Supplementary Information

Updated hourly emissions factors for Chinese power plants showing the impact of widespread ultra-low emissions technology deployment

Xiao Liu[†], *Xing Gao*[†], *Xinbin Wu*[‡], *Weilin Yu*[†], *Lulu Chen*[§], *Ruijing Ni*[§], *Yu Zhao*[∥], *Hongwei Duan*[‡], *Fuming Zhao*[‡], *Lilin Chen*[‡], *Shengming Gao*[‡], *Ke Xu*[†], *Jintai Lin*[*, §], *Anthony Y. Ku*[*, †, ⊥]

[†]National Institute of Clean-and-Low-Carbon Energy, Beijing 102211, China

[‡]Shenhua Geological Exploration Company, Shenhua Environment Remote Sensing and Monitoring Center, Beijing 102211, China

[§]Laboratory for Climate and Ocean-Atmosphere Studies, Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing 100871, China

[∥]State Key Laboratory of Pollution Control & Resource Reuse and School of the Environment, Nanjing University, 163 Xianlin Ave., Nanjing, Jiangsu 210023, China

[⊥]NICE America Research, 2091 Stierlin Ct, Mountain View, CA 94043, USA

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S1. ULE Implementation in China's power sector

All power plants that can "afford" ULE retrofitting cost are required to complete the process by 2020. Some "small" boilers and CFB units do not have to install ULE.[1] In some heavy polluted regions like BTH, regional air pollution control measures apply to all coal-fired power boilers larger than 100 MW. This presents a numerical threshold for small units and includes CFB units. Boilers with larger capacity should finished ULE retrofitting before October 2017, including CFB boilers.[2] In certain designed "environmentally important regions", coal-fired power units without ULE will be shut down by Jan of 2019.[2]

In addition, an incentive of 1 cent/kWh for units finishing ULE retrofitting before Dec 2016, and 0.5 cent/kWh for units finishing ULE retrofitting after 2016 has motivated some power plants with small boilers or CFB units to also perform ULE retrofits. This has occurred most frequently in regions with high levels of air pollution, including BTH, Shandong, Shanxi, Henan, and the Yangtze River Delta.

Altogether, we estimate that the combined impact will cover 90% of coal-fired power plants by the end of 2020.

S2. Location and characteristics of power units and ULE technologies

All raw data for EF calculations in this paper were collected from the CEMS of Shenhua Group (now merged with Guodian Group to form China Energy Investment Corporation). Shenhua's CEMS, the first company-based CEMS in China, was developed in the period from Oct 2012 through 2013 for digital management of emissions control, and started its formal operation in January 2014. By the end of 2017, Shenhua's CEMS has recorded the company's emission-related data from 162 power units and 131 other industrial boilers. The CEMS data includes daily records of coal consumption and sulfur content, and high-frequency real time data on pollutant concentrations, flue gas flow rate, and power load (i.e., electricity or standard vapor generation).

Figure S1 shows the locations of 17 power plants considered for this study, which are located across China. Table S2 lists the 38 units from 17 power plants, their geographical locations, nameplate generation capacity, emissions control technologies, and the date ULE technologies were installed at the plant. Plants are grouped by geographic region and type (i.e., with or without heat cogeneration). Eighteen power-only units and twenty electricity and heat cogeneration units are considered.

The equipment for a number of distinct configurations for ULE technologies at power units surveyed here are representative of the Chinese power sector. Low NO_x burner (LNB) and selective catalytic reduction (SCR) are used for NO_x control. SCR equipment had already been installed in all units before retrofitting with ULE technologies; LNB equipment was present at a few units as well; and ULE retrofit improved the efficiencies of these systems. These different configurations are representative of the situation across the China power sector.

For SO_2 removal, several ULE technologies were used across the power plants in this study. For plants near the ocean, seawater flue gas desulfurization (SFGD) is an ideal method for SO_2 control considering both cost and performance. Limestone-gypsum wet flue gas desulfurization (WFGD) systems offer reduction efficiencies at 95-99%, and have already been deployed at many systems before upgrading by ULE technologies; the upgrades typically involved optimizing the flow fields for flue gas and liquid contact leading to removal efficiencies at 98% or higher. Advanced single column WFGD systems can ensure compliance with SO_2 emissions standards as long as the sulfur content in the input coal is less than 1.25%. For coal with higher sulfur content coal, double column systems are required.[3]

For PM removal, power plants often combine different technologies to reach the ULE emissions standard. In total, there are six different configurations for PM control across the power plants in this study (Table S2). The most commonly used technology for PM removal was the dry electrostatic precipitator (ESP). All units had ESPs installed before retrofitting with ULE technologies. Upgrades typically replaced the electric drive with a high-frequency source. In several plants, these systems were combined with a low temperature economizer (LTE) to reduce the flue gas temperature and improve the capture efficiency of the ESP. This configuration is referred to as a low-low temperature electrostatic precipitator (LLT-ESP). For plants using higher ash content coal, wet electrostatic precipitators (WESP) were added at the end of the treatment train to remove fine, sticky particles and droplets. Although WESP systems are relatively expensive, they are well-suited to PM removal when the flue gas temperature is close to the dew point.[3] In addition, there is also a synergistic benefit in PM removal by WFGD and SFGD – for example, a previous study suggested an additional 30–60% reduction in PM at some plants with both WFGD and SCR.[4]

One emerging technology to reduce both SO_2 and PM has been introduced by Beijing State Power Environmental Protection Company (SPC) at some plants in China. The technology uses advanced spray nozzles, turbulent mixing and centrifugal separation to simultaneously drive the desulfurization reaction and efficiently remove SO_2 to below 35 mg/m^3 and PM to below 5 mg/m^3.

S3. Reliability of flue gas flow rate and pollution concentration measurements

Several steps were taken to ensure the quality of flue gas flow rate measurements for the units studied here. First, China Energy strictly enforces the rules established by the Chinese government to set up automated measurement sensors. Each sensor was installed in the horizontal pipe at the inlet of the stack, and the distance between the sensor and the pipe wall was at least 1.2 m.[5] The sensors measure gas velocity and the flow rate is calculated from the velocity and pipe cross-sectional area. Second, when setting up the sensors, the automated measurements of flow rates were compared to independent manual measurements made using pitot tubes by the Environmental Protection Agencies of local governments to ensure data quality. Data from the automatic sensors were only accepted if their measured flow rate values agreed, within acceptable limits, to manual calibration measurements. For measured flow rates above in terms of flow velocity above 10 m/s, the limit is agreement to within 10%. For measured flow rates below 10 m/s, the acceptance threshold was 12%.[6] For nine of the 38 units, the requirements were stricter: within 5% for rates above 10 m/s and within 8% for rates below 10 m/s. These bounds establish the uncertainty in the data. The calibration procedure involves not less than five calibration measurements for each sensor a day for four or more continuous days; the sensor and manual measurements must agree to within the target threshold for every measurement during this interval. Unacceptable sensors were replaced until the accuracy requirements were fulfilled. As shown in **Table S6**, all sensors in the units studied here met the requirements. Finally, the calibration was checked every three months with manual measurements. In all cases, the sensors studied here met the requirements.

The pollution concentration measurements were also validated under rigorous independent tests by the Environmental Protection Agencies of local governments when the sensors were set up, as was done for the flow rate measurements. Pollution control sensors are checked using independent manual measurements on a quarterly basis to ensure the accuracy of the automated measurements.

In response to requirements from the central government, China's coal-fired power plants have widely installed CEMS since 2007.[7,8] Data from pollution concentration measurements reported in the CEMS have formed the basis for many studies.[9-12]

S4. Comparison our post-ULE emissions factors with the literature

Table S7 compares our EF results with those in the literature for Chinese power plant emissions. Our results are post-ULE temporal average EF grouped by configuration of the ULE technologies at the 38 units. They are thus slightly different from the results of ULE retrofitting effects with ULE on EF for 25 units. Overall, our EF are lower than those in the literature, which represent years before 2017, by a factor of 8–23 for NO_x, 2–80 for SO_2, and 10–120 for PM. The magnitude of improvement depends on ULE configurations, among other factors.

As shown in Table S7, in the widely used multi-resolution emission inventory for China (MEIC), the most recent explicit information for EF of Chinese coal-fired power plants corresponds to 2010.[13] Using the latest power sector emissions in MEIC[14] and China's annual coal consumption data,[15,16] we derived national average EF for 2015 and 2016 corresponding to MEIC emissions. These MEIC-derived values for 2015–2016 may be slightly overestimated because the power sector emissions in MEIC include contributions from a small number of natural gas-fired power plants. Despite this limitation, Table S7 shows a clear decreasing trend in the MEIC EF over time, indicating that the effects of retrofitting with ULE technologies can be seen in their data sets. With retrofitting across the entire power sector expected to finish by 2020, the average EF in 2020 should be an order of magnitude lower than in 2014.

For NO_x, our post-ULE EF is 0.48±0.11 g/kg averaged across time and the 38 units (Table S7). This value is consistent with the range of 0.23-0.73 g/kg reported by Ma et al. for 2015.[17] Our average EF value is lower by a factor of 8–23 than those in the INTEX-B inventory for 2006,[18] the CEPD for 2010,[13] the pre-2010 values in Zhao et al.,[19] and the MEIC values for 2015–2016. These EF differences are substantially larger than the difference before and after retrofit in our paired data for the 25 units (see Fig. 2). This is mainly because all units studied here had SCR and (sometimes) LNB installed prior to retrofit, which is not always the case for other power units implicitly included in existing inventories.

For SO_2, our post-ULE temporal average EF for the 38 units are 0.02±0.01, 0.1±0.02 and 0.27 ± 0.09 g/kg for SFGD, SPC and WFGD, respectively (Table S7). For comparison with the literature, we also express these values as a function of the sulfur content (0.05-0.5 g S/kg fuel, after dividing the EF value by the annual average percentage sulfur content at each unit). Our post-ULE EF are much lower than INTEX-B (15.6 g/kg for 2006), CEPD (4.89 g/kg for 2010), Zhao et al. (0.9 g/kg before 2010, for a few power plants with WFGD), and derived MEIC values (3.39 g/kg for 2015 and 2.23 g/kg for 2016).

For PM, our EF range from 0.01 to 0.04 g/kg, depending on the ULE configuration (Table S7). Again, we express these values as a function of the percentage ash content (0.0016-0.0028 g ash /kg fuel, in the same manner as done for SO_2 EF) to facilitate the comparison with the literature. Our post-ULE EF are lower by at least one order of magnitude than the values in INTEX-B (1.2 g/kg for $PM_{2.5}$ in 2006), CEPD (0.83 g/kg for PM_{10} in 2010), Zhao et al. (0.0231A g/kg for PM before 2010, for a few power plants with ESP+WFGD), and derived MEIC values (1.13 g/kg for PM in 2015 and 1.07 g/kg for 2016).

We further compare our EF results with those for natural gas-fired power plants in several countries/regions in the literature.[20-23] These studies presented the EF values in terms of emissions per kWh of electricity generated (g/kWh). We thus converted the EF to emissions per unit of standard coal burned (g/kg) using the annual average standard coal burned per kWh of electricity in 2015 in China (0.315 kg/kWh), for comparison with our calculated EF. As shown in Table S7, our average post-ULE EF value for NO_x (0.48 g/kg) is higher than the EF for gas-fired plants equipped with SCR by 23-300%,[20,21,23] although it is lower than the value in Song et al. for LNB-equipped gas-fired plants in China in 2014 (2.15 g/kg).[22] For SO_2, our EF for units equipped with WFGD (0.27 g/kg) was higher than that for gas-fired plants (0.005–0.197 g/kg), whereas our EF for SPC (0.1 g/kg) and SFGD (0.02 g/kg) were lower than Spath et al. (0.197 g/kg). For PM, our EF values (0.01–0.05 g/kg) can be higher or lower than the EF for gas-fired plants (0.0003–0.028 g/kg). Our results show that power plants equipped with the most emission-stringent ULE technologies are approaching natural gas-fired power plants in emissions performance.

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Table S1. Regulatory emissions limits for NO_x, SO_2, and PM in coal-fired power plants

	ULE limits (mg/Nm^3)[a]	MEP 2012 limits (mg/m^3)		
		Special areas	Newly built units	Existing units
NOx	50	100	100	100
SO_2	35	50	100	200
PM	5	20	30	30

[a]"m^3" means at the standard state (1 atm and 273.15 K).

Table S2. Sampled power units and ULE configurations

No.	Units	Capacity (MW)	ULE configuration NOx removal	SO2 removal	PM removal	Retrofit date
			Electricity generation only units			
			BTH region			
1	DG3	328.5	LNB+SCR	WFGD	LLT ESP+WFGD	2014.5
2	DG4	328.5	LNB+SCR	WFGD	LLT ESP+WFGD	2014.3
			Northwest China			
3	YH1	660	LNB+SCR	WFGD	ESP+WFGD	2015.3
4	YH2	660	LNB+SCR	WFGD	ESP+WFGD	2015.3
			Central China			
5	MJ1	600	LNB+SCR	WFGD	ESP+WFGD+WESP	2015.5
6	M2	600	LNB+SCR	WFGD	ESP+WFGD+WESP	2015.4
7	XZ2	1000	LNB+SCR	WFGD	ESP+WFGD	2016.1
			East China			
8	JH1	320	LNB+SCR	WFGD	LLT ESP+WFGD+WESP	2016.6
9	JH2	320	LNB+SCR	WFGD	LLT	2015.8

					ESP+WFGD+WESP	
10	ZS4	350	LNB+SCR	SFGD	ESP+SFGD+WESP	2014.6
11	TC7	630	LNB+SCR	SPC	LLT ESP+SPC+WESP	2015.11
12	TC8	630	LNB+SCR	SPC	LLT ESP+SPC+WESP	2016.11
13	AQ3	1000	LNB+SCR	WFGD	ESP+WFGD+WESP	2015.5
14	AQ4	1000	LNB+SCR	WFGD	ESP+WFGD+WESP	2015.6
15	HS3	1000	LNB+SCR	SPC	SPC	2015.12
16	HS4	1000	LNB+SCR	SPC	SPC	2015.12
17	WZ1	1050	LNB+SCR	SPC	SPC	2015.2
18	WZ2	1050	LNB+SCR	SPC	SPC	2015.9
Electricity and heat cogeneration units						
BTH region						
19	QD1	215	LNB+SCR	SFGD	ESP+SFGD	2015.7
20	QD2	215	LNB+SCR	SFGD	ESP+SFGD	2015.4
21	QD3	320	LNB+SCR	SFGD	ESP+SFGD	2014.12
22	QD4	320	LNB+SCR	SFGD	ESP+SFGD	2015.7
23	SH1	350	LNB+SCR	WFGD	LLT	2014.7

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					ESP+WFGD+WESP	
24	SH2	350	LNB+SCR	WFGD	LLT ESP+WFGD+WESP	2014.11
25	SH3	300	LNB+SCR	WFGD	LLT ESP+WFGD	2015.12
26	SH4	300	LNB+SCR	WFGD	LLT ESP+WFGD+WESP	2015.7
27	PS1	530	LNB+SCR	WFGD	ESP+WFGD	2015.11
28	PS2	530	LNB+SCR	WFGD	ESP+WFGD	2015.12
29	DZ3	660	LNB+SCR	WFGD	ESP+WFGD+WESP	2014.12
30	DZ4	660	LNB+SCR	WFGD	ESP+WFGD+WESP	2014.12
			North China			
31	ZD1	330	LNB+SCR	WFGD	ESP+WFGD	2016.7
32	ZD2	330	LNB+SCR	WFGD	ESP+WFGD	2016.6
33	ZD3	330	LNB+SCR	WFGD	ESP+WFGD	2015.9
34	ZD4	330	LNB+SCR	WFGD	ESP+WFGD	2015.11
			Northeast China			
35	BD1	600	LNB+SCR	WFGD	ESP+WFGD+WESP	2016.8
36	BD2	600	LNB+SCR	WFGD	ESP+WFGD+WESP	2016.8

			Central China			
37	CD3	660	LNB+SCR	WFGD	ESP+WFGD+WESP	2015.11
38	CD4	660	LNB+SCR	WFGD	ESP+WFGD+WESP	2015.1

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Table S3. Monitoring methods and sensors used in field measurements in different units

	Analytical method[a]	Unit	Accuracy
Concentrations of SO_2 and NO_x	Non-Dispersive Infrared Absorption (NRIR)	DG3,DG4,YH1, YH2,AQ1,AQ2,CD3,CD4, ZD1, ZD2, ZD-3, ZD-4	±1%
	Non-Dispersive InfraRed (NDIR)	JH1, JH2, BD1, BD2, PS1, PS2, MJ3, MJ4	±1%
	Infrared Analysis (FTIR)	ZS4, TC7, TC8	≤±2.0 %
	Ultraviolet-visible light Absorption (UV-vis)	XZ2	±2.0 %
	Pulsed Ultraviolet Fluorescence Analysis	SH1, SH2, SH3, SH4	±0.5%
Concentration of PM	Laser forward scattering	WZ1, WZ2, YH1, YH2, AQ3, AQ4, ZS4, TC8, JH2, PS1, PS2, MJ3, MJ4, ZD1, ZD2, ZD-3, ZD-4	≤±2.0%
	Laser back scattering	CD3, CD4, QD1, GD2, QD3, QD4	≤±2.0%
	Double-path turbidity	JH1	≤±2.0%

	monitoring		
	Turbidity monitoring	XZ2	≤±2.0%
	Ac coupled charge induction	BD1, BD2	
	Light-scattering analysis	TC7	
Flow rate of flue gas	Pitot tube method	YH1, YH2, ZS4, JH7, JH8, CD3, CD4, MJ1, MJ2, XZ2, AQ3, AQ4	≤±0.5-5 %
	Ultrasonic flowmeter	DZ3, DZ4	±0.25%
	Thermal mass flowmeter	HS3, HS4, SH1, SH2, SH3, SH4, PS1, PS2	±0.5%
	Needle valve flowmeter	TC7, TC8	±1%
	AC charge flow meter	BD1, BD2	±1%

a: Linear error limit of each sensor:

Maximum allowable sensor zero drift: ±2% in 24 hours for pollutant concentration, and ±3% in 24 hours for flue gas flow rate.

Maximum allowable sensor span drift: ±2.5% in 24 hours for pollutant concentration, and ±3% in 24 hours for flue gas flow rate.

Repeatability of flue gas flow rate measurement: ±1% in 24 hours.

All plants make field calibration for all sensors of CEMS every 15 days.

Table S4. Annual average coal quality consumed at each sampled unit

No	Units	Region	Capacity[a] Power (MW)	Capacity[a] Vapor (ton St. vapor/hour)	S[b] (%) 2015	S[b] (%) 2016	S[b] (%) 2017	V[c] (%)	Coal consumption rate[d] (g/kWh)	Low heat value[e] (MJ/kg)
Electricity generation only units										
1	DG3	BTH	328.5	1100	0.45	0.4		13.23	306.7	20.67
2	DG4	BTH	328.5	1100	0.43	0.4		13.12	306.69	20.6
3	YH1	NW China	660	2141	0.92	0.74		22.53	292.69	20.75
4	YH2	NW China	660	2141	0.86	0.74		22.53	291.37	20.74
5	MJ1	C China	600	1900	0.39	0.39	0.38	19.2	290.78	22.05
6	MJ2	C China	600	1900	0.36	0.38	0.38	19.2	291.31	22.05
7	XZ2	C China	1000	3099	0.55	0.57	0.59	19.1	274.11	20.98
8	JH1	E China	320	1025	0.5	0.41	0.34	15.19	307.1	21.51
9	JH2	E China	320	1025	0.48	0.4	0.34	15.19	302.47	21.51
10	ZS4	E China	350	1146	0.48	0.46		12.7	279.76	21.56
11	TC7	E China	630	1942	0.41	0.43	0.4	10.7	286.9	24.14
12	TC8	E China	630	1913	0.41	0.42	0.39	10.7	286.9	24.14

13	HS3	E China	1000	3130	0.47	0.44		17.9	281.39	21.33
14	HS4	E China	1000	3130	0.48	0.47		17.9	281.39	21.33
15	AQ3	E China	1000	2910	0.47	0.3		13.5	267.57	22.1
16	AQ4	E China	1000	2910	0.48	0.3		13.5	267.14	22.1
17	WZ1	E China	1050	3035		0.42		9.3	260.9	22.88
18	WZ2	E China	1050	3035		0.47		9.3	260.9	22.88
				Electricity and heat cogeneration units						
1	QD1	BTH	215	670	0.51	0.5	0.46	26.89	325.36	20.56
2	QD2	BTH	215	670	0.51	0.5	0.46	26.89	325.25	20.56
5	QD3	BTH	320	1025	0.51	0.49	0.46	26.89	295.99	20.56
6	QD4	BTH	320	1025	0.51	0.49	0.46	26.89	295	20.56
9	SH1	BTH	350	1175	0.45	0.43	0.41	13.75	290.52	21.77
10	SH2	BTH	350	1175	0.45	0.42	0.41	13.75	292.16	21.71
3	SH3	BTH	300	1025	0.45	0.42	0.4	14.67	263.28	22.07
4	SH4	BTH	300	1025	0.44	0.42	0.4	14.67	267.61	21.98
11	PS1	BTH	530	1650	0.45	0.44	0.49	13.53	293.86	22.19
12	PS2	BTH	530	1650	0.45	0.44	0.49	13.53	296.18	22.19

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13	DZ3	BTH	660	2150	0.47	0.47		11	297.24	21.4
14	DZ4	BTH	660	2150	0.48	0.46		11	296.94	21.4
15	ZD1	N China	330	1018	0.39	0.43		31.7	299	16.29
16	ZD2	N China	330	1018	0.39	0.38		31.7	299	16.29
17	ZD3	N China	330	1018	0.39	0.42		31.7	299	16.29
18	ZD4	N China	330	1018	0.4	0.4		31.7	299	16.29
21	BD1	NE China	600	1913	0.19	0.17	0.16	9.18	296.83	15.11
22	BD2	NE China	600	1913	0.19	0.18	0.16	9.18	296.95	15.11
29	CD3	C China	660	2080	0.41	0.35	0.34	11.65	291.35	23.79
30	CD4	C China	660	2080	0.41	0.35	0.34	11.65	290.81	23.79

BTH = Beijing-Tianjin-Hebei; NE China= North East of China; NW China= North West of China; N China=North of China; E China=East of China.

a. Power = designed power (electricity and/or vapor) generation capacity of turbine.

b. Annual average sulfur content in coal (as-received basis).

c. Annual average ash content in coal consumed in 2016 (as-received basis).

d. Consumed standard coal per KWh of power generation.

e. Annual average lower heating value in coal consumed in 2016.

Table S5. ULE retrofit routes across 25 units

Pollutant	Retrofitting route	Unit
NO_x	Adding or improving LNB	SH1, SH2, TC7, TC8, YH1, YH2, QD1, QD2, QD3, QD4, PS1, PS2, JH1, JH2, HS3, HS4, ZD1, ZD2, ZD3, ZD4
	Improving SCR	SH1, SH2, CD3, CD4, DZ3, DZ4, TC7, TC8, DG3, DG4, YH1, YH2, QD1, QD2, QD3, QD4, CD3, CD4, JH1, JH2, HS3, HS4, BD1, BD2, ZD1, ZD2, ZD3, ZD4
	Improving operation and coal quality	MJ1, MJ2, YH1, YH2, JH1, JH2
SO_2	Replacing WFGD by SFGD	QD1, QD2, QD3, QD4
	Upgrading WFGD	SH1, SH2, ZS4, DG3, DG4, YH1, YH2, PS1, PS2, JH1, JH2, BD1, BD2, ZD1, ZD2, ZD3, ZD4
	Replacing WFGD by SPC	HS3, HS4, TC7, TC8
	Improving operation and coal quality	MJ1, MJ2, CD3, CD4, JH1, JH2, PS1, PS2
PM	Upgrading ESP	SH1, SH2, MJ1, MJ2, TC7, TC8, YH1, YH2, CD3, CD4, BD1, BD2, ZD1, ZD2, ZD3, ZD4, PS1, PS2
	Adding LLT ESP	SH1, SH2, TC7, TC8, YH1, YH2, JH1, JH2
	Adding PM filter	QD1, QD2, QD3, QD4

Adding WESP	SH1, SH2, TC7, TC8, CD3, CD4, JH1, JH2
Adding SPC	TC7, TC8, HS3, HS4
Upgrading demister in WFGD	YH1, YH2, QD1, QD2, QD3, QD4, PS1, PS2, JH1, JH2, ZD1, ZD2, ZD3, ZD4, MJ1, MJ2

Table S6. Accuracy test results by independent manual measurements for flue gas flow rate measurements in the CEMS.

Unit	Relative error with respect to manual measurements [a] (%)
CD3	2.90
CD4	5.45
HS3	1.04
HS4	4.14
ZS4	1.20
QD1	±8.00 [b]
QD2	±8.00 [b]
QD3	±8.00 [b]
QD4	±8.00 [b]
XZ2	-7.77
JH1	-4.50
JH2	-6.80
AQ3	1.60
AQ4	-3.40
PS1	8.50
PS2	2.90
WZ1	-7.20
WZ2	-7.50
MJ1	7.80
MJ2	8.20
TC7	-3.16
TC8	-2.58
ZD1	1.50
ZD2	0.70
ZD3	-10.50
ZD4	7.20
SH1	11.30
SH2	-10.00
SH3	-10.20
SH4	-10.30
DZ3	±12.00 [b]
DZ4	±12.00 [b]
BD1	2.00
BD2	-5.90
DG3	±12.00 [b]
DG4	±12.00 [b]
YH1	±12.00 [b]
YH2	±12.00 [b]

a. The first nine units were enforced with stricter requirements for sensor quality: within 5% of the manual measurements when manually measured flow rates were above 10 m/s, or within 8% when measured flow rates were below 10 m/s. For other units, the requirements were as follows: within 10% for rates above 10 m/s and within 12% for rates below 10 m/s.

b. These units complied with the sensors requirements, although the detailed test results are not available.

Table S7. Emissions factors for NOx, SO_2, and PM from Chinese power plants in the literature and this study

Reference	EF (g/kg of St. coal)	Control device	Year	Methodology
		NO_x		
INTEX-B; Zhang et al. (2009)	7.1	Asian average	2006	Top-down
MEIC; Liu et al. (2015)	5.26	China average	2010	Unit-based and bottom-up
MEIC; Zheng et al. (2018)	4.43	China average	2015	
	3.79		2016	
Zhao et al. (2011)	4.70-11.2	LNB	before 2010	Field measurement-based
Ma et al.	0.23-0.73	LNB+SCR	2015	Field measurement-based
Spath et al.(2000)	0.302[a]	SCR (gas-fired plant)	1997 (USA)	Unit-based
Jarre et al.	0.18-0.39[a]	SCR (gas-fired plant)	2014	Continuous field

(2016)			(Italy)	measurement-based
Song et al. (2018)	2.15[a]	LNB (gas-fired plant)	2014 (China)	Case study
Wang et al. (2016)	0.12[a]	SCR (gas-fired plant)	2015 (China)	Case study
This paper	0.48	LNB+SCR	2015-2017	Continuous field measurement-based
		SO_2		
INTEX-B; Zhang et al. (2009)	15.6	Asian average	2006	Top-down
MEIC; Liu et al. (2015)	4.89	China average	2010	Unit-based and bottom-up
MEIC; Zheng et al. (2018)	3.39	China average	2015	
	2.23		2016	
Zhao et al. (2011)	0.9S[b]	WFGD	before 2010	Field measurement-based
Spath et al.(2000)	0.197[a]	No control (gas-fired plant)	1997 (USA)	Unit-based

Song et al. (2018)	0.007[a]	No control (gas-fired plant)	2014 (China)	Case study
Wang et al. (2016)	0.005[a]	No control (gas-fired plant)	2015 (China)	Case study
This paper	0.27 (0.5S[b])	WFGD	2015-2017	Continuous field measurement-based
	0.10 (0.25S[b])	SPC		
	0.02 (0.05S[b])	SFGD		
		PM		
INTEX-B; Zhang et al. (2009)	1.2 (PM2.5)	Asian average	2006	Top-down
MEIC; Liu et al. (2015)	0.83(PM10)	China average	2010	Unit-based and bottom-up
MEIC; Zheng et al. (2018)	1.13	China average	2015	
	1.07		2016	
Zhao et al. (2011)	0.0231A[c]	ESP+WFGD	before 2010	Field measurement-based
Sui et al. (2016)	≤0.002A[c]	LLT ESP+WFGD+WESP	2015	Case study

Spath et al.(2000)	0.006[a]	No control (gas-fired plant)	1997 (USA)	Unit-based
Song et al. (2018)	0.028[a]	No control (gas-fired plant)	2014 (China)	Case study
Wang et al. (2016)	0.0003[a]	No control (gas-fired plant)	2015 (China)	Case study
This paper	0.05 (0.0027A[c])	ESP+WFGD (or SFGD)	2015-2017	Continuous field measurement-based
	0.02 (0.0019A[c])	SPC		
	0.04 (0.0025A[c])	LLT ESP+WFGD		
	0.03 (0.0028A[c])	ESP+WFGD+WESP		
	0.03 (0.002A[c])	LLT ESP+WFGD+WESP		
	0.01 (0.00078A[c])	LLT ESP+SPC+WFGD+WESP		

[a]The original gas-fired plants EF values presented in units of g/kWh were converted to g/kg by using the annual average standard coal burned per kWh of electricity in 2015 in China (0.315 kg/kWh).

[b]EF are expressed as proportional to the annual average sulfur content.

[c]EF are expressed as proportional to the annual average ash content.

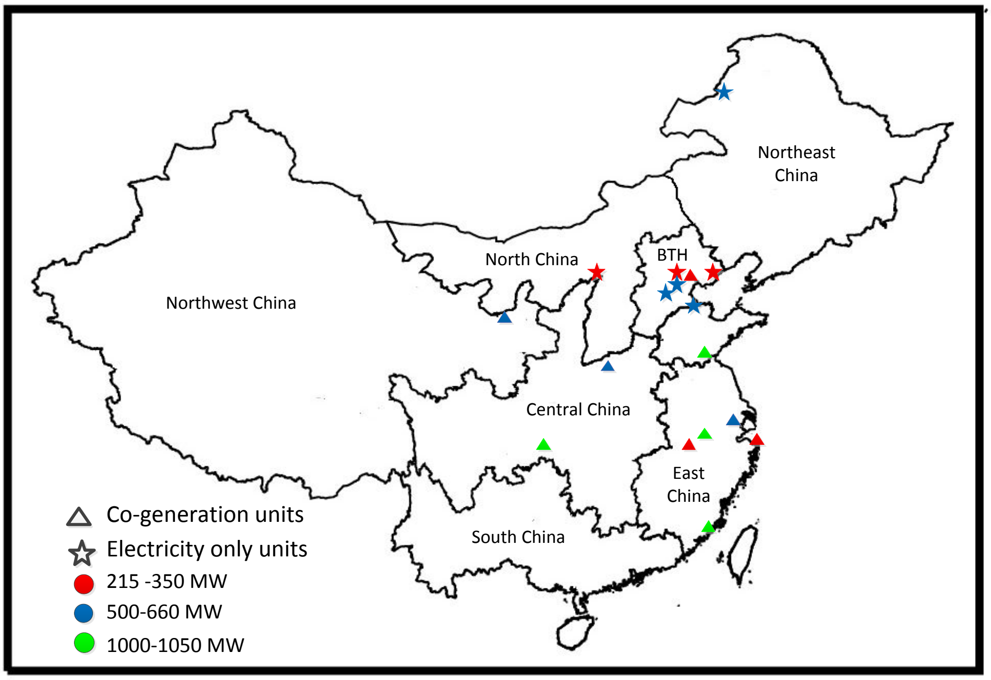

Figure S1. Map of power plants sampled in this study.

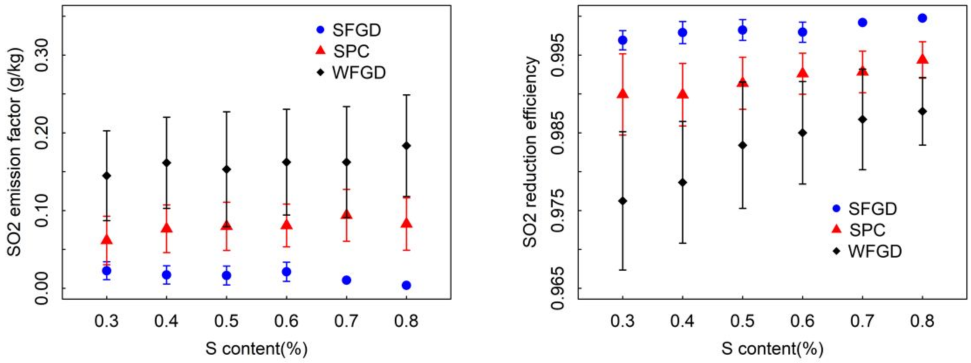

Figure S2. EF and removal efficiency as a function of the sulfur content in coal, averaged over all units implementing the same ULE technologies. Error bars represent one standard deviation across the units.