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High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010

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Table S1 Probability distributions of the national emission estimation-related parameters of coal-fired power plants in China

Category	Subcategory	Value in 1990	Distribution in 1990	Value in 2010	Distribution in 2010	Rating[a]
Activity	Coal Consumption (Tg)	272	Normal (CV: 10%)	1576	Normal (CV: 5%)	B
Boiler Type	Pulverized Boiler Ratio	79% (84%–74%)	Triangular	82% (79%–84%)	Triangular	C
	Circulating Fluidized Bed Ratio	NIP[b]		NIP[b]		
	Grate Furnace Ratio	8% (3%–13%)	Triangular	4% (2%–7%)	Triangular	C
Coal Type	Bituminous Coal Ratio	98% (88%–100%)	Triangular	98% (93%–100%)	Triangular	C
	Anthracite Coal Ratio	NIP[b]		NIP[b]		
Unabated SO_2 Emission Factor	Sulfur Content of Coal (%)	1.01	Normal (CV: 20%)	0.95	Normal (CV: 5%)	C
	Sulfur Retention in Ash (%)	15 (12–18)	Beta	same[c]		B
Unabated NO_x Emission Factor (g/kg)	Large Units$_{\text{Advanced LNB_Bituminous}}$	4.06	Logistic (Scale: 0.16)	same[c]		A
	Large Units$_{\text{Advanced LNB_Anthracite}}$	6.50 (4.34–8.23)	Triangular	same[c]		A
	Large Units$_{\text{LNB_Bituminous}}$	5.08	Logistic (Scale: 0.71)	same[c]		A
	Large Units$_{\text{LNB_Anthracite}}$	8.04	Logistic (Scale: 1.29)	same[c]		A
	Medium Units$_{\text{LNB_Bituminous}}$	6.78	Logistic (Scale: 0.32)	same[c]		A
	Medium Units$_{\text{LNB_Anthracite}}$	7.29 (6.58–7.88)	Triangular	same[c]		A
	Medium Units$_{\text{Non-LNB_Bituminous}}$	7.63 (3.59–12.17)	Triangular	same[c]		A
	Medium Units$_{\text{Non-LNB_Anthracite}}$	10.46	Logistic (Scale: 1.31)	same[c]		A
	Small Units$_{\text{Non-LNB_Bituminous}}$	6.66 (6.17–6.93)	Triangular	same[c]		A
	Small Units$_{\text{Non-LNB_Anthracite}}$	10.50 (9.36–11.50)	Triangular	same[c]		A

	Ash Content of Coal (%)	27.7	Normal (CV: 20%)	25.90	Normal (CV: 5%)	C
	$ar_{\text{Pulverized Boilers}}$[d]	20% (13%–28%)	Beta	same[c]		B
Unabated $PM_{2.5}$ Emission Factor	$ar_{\text{Circulating fluidized beds}}$[d]	44% (40%–52%)	Uniform	same[c]		B
	$ar_{\text{Grate furnaces}}$[d]	85%	Logistic (Scale: 0.05)	same[c]		B
	$f_{\text{Pulverized boilers}}$[d]	6%	Lognormal (GSD: 1.19%)	same[c]		B
	$f_{\text{Circulating fluidized beds}}$[d]	7% (5%–10%)	Uniform	same[c]		B
	$f_{\text{Grate furnaces}}$[d]	14% (3%–25%)	Uniform	same[c]		B
Unabated $PM_{2.5\text{-}10}$ Emission Factor	$f_{\text{Pulverized boilers}}$[d]	17% (13%–19%)	Beta	same[c]		B
	$f_{\text{Circulating fluidized beds}}$[d]	22% (21%–24%)	Uniform	same[c]		B
	$f_{\text{Grate furnaces}}$[d]	23% (3%–23%)	Uniform	same[c]		B
Unabated CO_2 Emission Factor	$\text{Carbon Content}_{\text{Bituminous}}$ (kg-C/GJ)	25.8	Lognormal (GSD: 1.5%)	same[c]		B
	$\text{Carbon Content}_{\text{Anthracite}}$ (kg-C/GJ)	26.7	Lognormal (GSD: 1.5%)	same[c]		B
	Oxidization Rate	100%	Lognormal (GSD: 0.2%)	same[c]		B
	Heating Value (kJ/g-coal)	20.1	Normal (CV: 10%)	18.8	Normal (CV: 5%)	C
Control Technology Penetration	FGD	0% (0%–5%)	Triangular	1% (0%–3%)	Triangular	C
	FGD+Wet Scrubbers	0% (0%–5%)	Triangular	86% (83%–88%)	Triangular	C
	$\text{Non-LNB}_{\text{Large Units}}$	NIP[b]		–		
	$\text{LNB}_{\text{Large Units}}$	100% (90%–100%)	Uniform	40% (30%–50%)	Uniform	C
	$\text{Advanced LNB}_{\text{Large Units}}$	–		NIP[b]		

	Non-LNB$_{\text{Medium Units}}$	100% (90%–100%)	Uniform	38% (28%–48%)	Uniform	C
	LNB$_{\text{Medium Units}}$	NIP[b]		NIP[b]		
	Non-LNB$_{\text{Small Units}}$	100% (90%–100%)	Uniform	100% (90%–100%)	Uniform	C
	LNB$_{\text{Small Units}}$	NIP[b]		NIP[b]		
	Cyclones$_{\text{Pulverized boilers}}$	5% (2%–7%)	Uniform	0% (0%–1%)	Uniform	C
	Wet Scrubbers$_{\text{Pulverized boilers}}$	43% (41%–46%)	Uniform	1% (0%–2%)	Uniform	C
	Electrostatic Precipitators$_{\text{Pulverized boilers}}$	NIP[b]		NIP[b]		
	Bag Filters$_{\text{Pulverized boilers}}$	2% (0%–5%)	Uniform	3% (2%–4%)	Uniform	C
	Cyclones$_{\text{Circulating fluidized beds}}$	25% (22%–27%)	Uniform	0% (0%–1%)	Uniform	C
	Wet Scrubbers$_{\text{Circulating fluidized beds}}$	47% (44%-49%)	Uniform	3% (2%–4%)	Uniform	C
	Electrostatic Precipitators$_{\text{Circulating fluidized beds}}$	NIP[b]		NIP[b]		
	Bag Filters$_{\text{Circulating fluidized beds}}$	0% (0%–3%)	Uniform	11% (10%–12%)	Uniform	C
	Cyclones$_{\text{Grate furnaces}}$	8% (6%–11%)	Uniform	5% (4%–6%)	Uniform	C
	Wet Scrubbers$_{\text{Grate furnaces}}$	75% (72%–77%)	Uniform	27% (26%–28%)	Uniform	C
	Electrostatic Precipitators$_{\text{Grate furnaces}}$	NIP[b]		NIP[b]		
	Bag Filters$_{\text{Grate furnaces}}$	0% (0%–3%)	Uniform	3% (2%–4%)	Uniform	C
Removal Efficiency	Wet Scrubbers$_{SO_2}$	20%	Normal (CV: 10%)	same[c]		B
	FGD$_{SO_2}$	78%	Normal (CV: 10%)	78%	Normal (CV: 5%)	C
	Cyclones$_{PM_{2.5}}$	10% (5%–15%)	Triangular	same[c]		B

Wet Scrubbers$_{PM2.5}$	50% (38%–72%)	Triangular	same[c]	B
Electrostatic Precipitators$_{PM2.5}$	93%	Lognormal (GSD: 1.0%)	same[c]	B
wet-FGD$_{PM2.5}$	50%	Normal (CV: 2.5%)	same[c]	B
Bag Filters$_{PM2.5}$	99% (98.7%–99.4%)	Triangular	same[c]	B
Cyclones$_{PM2.5-10}$	70% (65%–73%)	Triangular	same[c]	B
Wet Scrubbers$_{PM2.5-10}$	90% (83%–95%)	Triangular	same[c]	B
Electrostatic Precipitators$_{PM2.5-10}$	98%	Lognormal (GSD: 1.0%)	same[c]	B
wet-FGD$_{PM2.5-10}$	90%	Normal (CV: 2.8%)	same[c]	B
Bag Filters$_{PM2.5-10}$	99.5% (99.3%–99.7%)	Triangular	same[c]	B

[a]A: the distribution is obtained via data fitting based on field measurements / CPED; B: the distribution is determined from extant studies; C: the distribution is subjectively provided.

[b]Non-independent parameter, calculated as 1 minus the penetrations of other boiler types / coal types / control technologies.

[c]The distribution is the same as that in 1990.

[d]*ar*: the mass fraction of retention ash; *f*: the mass fraction of $PM_{2.5}$/ PM_{10} to the total particulate matter in fly ash.

Table S2 Probability distributions of emission estimation-related parameters for a large coal-fired generation unit in China[a]

Category	Subcategory	Value in 2000	Distribution in 2000[b]	Value in 2010	Distribution in 2010[b]
Activity	Coal Consumption Rate (gce/kW·h^{-1})	328	Normal (CV: 10%)	328	Normal (CV: 5%)
	Annual Operation Hours (hours)	4118	Normal (CV: 20%)	4699	Normal (CV: 5%)
Coal Quality	Probability of Bituminous Coal	95%	Yes-No	99%	Yes-No
	Probability of Anthracite Coal	NIP[c]		NIP[c]	
	Ash Content of Coal (%)	25.1	Normal (CV: 10%)	25.1	Normal (CV: 5%)
	Heating Value (kJ/g-coal)	21.5	Normal (CV: 10%)	19.3	Normal (CV: 5%)
	Sulfur Content of Coal (%)	1.13	Normal (CV: 10%)	0.98	Normal (CV: 5%)
Control Technology	FGD	50%	Yes-No	99%	Yes-No
	Removal Efficiency of FGD on SO_2	42% (0%–84%)	Triangular	84% (81%–86%)	Triangular
	LNB	50%	Yes-No	50%	Yes-No

[a]The selected unit is a 600 MW, pulverized boiler, equipped with FGD, LNB, and an electrostatic precipitator. The uncertainties of the unlisted emission-related parameters are the same as those given in Table S1.

[b]The distribution is subjectively provided.

[c]Non-independent parameter, calculated as 1 minus the ratio of bituminous coal.

Table S3 Provincial coal consumption rate, heating value, sulfur content and ash content in 2010.

Province	Coal Consumption Rate	Heating Value	Sulfur Content	Ash Content
	gce kWh^{-1}	kJ $g\text{-}coal^{-1}$	%	%
Beijing	319.7	20.0	0.56	20.6
Tianjin	311.9	19.5	0.76	24.3
Hebei	326.9	18.3	1.02	27.7
Shanxi	344.4	17.7	1.10	30.2
Inner Mongolia	367.0	19.7	0.79	22.8
Liaoning	369.4	19.0	0.64	25.1
Jilin	394.4	18.6	0.38	25.6
Heilongjiang	377.5	17.4	0.33	29.9
Shanghai	314.5	21.9	0.59	15.7
Jiangsu	323.4	20.3	0.79	20.8
Zhejiang	312.0	21.8	0.76	17.1
Anhui	323.0	16.5	0.48	31.9
Fujian	317.6	21.2	0.65	16.9
Jiangxi	319.4	18.4	1.13	27.7
Shandong	320.3	18.5	1.09	27.3
Henan	320.6	17.1	0.77	32.4
Hubei	328.6	16.1	1.27	34.7
Hunan	322.6	16.4	1.10	35.4
Guangdong	343.8	21.2	0.69	17.7
Guangxi	329.0	18.1	1.88	29.0
Hainan	317.2	22.5	1.08	15.8
Chongqing	367.2	16.7	3.04	34.3
Sichuan	391.0	17.0	1.67	34.0
Guizhou	343.2	16.4	2.43	35.2
Yunnan	359.2	17.5	1.23	30.2
Tibet	-	-	-	-
Shaanxi	329.5	19.3	1.29	24.4
Gansu	312.3	19.7	0.73	22.3
Qinghai	358.0	20.5	0.80	22.3
Ningxia	347.5	17.8	1.07	28.8
Xinjiang	338.7	22.0	0.58	17.4

Comparison with satellite observations

Here we validated the NO_x emission trends of two isolated power plants in CPED by comparing with trends in NO_2 columns derived from OMI. We use the OMI standard tropospheric NO_2 column data product (version 2.1, collection 3), which is available from the NASA Goddard Earth Science Data and Information Services Center (http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omno2_v003.shtml). OMI is a UV-VIS nadir-viewing satellite spectrometer (Levelt et al., 2006) on board the Aura satellite (Celarier et al., 2008). NO_2 columns are derived from radiance measurements, using the Differential Optical Absorption Spectroscopy (DOAS) algorithm (Platt, 1994). OMI detects radiance spectra by 60 across-track pixels with ground pixel sizes ranging from 13×24 km^2 at nadir to about 13×150 km^2 at the outermost swath angle (57°). The 10 outermost pixels on both sides of the swath are excluded in this study to limit the across-track pixel width <40 km. From June 2007, OMI has shown severe spurious stripes, known as row anomalies that are likely caused by an obstruction in part of OMI's aperture (http://www.knmi.nl/omi/research/product/rowanomaly-background.php). The affected pixels are also excluded from the analysis. Only mostly cloud free observations (effective cloud fraction <30%) are considered in this study. For the purpose of plant-level study, we also binned OMI measurements to a 0.1°×0.1° grid by performing an area-weighted averaging.

Two large isolated power plants were compared, the Tuoketuo Power Plant located in Inner Mongolia with a total capacity of 5400 MW and the Yangcheng Power Plant located in Shanxi province with a total capacity of 3300 MW. We inspected satellite imagery from Google Earth to ensure the power plants are isolated and not inferred by other anthropogenic sources. We chose circular regions around each power plant with radii of 20 km, which is large enough to capture NO_2 plumes from each plant, to calculate yearly averages of OMI NO_2 column densities. Figure S1 compares the rates of change in NO_x emissions from two power plants and OMI NO_2 columns during 2005–2010. Good agreement between NO_2 column trend and NO_x emission trend were found, indicating the reasonable accuracy of emission trend estimates in CPED.

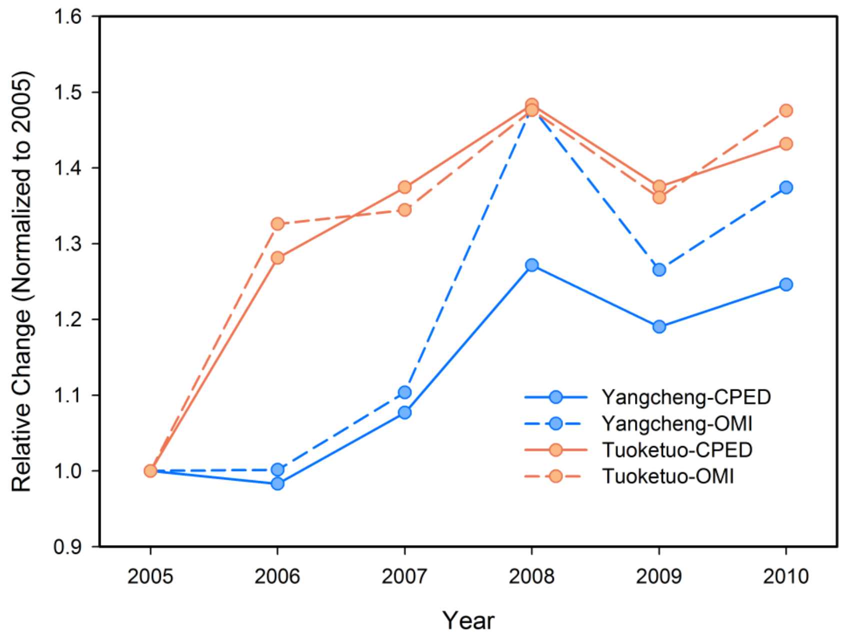

Figure S1. Relative changes of NO_x emissions from two isolated power plants and collocated OMI NO_2 columns during 2005–2010.