Fig. 6. Expected displacement rates of coal consumption and air emissions by wind fractions.

Table 3
Wind-Coal Combined System Dispatch Strategies.

	Theoretical Wind Power (MW)	Coal Power (MW)	Coal Power Units Combination
1	0 ~ 240	600 ~ 840	600 MW + 300 MW
2	240 ~ 540	300 ~ 600	600 MW + 300 MW or 600 MW
3	540 ~ 630	210 ~ 300	300 MW or 600 MW
4	630 ~ 735	105 ~ 210	300 MW

emissions using Eq. (6), and show the results in Fig. 4. If predicted value were equivalent to expected value, the expected displacement rate would be 100%; if predicted value were higher than expected value, the expected displacement rate would be higher than 100%.

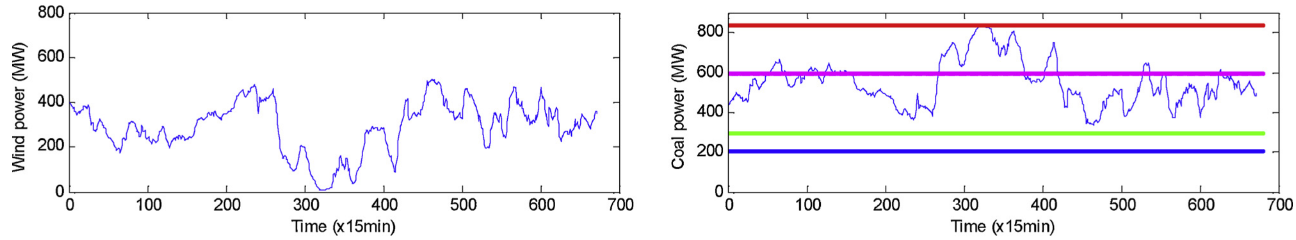
Fig. 4(a) and (b) shows that expected displacement rates of coal consumption and CO_2 emission decrease by wind fraction in both systems, indicating reduced energy savings from wind power per unit of increase in wind capacity. Fig. 4(c) and (d) shows equivalent plots for NO_x and Dust emissions. It can be seen that while expected displacement rate of NO_x emissions in 300 MW system decreases by wind fraction, expected displacement rate in 600 MW system is parabolic with wind fraction. When daily wind fraction equal to 0.27, the expected displacement rate reaches maximum value of 112%. Intuitively, this parabolic relationship corresponds to the parabolic relationship between the daily NO_x emissions and the wind fraction as shown in Appendix (in Supplementary material). In Fig.4(d), the expected displacement rate of Dust emission exhibit opposite relationship with wind fraction for 300 MW and 600 MW systems, and we attribute the difference to the different Dust emission characteristics of 300 MW and 600 MW units(Dong and Jiang (2018)).

3.3.2. Wind power accommodated by multiple-sized coal power units

In Scenario 3, the system consists of 17 wind farms, a 300 MW coal power unit, and a 600 MW coal power unit, and we prioritize the dispatch of wind power and fulfill the remaining load with coal power by adjusting its output level. We respect to operation constraints of coal power units, in particular the maximum and minimum stable output, when considering the following two modes.

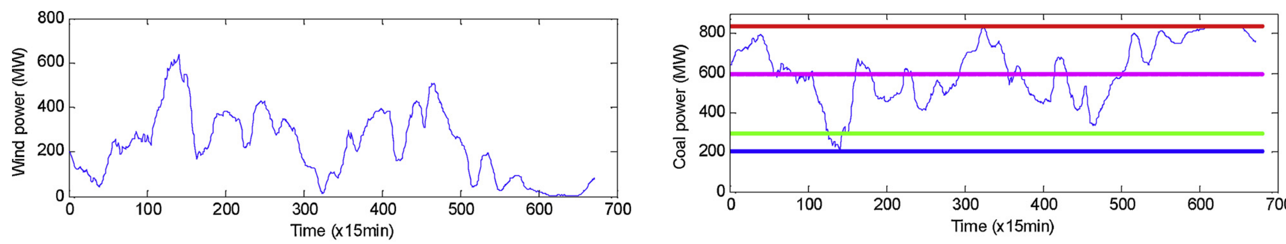
Mode 1: Use 300 MW unit for peak shaving first, and then 600 MW unit;

Mode 2: Use 600 MW unit for peak shaving first, and then 300 MW unit.



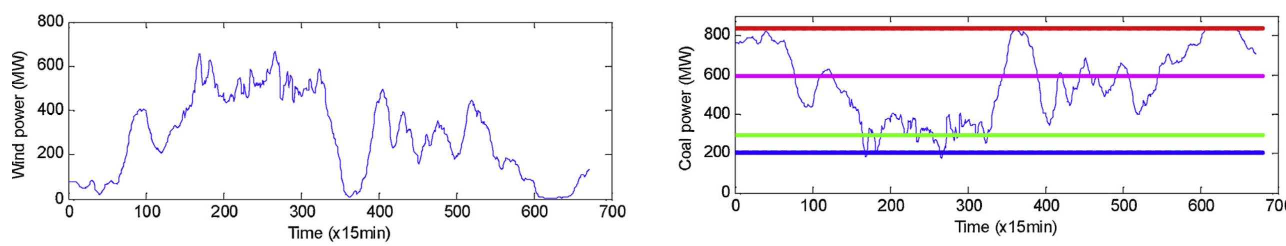
(a)Wind Power Profile(b) Coal Power Profile

Fig. 7. Wind and corresponding coal power profilesof week 16.



(a)Wind Power Profile(b) Coal Power Profile

Fig. 8. Wind and corresponding coal power profiles of week 41.



(a) Wind Power Profile(b) Coal Power Profile

Fig. 9. Wind and corresponding coal power profiles of week 42.

Table 4
Average coal consumption rates and emission factors of three weeks.

Weekly Average Values	Week 16		Week 41		Week 42	
	Without shutdown and startup	With shutdown and startup	Without shutdown and startup	With shutdown and startup	Without shutdown and startup	With shutdown and startup
Coal Consumption Rate(gce/KWh)	216.6781	217.9370	247.4164	248.6753	209.0091	210.2680
CO2 Emission Factor (g/KWh)	507.5632	511.0637	579.0172	582.5177	489.5005	493.0010
NOx Emission Factor (g/MWh)	60.8	62.9	73.6	75.7	62.8	64.9
Dust Emission Factor(g/MWh)	8.1	8.3	8.9	9.0	8.1	8.2

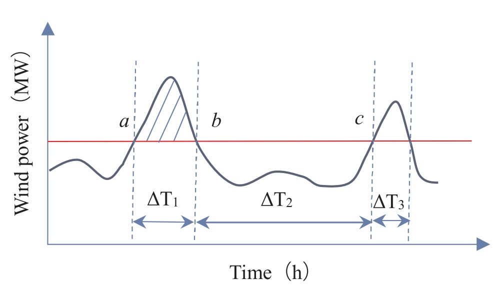


Fig. 10. Illustration of Shutdown and Startups of Coal Power.

Using energy consumption rates and emission factors of coal-fired power units(Dong and Jiang (2018)), we plot the relationship between energy consumption rates and system emission factors by wind fractions at a day scale. The results are shown in Fig. 5.

Figs. 5(a) and 6(b) show that under the same wind fraction, the daily average coal consumption rate and CO_2 emission factor of mode 1 are slightly higher than mode 2, which is a result of higher emissions from300 MW unit during peak-shaving cycling. Therefore, it is suggested to fully dispatch units with higher emission penalties and cycle those with lower emission penalties. Fig. 5(c) shows that when wind fraction is less than 0.35, mode 1 has lower NO_x emission factors than mode 2; when wind fraction is greater than 0.35, mode 2 has lower NO_x emission factors. Therefore, dispatch decisions should take this into account if NO_x emissions were to controlled. Fig. 5(d) shows that mode 2 generally has lower Dust emission factors than mode 1.

Fig. 6 shows the expected displacement rates of coal consumption and air emissions by wind fractions in Scenario 3. It shows that expected displacement rate of CO_2 in mode 2 is greater than mode 1. For NO_x emissions, when wind fraction is below 0.35, mode 1 has higher expected displacement rates, but when wind fraction is above 0.35, mode 2 has higher expected displacement rates. For Dust emissions, for wind penetration between 0.1 and 0.6, mode 2 has higher expected displacement rate than mode 1.

3.4. Week-scale analysis and results

Because it can take coal power units 3 h for a hot startup and 9 ~ 10 h for a cold startup, the day-scale analysis did not consider the option of shutdown and startup to shave peak. Ina week-scale analysis, however, we should take into account startups and shutdowns of coal power units. We use Scenario 3 as an example to simulate system emissions with and without an operation of shutdown and startup of coal power units. Table 3 lists different dispatch strategies for different levels of theoretical wind output. When wind output is between 0 and 240 MW, for instance, the coal power needs to produce an output of 600–840 MW to serve the load of 840 MW. That means both coal power units (600 MW + 300 MW) need to be dispatched. Likewise, when wind output is between 630–735 MW, coal power should output between 105–210 MW, and we just need to dispatch a 300 MW coal power unit.

3.4.1. Simulation model

We select three weeks with different wind power profiles and simulate the coal consumption and emissions with and without an operation of shutdown and startup of coal power units. Figs. 7–9 show the wind profiles and corresponding coal power profiles required to balance load. The four lines (red, pink, green, and blue) correspond to different coal power outputs, and they are boundary lines of the four dispatch strategies (coal power units combination) in Table 3.

Table 4 shows the average coal consumption rates and emission factors of three weeks, with and without an operation of shutdown and startup. It can be seen that there is a small increase in coal consumption rate and emission factor with shutdown and startup.

3.4.2. Future study: shutdown/startup decision-making

When there are multiple coal-fired power units in the system to accommodate wind power, the option of shutdown and startup of coal power units should be considered. When wind output is robust, accommodating wind may require coal power units to produce below its minimum stable output level. In this case, it would be necessary to curtail wind power or shut down one of the coal power units. As Fig. 10 shows, at point a, in order to accommodate more wind power, at least one coal power unit needs to be shut down; at point b, as wind power output reduces, coal power units need to start up again; point c is the next potential shut-down point.

As China's renewable power expands, shutdown/startup of coal power units can provide extra flexibility to the grid system, and dispatch decisions should take this option into account and optimize power generation economically and environmentally.

4. Conclusion

In this paper, we model a wind-coal combined power generation system and use historical theoretical wind power output data to simulate coal consumption rates and emission factors of the system for different wind fractions. We construct three hypothetical scenarios for different wind-coal combinations, in all of which we prioritize dispatch of wind power and fulfill the remaining load with coal power by adjusting its output level. In particular, we conduct day-scale analyses for all three scenarios, and do not consider the option of startup and shutdown to shave peak due to long time needed for a shutdown/startup process. For the third scenario, we further conduct a week-scale analysis and simulate coal consumption and emissions with and without an operation of shutdown and startup of coal power units during a week.

We find that expected displacement rates of coal consumption and CO_2 emission decrease by wind fraction, indicating reduced energy savings from wind power per unit of increase in wind capacity. For NO_x emission, expected displacement rate of NO_x in 300 MW system decreases by wind fraction, but expected displacement rate in 600 MW system is parabolic with wind fraction. When wind fraction equal to 0.27, the expected displacement rate reaches maximum value of 112%. The expected displacement rate of Dust emission exhibit opposite relationships with wind fraction for 300 MW (positive relation) and 600 MW systems (negative relation), and we attribute the difference to the different Dust emission characteristics of300 MW and 600 MW units (Dong and Jiang (2018)). For week-scale analysis, we simulated the magnitude of increase in coal consumption rate and emission factor with an operation of shutdown and startup. It is a limitation of this paper not to include a decision-making strategy for when and which unit to shut down coal power units, and we suggest future study on dispatch decisions to optimize power generation economically and environmentally.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.11.012.

References

CEC (China Electricity Council), 2018. 2017 Statistics Bulletin of the Power Sectors in China.
Chen, Q., Cai, B., et al., 2017. CO2 emission data for Chinese cities. Resour. Conserv. Recycl. 126, 198–208.
Denny, E., O'Malley, M., 2006. Wind generation, power systemoperation, and emissions reduction. IEEE Trans. Power. Syst 21 (1), 341–347.
Dong, Y., Jiang, X., et al., 2018. Coal power flexibility, energy efficiency and pollutant emissions implications in China: a plant-level analysis based on case units. Resour. Conserv. Recycl. 134, 184–195.
Katzenstein, W., Apt, J., 2009. Air emissions due to wind and solarpower. Environ. Sci. Technol. 43 (2), 253–258.
Gonzalez-Salazara, M.A., Kirsten, T., Prchlik, L., 2018. Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. Renew. Sustain. Energy Rev. 82, 1497–1513.
Liu, D., Wang, J., Wang, H., 2015. Short-term wind speed forecasting based on spectral clustering and optimised echo state networks. Renew. Energy 78, 599–608.
Liu, Q., Zhang, W., Yuan, J., 2017. Carbon emissions performance regulation for China's top generation groups by 2020. Resour. Conserv. Recycl. 122, 326–334.
Lu, X., Elroy, M., Sluzas, N., 2011. Costs for integrating wind into the future ERCOT system with related costs for savings in CO_2 emissions. Environ. Sci. Technol. 45 (7) 3160 − 3116.
Lu, X., et al., 2014. Opportunity for offshore wind to reduce future demand for coal-fired power plants in China with consequent savings in emissions of CO2. Environ. Sci. Technol. 48 (24), 14764–14771.
Na, C., et al., 2018. Economic decision-making for coal power flexibility retrofitting and compensation in China. Sustainability 10 (348). https://doi.org/10.3390/su10020348.
NDRC (National Development and Reform Commission), SERC (State Electricity Regulatory Commission), 2011. Notification of The Renewable Energy Tariff Subsidy and Quota Trading Scheme. http://www.ndrc.gov.cn/fzgggz/jggl/zcfg/201102/t20110215_748295.html.
NDRC(National Development and Reform Commission), NEA (National Energy

Administration), 2016. The 13th FYP Power Development Planning. http://www.ndrc.gov.cn/zcfb/zcfbghwb/201612/P020161222570036010274.pdf.
NEA(National Energy Administration), NDRC(National Development and Reform Commission), 2017. Guidance on The Implementation of the 13th Five-year Plan for Renewable Energy Development. http://zfxxgk.nea.gov.cn/auto87/201707/t20170728_2835.htm?keywords=.
NREL, 2013. The Western Wind and Solar Integration Study Phase. pp. 2.
Oates, D.L., Jaramillo, P., 2013. Production cost and air emissions impacts of coal cycling in power systems with large-scale wind penetration. Environ. Res. Lett. 8, 024022.
Peng, J., Xie, R., et al., 2018. Energy-related CO2emissions in the China's iron and steel industry: aglobal supply chain analysis. Resour. Conserv. Recycl. 129, 392–401.
Su, S., Fang, X., et al., 2016. Spatiotemporal characteristics of consumption-based CO2emissionsfrom China's power sector. Resour. Conserv. Recycl. 121, 156–163.
Tang, X., et al., 2018. China's coal consumption declining—impermanent orpermanent? Resour. Conserv. Recycl. 129, 307–313.
Valentino, L., Valenzuela, V., et al., 2012. System-wide emissions implications of increased wind power penetration. Environ. Sci. Technol. 46 (7), 4200–4206.
Xiao, C., et al., 2010. System power regulation scheme for Jiuquan wind power base. Proceedings of the CSEE 30, 1–7.
Ye, H., Ren, Q., et al., 2018. Modelling energy-related CO_2emissions from office buildings using generalregression neural network. Resour. Conserv. Recycl. 129, 168–174.
Yuan, J., et al., 2007. Electricity consumption and economic growth in China: cointegration and co-feature analysis. Energy Econ. 29 (6), 1179–1191.
Yuan, J., 2016a. Wind energy in China: estimating the potential. Nat. Energy 1 (16095). https://doi.org/10.1038/NENERGY.2016.95.
Yuan, J., Xu, Y., et al., 2014a. Peak energy consumption and CO2 emissions in China. Energy Policy 68 (2), 508–523.
Yuan, J., Xu, Y., et al., 2014b. China's 2020 clean energy target: consistency, pathways and policy implications. Energy Policy 65, 692–700.
Yuan, J., Lei, Q., et al., 2016. The prospective of coal power in China: will it reach aplateau in the coming decade. Energy Policy 98, 495–504.
Yuan, J., Na, C., et al., 2016. Coal use for power generation in China. Resour. Conserv. Recycl. 129, 443–453.
Yuan, J., 2016b. The future of coal in China. Resour. Conserv. Recycl. 129, 290–292.
Zhou, C., Wang, S., et al., 2018. Examining the socioeconomic determinants of CO2emissions in China: ahistorical and prospective analysis. Resour. Conserv. Recycl. 130, 1–11.