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Coal power flexibility, energy efficiency and pollutant emissions implications in China: A plant-level analysis based on case units

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ABSTRACT

Integration of intermittent renewable energy in the power systems requires balancing service of conventional fossil fuel power plants, which is mainly provided by coal power in China. However, flexible operation of coal power units will incur energy efficiency penalty, and output additional CO_2 and pollutant emissions. In this paper, we use a high-resolution operation dataset collected from two typical coal power units to evaluate environmental impacts of flexible operation of coal power in China. To address this, we examine the generation mechanisms of CO_2 and three atmospheric pollutants by coal power units, and then calculate the emissions. We also outline the potential of coal power units to perform flexible operation and discuss retrofit options for more efficient flexible operation. In addition, we use plant-level operation data from typical-sized coal power units to estimate emission levels during processes of start-up, deep cycling and regular operations. In the case 300 MW and 600 MW unit respectively, deep cycling operation would incur an increase of 17.5% and 11.3% in heat rate and CO_2 emissions factor, 10.2% and 108.4% in NOx factor, and 41% in dust factor, compared with full load operation. The NOx emissions of a cold start-up in the case 300 MW and 600 MW unit are roughly the amount of 8 hours and 12.3 hours of regular full load operation, respectively. This paper has implication on employing flexible operation of coal power to integrate renewable energy in China's coal-dominated power systems.

1. Introduction

China has put forward ambitious plans for renewable energy (NDRC and SERC, 2011; NDRC and NEA, 2016; NEA and NDRC, 2017; Yuan, 2016). The targets include a 15% non-fossil primary energy supply by 2020 and a 20% non-fossil primary energy supply by 2030, most of which needs to be achieved by increased use of wind and solar power. Under strong policy support, renewable power has experienced robust growth in China for more than a decade. By end of 2016, China has become the largest user of wind and solar power. By end of November 2017, a spectacular new capacity of 45 GW PV panels was added and the new capacity addition for the entire year is 55 GW, setting a new world record in the absolute growth of PV capacity in a single year in one nation (CEC (China Electricity Council), 2018).

The fuel mix of China's power system is dominated by coal power. Due to resource limitations and institutional conditions, flexible power sources such as natural gas and pumped-storage hydropower only constitute a trivial share in China's power generating fleet. In North, Northwest, and Northeast regions of China (Three North) where wind and solar resources are abundant, balancing service of renewable power is mostly provided by coal power. While wind and solar power generate zero emissions, their variability and uncertainty impose negative effects on emissions from the rest of the power system. With increasing wind power penetration, fossil-fired power plants may be forced to adjust their output level and increase frequency of start-up and shut-down to accommodate wind power generation (Denny and O'Malley, 2006; Katzenstein and Apt, 2009; Valentino et al., 2012; Lu et al., 2011; Oates and Jaramillo, 2013; Lu et al., 2014; Gonzalez-Salazara et al., 2018).

As wind and solar power play an increasingly important role in electric power system of north regions in China, start-up and deep cycling of coal units are expected to occur more frequently (Liu et al., 2015; Na et al., 2018). However, due to historical reasons, coal power units in stock were designed for base load with feasible output starting at 50% of rated capacity, which means very limited capacity for deep cycling operations. In addition to lack of flexibility in the power system, institutional barriers to cross-border trade and dispatch system have led

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to unprecedented high curtailment rates in China's renewable energy (NEA, 2014, 2016a; Lu et al., 2016). Wind curtailment rate in provinces of Xinjiang, Gansu and Jilin provinces was as high as 40%, and the national average was 17.1% in 2016 (NEA (National Energy Administration), 2017; CEC (China Electricity Council), 2017a).

In response to the high renewable curtailment rates, NEA and NDRC required existing coal fleets to conduct flexibility retrofitting with the target to retrofit 82 GW of pulverized condensing (PC) units and 133 GW combined heat and power generation (CHP) units by 2020 (NEA and NDRC, 2016a,b), starting with 16 pilot projects in Three-north regions in 2016 (NEA (National Energy Administration), 2016b). Economic and environmental implications of renewables on fossil-combusting power plants and the power systems have been extensively studied in literature, but almost all under the United States' background (NREL, 2013). As China substantially differs from the U.S. in institutional environment and fuel mix, conclusions drawn from the U.S. power system cannot directly apply to China. Although studies on the overall CO_2 or pollutant emissions scenarios in China's energy system and power sector in literature is also extensive (Yuan et al., 2014a; Yuan et al., 2014b; Yuan, 2016; Yuan et al., 2016a; Yuan 2018; Yuan et al., 2018; Chen and Cai et al., 2017; Su et al., 2016; Peng et al., 2016; Liu et al., 2017; Zhou et al., 2018; Ye et al., 2018; Tang et al., 2018, among others), to the scope of our knowledge, there is yet no study on the environmental implications of renewables on fossil-combusting power plants with an explicit Chinese background in literature. More importantly, as retrofitted coal units can now ramp down to 30% of rated capacity, the energy efficiency and environmental implications of flexible operation are yet to be revealed for a system-wide optimized operation of the power system. The base for this kind of study is a clear understanding on the energy efficiency and CO_2 & pollutant emissions implications of flexible operation of coal power units.

This study aims to appraise the energy efficiency and pollutant emissions implications of flexible operation in coal power plants with long-term operation data from case power plants in China. Section 2 will address the methodology of our study. Section 3 will present the results and discussions. Section 4 concludes the paper with policy implication and the future directions.

2. Methodology

2.1. The emissions generation mechanism

2.1.1. CO_2

According to IPCC (Intergovernmental Panel on Climate Change) (2007), total CO_2 emissions by coal combustion is the product of primary energy consumption and its emission factor. However, this method is only applicable to macroscopic accounting and is subject to large variations in measuring the emissions of a specific power plant. On the other hand, the EU Core Inventory of Air Emissions data are compiled with unit-level monitoring data, which is accurate but costly with a full set of monitoring equipment installed on every power plant (EEA (European Environment Agency), 2006).

The direct CO_2 emissions in the operation of a coal power unit include the CO_2 emissions released during the combustion process of coal and the CO_2 emissions during the desulfuration process. Key factors that determine the volume of CO_2 emissions are heat rate, desulfurizer, auxiliary power consumption rate, and the quality of coal, among which, heat rate is closely correlated with load factor: the higher the load factor, the less the heat rate and CO_2 emissions. The increase of desulfurizer will add to CO_2 emissions. Auxiliary power consumption rate is positively correlated with CO_2 emissions and the same is the volatile component and fixed carbon of coal.

1) The CO_2 emissions by coal combustion

(1) $W_{rc} = W_{coal} \times C_{ar} \times (1-q_4) \times \frac{44}{12}$

(2) $W_{rc} = W_{coal} \times Q_{net,ar} \times I$

Where,

W_{rc}——the volume of CO_2 emissions, measured in ton (t),

W_{coal}——the consumption of raw coal, measured in ton (t),

C_{ar}——the average carbon content of coal, %

q_4——the heat loss of imperfect combustion of boiler solid, %,

$Q_{net,ar}$——the lower heating value (LHV) of coal, measured in MJ/kg,

I——carbon emission factor, 94600 kg/TJ for bituminite (IPCC (Intergovernmental Panel on Climate Change), 2006).

When the data of standard coal consumption rate of power supply is available, the corresponding CO_2 emission factor can be calculated with Eq. (3):

(3) $EI_{rC} = b_n^s \times Q_n \times I$

Where,

EI_{rC}——CO_2 emission factor, g/kWh,

b_n^s——Standard coal consumption rate of power supply, gce/kWh

Q_n——standard LHV, 29270 kJ/kg.

2) The CO_2 emissions by wet desulphurization

Eq. (4) is used to calculate the CO_2 emissions by wet desulphurization (Dai et al., 2013):

(4) $EI_{sc} = W_{CaCO_3} \times \frac{44}{100} / P_{el}$

(5) $W_{CaCO_3} = \frac{Q_{snd} \times (C_{S1} - C_{S2})}{1000} \times \frac{100}{64} \times \frac{1}{F_r} \times S_t$

Where,

EI_{sc}——CO_2 emissions factor by wet desulphurization, g/ kWh,

W_{CaCO_3}——design limestone consumption, g/h,

Q_{snd}——dry flue gas discharge under standard state, Nm^3/h,

P_{el}——unit wet power, MW,

C_{s1} and C_{s2}——SO_2 concentration of untreated and treated flue gas, mg/Nm^3,

F_r——purity of limestone, %,

S_t——design calcium sulphur ratio, valued at 1.03 here.

2.1.2. NO_x

The NO_x emissions of coal combustion are mainly NO (95%) and NO_2. There are three types of NO_x generated in the combustion process, namely thermal NO_x, fuel related NO_x, and prompt NO_x. Thermal NO_x is oxidation of airborne N2 under high temperature, accounting for roughly 30% of total NO_x generation. Fuel related NO_x is generated with a series of chemical reactions the chemical reaction by the organic nitrogen in the coal, accounting for 70%–90% of total NO_x. Prompt NO_x is the conversion of dinitrogen in the early stage of flame edge via intermediate products, accounting for at most 5% of total NO_x and is usually ignored in the account.

Therefore, the key factors related with NO_x are coal quality, way of combustion, unit size and load factor. In engineering practice, there are two main methods to control NO_x emissions, the first being low NO_x combustion technology in which the generation of NO_x is controlled during combustion process, and the second being flue gas denitration technology with a selective catalytic reduction (SCR) process. In China, the common technology used by thermal power plants is SCR.

With an on-line monitoring system, the emission factor of NO_x for the treated flue gas can be calculated by Eq. (6):

$$EI_{NOx} = Q_{snd} \times C_{NOx} / P_{el} \quad (6)$$

Where,

EI_{NOx}——the emission factor of NOx, g/kWh,

Q_{snd}——the discharge volume of flue gas under standard state, Nm^3/h,

C_{NOx}——the concentration of treated flue gas, mg/ Nm^3,

P_{el}——unit wet power, MW.

2.1.3. SO_2

The coals' sulphur content includes about 60%–70% inorganic sulphur, 30-40% organic sulphur, and a little elemental sulphur. In the