Pollutant Emission and Energy Consumption Analysis of Environmental Protection Facilities in Ultra-Low Emission Coal-Fired Power Units

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Abstract. A total of 30 coal-fired power units in China were assessed with regard to the effects of ultra-low emission retrofitting on pollutant emission and on the consumption of both energy and materials of environmental protection facilities. SO2, NOx, and dust emission were compared, together with the energy and material usage of desulfurization and selective catalytic reduction denitrification facilities before and after retrofitting. Following retrofitting, the average SO2, NOx, and dust emission performance were 0.042, 0.1, and 0.004 g/(kW·h), respectively, all of which are much lower than the current averages of coal-fired units in the United States. The average station service power consumption rate of desulfurization facilities increased from 1.12 to 1.29% following retrofitting, while limestone usage increased from 112.6 to 155.5 kg/(104 kW·h) and liquid ammonia consumption increased from 4.1 to 4.31 kg/(104 kW·h).

1. Introduction
Coal-fired power plants are a source of atmospheric pollutants in China. To reduce pollutant emission, the Chinese government now requires the implementation of ultra-low emission measures in plants that are suitable for retrofitting, to obtain dust, SO2, and NOx emission concentration no higher than 10, 35, and 50 mg/m3, respectively, at a baseline oxygen level of 6% [1]. In addition, the average energy consumption of in-service coal-fired generating units after retrofitting must be less than 310 g/(kW·h) by 2020. The implementation of ultra-low emission requirement for coal-fired units increases the difficulty of controlling and adjusting operating indicators of environmental protection facilities such as desulfurization, denitrification and dust remover, and on the same time, increases the energy consumption and material consumption of environmental protection facilities. Zhu showed that the capital investment and operating costs related to environmental protection for a new coal-fired unit with ultra-low emission are increased by approximately 30% with the implementation of special emission limits [2]. However, studies to date regarding the operating costs of coal-fired units with ultra-low emission have primarily involved estimations based on data acquired before retrofitting, and therefore have lacked significant amounts of field-test statistical data [3-4].

In the present study, 30 ultra-low emission coal-fired units in China were selected. The emission characteristics of SO2, NOx and dust before and after ultra-low emission transformation, as well as the operating energy and material consumption data of desulfurization and denitrification facilities are compared. The effects of ultra-low emission retrofitting on energy and material consumption of units were assessed.
2. Materials and methods

2.1. Materials

Table 1. Details of the coal-fired units and environmental protection facilities.

| Unit number | Unit capacity (MW) | Desulfurization facility | Denitrification facility | Dust removal facility |
|-------------|-------------------|--------------------------|-------------------------|----------------------|
| 1           | 300               | double-tower             | SCR                     | ESP+WESP             |
| 2           | 300               | double-tower             | SCR                     | ESP+WESP             |
| 3           | 300               | double-tower             | SCR                     | ESP+WESP             |
| 4           | 300               | double-tower             | SCR                     | ESP+WESP             |
| 5           | 1000              | single-tower             | SCR                     | Low temperature ESP  |
| 6           | 1000              | single-tower             | SCR                     | Low temperature ESP  |
| 7           | 300               | double-tower             | SCR                     | EFIP+WESP            |
| 8           | 300               | double-tower             | SCR                     | EFIP+WESP            |
| 9           | 300               | double-tower             | SCR                     | EFIP+WESP            |
| 10          | 300               | double-tower             | SCR                     | EFIP+WESP            |
| 11          | 330               | double-tower             | SCR                     | EFIP+WESP            |
| 12          | 330               | double-tower             | SCR                     | EFIP+WESP            |
| 13          | 660               | double-tower             | SCR (Two-layer catalyst)| Low temperature ESP  |
| 14          | 660               | double-tower             | SCR (Two-layer catalyst)| Low temperature ESP  |
| 15          | 315               | double-tower             | SCR                     | ESP+WESP             |
| 16          | 315               | double-tower             | SCR                     | ESP+WESP             |
| 17          | 330               | double-tower double-cycle| SCR                     | ESP+WESP             |
| 18          | 330               | double-tower             | SCR                     | ESP+WESP             |
| 19          | 670               | double-tower             | SCR                     | EFIP                 |
| 20          | 670               | double-tower             | SCR                     | ESP+WESP             |
| 21          | 335               | double-tower             | SCR                     | ESP+WESP             |
| 22          | 300               | double-tower             | SCR                     | EFIP+WESP            |
| 23          | 335               | single-tower             | SCR                     | ESP+WESP             |
| 24          | 335               | single-tower             | SCR                     | ESP+WESP             |
| 25          | 335               | single-tower             | SCR                     | ESP+WESP             |
| 26          | 335               | single-tower             | SCR                     | ESP+WESP             |
| 27          | 600               | double-tower             | SCR                     | Low temperature ESP  |
| 28          | 635               | double-tower             | SCR                     | Low temperature ESP  |
| 29          | 1000              | single-tower             | SCR                     | Low temperature ESP  |
| 30          | 1000              | single-tower             | SCR                     | Low temperature ESP  |

30 ultra-low emission coal-fired units in China were chosen for evaluation. These included 20, six and four 300, 600 and 1000 MW units, respectively, and the details regarding these plants and their environmental protection facilities are summarized in Table 1. All 30 units employed limestone–gypsum wet flue gas desulfurization (WFGD) for SO2 control, with 8 units having a single-tower process and the remainder using a double-tower double-cycle process. All plants also employed low nitrogen combustion with selective catalytic reduction (SCR) denitrification to limit NOx emissions. Of these, 28 were based on a three layer catalyst system for SCR, while the two new 600 MW units used two layers of catalyst. These plants employed wet electrostatic (WESP) or synergistic dust removal in conjunction with a low temperature electrostatic precipitator (ESP) or electrostatic-fabric
integrated precipitator (EFIP) and WFGD. WESP was used by 19 units, while 11 units used synergistic dust removal.

2.2. Methods
The amounts of SO$_2$, NOx, and dust emitted by the plants were calculated from data obtained using a continuous flue gas emissions monitoring system (CEMS). The power consumption of each desulfurization unit was measured using an electric energy meter, while the consumption rates of limestone and liquid ammonia were calculated from data acquired using an on-line monitor. The pre-retrofit data in this study represent the average annual values for the units one year prior to the ultralow emissions retrofitting, while the post-retrofitting data are the annual averages for the units one year after the retrofitting.

3. Results and discussion
Tables 2 and 3 summarize the SO$_2$, NOx, and dust emission of the various units, as well as the operating energy and material consumption related to desulfurization and denitrification facilities before and after ultra-low emission retrofitting, respectively.

**Table 2.** Pollutant emission before and after ultra-low emissions retrofitting.

| Unit | SO$_2$ | NOx | Dust |
|------|--------|-----|------|
| | Concentration (mg/m$^3$) | Performance (g/(kW-h)) | Concentration (mg/m$^3$) | Performance (g/(kW-h)) | Concentration (mg/m$^3$) | Performance (g/(kW-h)) |
| before | after | before | after | before | after | before | after | before | after |
| 1 | 26.2 | 16.3 | 0.09 | 0.059 | 60.8 | 35 | 0.21 | 0.13 | 7.9 | 0.9 | 0.031 | 0.003 |
| 2 | 31.8 | 16.3 | 0.12 | 0.044 | 61.3 | 35.1 | 0.25 | 0.1 | 13.2 | 1.8 | 0.061 | 0.005 |
| 3 | 33.1 | 16.3 | 0.08 | 0.048 | 64.9 | 34.5 | 0.15 | 0.1 | 16.2 | 1.9 | 0.042 | 0.005 |
| 4 | 27.3 | 16 | 0.08 | 0.053 | 64.4 | 34.6 | 0.19 | 0.12 | 13 | 0.9 | 0.04 | 0.003 |
| 5 | 97.9 | 23.9 | 0.29 | 0.071 | 80.3 | 31.8 | 0.24 | 0.09 | 15 | 1.5 | 0.05 | 0.004 |
| 6 | 68.8 | 23.8 | 0.27 | 0.076 | 77 | 31.5 | 0.3 | 0.1 | 13.4 | 1.4 | 0.061 | 0.005 |
| 7 | 8.8 | 10.1 | 0.02 | 0.031 | 85 | 35.6 | 0.24 | 0.12 | 5.7 | 2.8 | 0.023 | 0.01 |
| 8 | 15.3 | 11.5 | 0.04 | 0.041 | 60.7 | 31.6 | 0.26 | 0.11 | 4.7 | 2.3 | 0.023 | 0.01 |
| 9 | 34.3 | 10.6 | 0.11 | 0.033 | 75.9 | 36.8 | 0.3 | 0.12 | 4.3 | 2.2 | 0.023 | 0.011 |
| 10 | 25.6 | 8.7 | 0.08 | 0.029 | 71.9 | 37.2 | 0.2 | 0.12 | 3.9 | 2 | 0.024 | 0.011 |
| 11 | 145.8 | 8.7 | 0.42 | 0.031 | 76.9 | 32.5 | 0.23 | 0.11 | 20.3 | 1.3 | 0.058 | 0.005 |
| 12 | 154.2 | 8.7 | 0.45 | 0.027 | 81.5 | 33.6 | 0.24 | 0.11 | 21.9 | 0.7 | 0.064 | 0.002 |
| 13 | / | / | 9.5 | / | 0.03 | / | 32.4 | / | 0.11 | / | 1.3 | / | 0.004 |
| 14 | / | / | 9.3 | / | 0.03 | / | 33.5 | / | 0.11 | / | 1.4 | / | 0.004 |
| 15 | 92.5 | 19 | 0.3 | 0.062 | 75.6 | 27.8 | 0.25 | 0.09 | 15.6 | 2.9 | 0.049 | 0.01 |
| 16 | 82.4 | 19.2 | 0.26 | 0.065 | 66.3 | 29.2 | 0.24 | 0.1 | 9.2 | 2.9 | 0.029 | 0.01 |
| 17 | 33.9 | 11.3 | 0.08 | 0.033 | 56.9 | 33.5 | 0.16 | 0.11 | 11.1 | 1.6 | 0.028 | 0.004 |
| 18 | 41.1 | 9.7 | 0.11 | 0.024 | 63.7 | 39.1 | 0.18 | 0.08 | 12.4 | 1.2 | 0.033 | 0.003 |
| 19 | 44.8 | 13.1 | 0.1 | 0.032 | 69.4 | 33.6 | 0.17 | 0.09 | 15.4 | 0.9 | 0.035 | 0.002 |
| 20 | 37.6 | 12.8 | 0.1 | 0.032 | 71.4 | 36.7 | 0.19 | 0.09 | 14.2 | 1 | 0.039 | 0.003 |
| 21 | 15.1 | 20.9 | 0.06 | 0.075 | 41.6 | 37.5 | 0.16 | 0.13 | 1.8 | 1.7 | 0.008 | 0.006 |
| 22 | 53.6 | 22.8 | 0.18 | 0.077 | 84.8 | 39.2 | 0.28 | 0.13 | 8.8 | 1.3 | 0.032 | 0.004 |
| 23 | 66.5 | 12 | 0.24 | 0.03 | 73.6 | 30.8 | 0.23 | 0.08 | 22.6 | 1.7 | 0.082 | 0.004 |
| 24 | 68.5 | 12.7 | 0.2 | 0.042 | 73.5 | 32.2 | 0.21 | 0.11 | 18.9 | 0.6 | 0.054 | 0.002 |
| 25 | 68.1 | 11.5 | 0.22 | 0.034 | 73.4 | 38.6 | 0.22 | 0.1 | 17.9 | 1.9 | 0.059 | 0.006 |
| 26 | 76.1 | 11.6 | 0.27 | 0.04 | 69.9 | 32.4 | 0.25 | 0.12 | 26.2 | 1.1 | 0.091 | 0.004 |
| 27 | 84.6 | 6.1 | 0.23 | 0.018 | 75.7 | 36.7 | 0.19 | 0.11 | 15.5 | 1.4 | 0.039 | 0.004 |
| 28 | 76.8 | 8.5 | 0.22 | 0.025 | 70.8 | 38.3 | 0.19 | 0.11 | 16.2 | 1.1 | 0.045 | 0.003 |
| 29 | 122 | 14.6 | 0.42 | 0.046 | 66.1 | 34.4 | 0.22 | 0.11 | 15.8 | 1.2 | 0.052 | 0.004 |
| 30 | 103 | 11.3 | 0.33 | 0.036 | 72.4 | 39.7 | 0.21 | 0.1 | 14.2 | 1.7 | 0.041 | 0.005 |
| Average | 70.6 | 14.3 | 0.22 | 0.042 | 70.9 | 32.7 | 0.22 | 0.1 | 13.2 | 1.4 | 0.046 | 0.004 |
Table 3. The operating energy and material consumption related to desulfurization and denitrification before and after retrofitting.

| Unit | Desulfurization facility | Denitrification facility |
|------|--------------------------|-------------------------|
|      | Station service power consumption rate (%) | Desulfurizer consumption (kg/(10^4 kW-h)) | Liquid ammonia consumption (kg/(10^4 kW-h)) |
|      | Before | After | Before | After | Before | After |
| 1    | 1.01   | 1.18  | 114.3  | 248.8  | 3.83   | 4.81  |
| 2    | 0.93   | 1.16  | 107.1  | 238.7  | 4.39   | 5     |
| 3    | 1.04   | 1.21  | 105.1  | 221.2  | 4.6    | 4.81  |
| 4    | 0.93   | 1.22  | 104.2  | 225.1  | 4.53   | 6.01  |
| 5    | 0.51   | 0.83  | 76.3   | 103.6  | 2.7    | 3.25  |
| 6    | 0.46   | 0.86  | 69.6   | 108.9  | 2.59   | 3.25  |
| 7    | 1.44   | 1.71  | 85.5   | 158.5  | 6.56   | 7.65  |
| 8    | 1.61   | 1.97  | 84.9   | 142.9  | 6.68   | 7.31  |
| 9    | 1.61   | 1.08  | 85.9   | 160.8  | 6.1    | 7.39  |
| 10   | 1.67   | 1.93  | 88     | 149.6  | 5.32   | 6.57  |
| 11   | 1.76   | 1.44  | 140.4  | 213    | 3.07   | 3.68  |
| 12   | 1.74   | 1.32  | 138.1  | 211.5  | 2.81   | 3.4   |
| 13   | /      | 0.82  | /      | 185.9  | /      | 6.52  |
| 14   | /      | 0.9   | /      | 178.5  | /      | 6.15  |
| 15   | 1.32   | 1.69  | 163.9  | 218    | 2.98   | 3.81  |
| 16   | 1.3    | 1.57  | 184.1  | 212.6  | 3.04   | 3.66  |
| 17   | 0.96   | 1.13  | 159.4  | 173.6  | 5.06   | 5.08  |
| 18   | 0.97   | 1.1   | 158    | 170.6  | 4.46   | 4.39  |
| 19   | 1.68   | 2.12  | 165.6  | 229.5  | 4.76   | 5.77  |
| 20   | 1.66   | 1.93  | 164.4  | 234.9  | 4.61   | 5.15  |
| 21   | 1.51   | 1.55  | 150    | 232.5  | 3.04   | 3.91  |
| 22   | 1.45   | 1.54  | 141.3  | 214.5  | 3.04   | 3.67  |
| 23   | 1.8    | 1.55  | 123    | 137.1  | 3.51   | 4.57  |
| 24   | 1.38   | 1.48  | /      | /      | 3.35   | 5.15  |
| 25   | 1.49   | 1.25  | /      | /      | 3.91   | 4.75  |
| 26   | 1.76   | 2.02  | /      | /      | 3.05   | 4.34  |
| 27   | 0.73   | 1.08  | 108.2  | 109.2  | 3.71   | 4.97  |
| 29   | 1.03   | 1.38  | 79.1   | 120.9  | 2.84   | 2.54  |
| 30   | 1.08   | 1.28  | /      | /      | 2.74   | 3.03  |
| Average | 1.12  | 1.29  | 112.6  | 155.5  | 4.1    | 4.31  |

3.1. Emission characteristics of NOx, SO2 and dust

Prior to ultra-low emission retrofitting, these coal-fired units conformed to the requirements provided by the Emission Standard of Air Pollutants for Thermal Power Plants (GB13223–2011). The SO2 concentration output by these units ranged from 8.8 to 154.2 mg/m3, with an average of 70.6 mg/m3. During the analysis period, the average inlet SO2 concentration was 2067 mg/m3 and the average desulfurization efficiency was 96.59%. The NOx emission ranged between 41.6 and 85 mg/m3 with an average of 70.9 mg/m3, together with an average inlet concentration of 367.9 mg/m3, giving an average denitrification efficiency of 80.73%. The dust concentration emitted varied from 1.8 to 26.2 mg/m3, with an average of 13.2 mg/m3.

After ultra-low emissions retrofitting, the units were required to emit SO2, NOx, and dust at concentrations of less than 35, 50, and 5 mg/m3, respectively. The actual SO2 emission ranged from 6.1 to 23.9 mg/m3 with an average of 14.3 mg/m3, an average inlet SO2 concentration of 2778.7 mg/m3, and an average desulfurization efficiency of 99.49%. The NOx emission were between 27.8 and 39.7 mg/m3 with an average of 32.7 mg/m3, average inlet concentration of 350.3 mg/m3, and average
denitrification efficiency of 90.65%. The dust emission concentration varied over the range of 0.6–2.9 mg/m³ with an average of 1.4 mg/m³.

These data indicate that the concentrations of SO₂, NOₓ, and dust emitted by the units were lowered after retrofitting. Specifically, the rates at which SO₂, NOₓ, and dust were generated relative to power generation were respectively reduced from 0.22, 0.22, and 0.046 g/(kW∙h) before retrofitting to 0.042, 0.1, and 0.004 g/(kW∙h) after retrofitting. All of these post-retrofit values are much lower than the average emission performance of coal-fired units operating in the United States [5].

3.2. Operating energy and material consumption of desulfurization facilities
Before ultra-low emission retrofitting, the station service power consumption rate of the desulfurization processes were in the range of 0.46–1.8%, with an average of 1.12%. The power consumption rates associated with desulfurization were relatively high in some units because of the installation of booster fan. After ultra-low emission retrofitting, the power consumption rates varied over the range of 0.82–2.12% with an average of 1.29%, representing an increase of 0.17% compared with the average rate before retrofitting. Because the retrofitted units had to meet lower emission standard, higher desulfurization efficiency was required, which was achieved primarily through increasing the liquid-to-gas ratio. This, in turn, involved increasing the number of slurry circulation pumps. The power usage of such pumps accounts for 60–70% of the overall power required for desulfurization [6-7], and so the power consumption rate was increased.

![Figure 1. Power consumption rates for desulfurization processes in various coal-fired units before and after ultra-low emissions retrofitting.](image)

Figure 1 summarizes the changes in power consumption rates of desulfurization facilities in the coal-fired plants before and after ultra-low emissions retrofitting. From these data, it is evident that the power usage was increased after retrofitting in every unit. It is also apparent that the power consumption rate of the desulfurization process gradually decreases as the unit capacity increases.

Before ultra-low emission retrofitting, the limestone consumption rates of the desulfurization facilities were in the range of 69.6–184.1 kg/(10⁴ kW∙h), with an average of 112.6 kg/(10⁴ kW∙h). After retrofitting, the usage was changed to 103.6–248.8 kg/(10⁴ kW∙h) with an average of 155.5 kg/(10⁴ kW∙h), representing an increase of 42.9 kg/(10⁴ kW∙h). The consumption of limestone correlates with the inlet SO₂ concentration, the activity of the limestone, and the desulfurization operational parameters, such as the liquid–gas ratio and absorption tower slurry pH. Of course, the more stringent emission standard requires a greater amount of SO₂ to be removed, such that the limestone consumption has to increase purely on the basis of reaction stoichiometry.

3.3. Material consumption of denitrification facilities
Prior to ultra-low emission retrofitting, the liquid ammonia consumption of the SCR flue gas denitrification processes ranged from 2.59 to 6.68 kg/(10⁴ kW∙h), with an average of 4.1 kg/(10⁴ kW∙h). After retrofitting, the range was 2.54–7.65 kg/(10⁴ kW∙h) with an average of 4.31 kg/(10⁴ kW∙h).
kW·h), equivalent to an increase of 0.21 kg/(10^4 kW·h). The liquid ammonia usage in such plants is primarily related to various denitrification parameters, including the inlet NOx concentration, catalytic activity, flue gas temperature, and distribution uniformity of the ammonia-nitrogen molar ratio. The new emission standard requires more NOx to be removed, and so the consumption of liquid ammonia inevitably increases. Taking Unit 30 as an example, the inlet and outlet NOx concentrations were 296.6 and 72.4 mg/m^3, in conjunction with a liquid ammonia consumption of 2.74 kg/(10^4 kW·h) before the retrofit. Following the retrofit, these values were 294.4 mg/m^3, 39.7 mg/m^3, and 3.03 kg/(10^4 kW·h), respectively.

4. Conclusions
Ultra-low emission retrofitting is being used to lower SO_2, NOx, and dust emission from coal-fired power plants in China. The present data indicate that the average SO_2, NOx, and dust emission performance were respectively decreased from 0.22, 0.22, and 0.046 g/(kW·h) before retrofitting to 0.042, 0.1, and 0.004 g/(kW·h) after retrofitting. All these values are much lower than the average emission performance of coal-fired units presently operational in the United States.

Ultra-low emission retrofitting simultaneously increased the energy and material consumption of desulfurization and denitrification facilities in these coal-fired units. The average power consumption rate associated with desulfurization increased from 1.12 to 1.29%, while limestone consumption increased from 112.6 to 155.5 kg/(10^4 kW·h) and liquid ammonia usage consumption in denitrification processes increased from 4.1 to 4.31 kg/(10^4 kW·h).

Based on these data, optimization of the desulfurization and denitrification facilities in coal-fired plants is recommended to reduce energy and material consumption rates with meeting the new emissions standards.

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5. References
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