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Carbon and air pollutant emissions from China's cement industry 1990–2015: trends, evolution of technologies, and drivers

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Materials and Methods

Besides the linear model, we tried the non-linear regression with Generalized Additive Model (GAM) as a sensitivity test. GAM is a semi-parametric approach which can predict non-linear responses to selected predictor variables. As shown in Fig. S1, we compared the regression of the logarithm of coal use intensity for different kiln types with linear and non-linear method. We found that the GAM regression of the logarithm of coal use intensity has slight higher r square in the regressions for PC and OR, and predicts shaper decrease of coal use intensity in recent years. However, the 95% confidential intervals of both curves were overlapping, illustrating no significant differences between the two types of regressions.

Further, we compared the emission results of CO_2, SO_2, NO_x, and CO, which were estimated through the coal-use based emission factors. Fig. S2 shows the emission ratio between the emission estimates through the coal use derived by GAM regression and the emission estimates through the coal use derived by the linear regression for CO_2, CO, SO_2, and NO_x. The GAM regression predicted higher emission estimates during 1995-2007, and lower emission estimates during 1990-1994 and 2008-2015. The relative differences between both estimates were within the ranges of ±5%, which were much lower than the overall uncertainty ranges of the emission estimates. Therefore, considering the simple explicit expression, we present the final results with the coal use intensity predicted by the linear regression model.

Table S1 Development of emission control standards in the cement industry (unit: mg/m^3 PM)

Processes	GB 4915-1985	GB 4915-1996	GB 4915-2004	GB 4915-2013
Clinker production	150/400/600/800 (Existing） -/150/150/150(Newly-built/Rebuilt/Extended)	150 /400 /600(Built before 1985) -/150 /300 (Built during 1985-1996) -/100 /150 (Built after 1997)	100/50 (Existing/Newly-built)	30/20 (Key regions/ordinary regions)
Cement grinding	100/150/200/400 (Existing） -/100/100/100 (Newly-built /Rebuilt /Extended)	150 /250/400 (Built before 1985) -/150 /250 (Built during 1985-1996) -/100 /150 (Built after 1997)	100/50 (Existing/Newly-built)	50/30 (Key regions/ordinary regions)
Fugitive	-	1/2/4 - /1.5/3 - /1/1.5	1	0.5
Characteristics	Devided into four regions	Corresponding to three-level of functional areas in GB 3095		Key regions/ General regions

Table S2 Probability distributions of the national emission estimation-related parameters of cement industry in China

Variables	Species	Subsectors	Value	type	Distribution	Rating [a]
cement production					Normal (CV: 10%)	B
clinker production					Normal (CV: 10%)	B
coal consumption					From linear regression	A
Uabated EF	NO_x	PC	10.9	PC	logistic (scale=0.5)	B
	NO_x	SK	1.2	SK	Logistic (scale=0.1)	B
	NO_x	OR	13.8	OR	Logistic (scale=1)	B
	CO	PC	15.35 (12.9-17.8)	PC	Uniform	B
	CO	SK	145.55 (135.4-155.7)	SK	Uniform	B
	CO	OR	17.8 (15.5-20)	OR	Uniform	B
	CO_2	PC (clinker)	519.66 (517.46~521.82)	CliPC	lognormal (GSD=1.002)	A
	CO_2	SK (clinker)	499.83(491.28~507.00)	CliSK	lognormal (GSD=1.008)	A
	CO_2	OR (clinker)	499.83(491.28~507.00)	CliOR	lognormal (GSD=1.008)	A
	CO_2	Coal	1940	Coal	lognormal (GSD=1.5%)	B
	PM	PC	250.97 (223.3, 278.6)	PC	Uniform	B
	PM	SK	129.5 (42, 217)	SK	Uniform	B
	PM	OR	270.5 (262.5, 278.5)	OR	Uniform	B
	PM	GRD	35.1 (20.3, 50)	GRD	Uniform	B
	PM	Fugitive PC (≥4000 t)	0.2 (0.1~0.3)	F_PCL4000	Triangular	B
	PM	Fugitive PC (2000-4000 t)	0.3 (0.1~0.5)	F_PC2000_4000	Triangular	B
	PM	Fugitive PC (<2000 t)	0.45 (0.15~0.75)	F_PCB2000	Triangular	B
	PM	Fugitive SK	1.2 (0.4~2.0)	F_SK	Triangular	B
	PM	Fugitive OR	1.2 (0.4~2.0)	F_OR	Triangular	B
	PM	Fugitive Grinding ≥0.6 million tons/year	0.6 (0.2~1.0)	F_GRDL60	Triangular	B
	PM	Fugitive Grinding<0.6 million tons/year	0.9 (0.3~1.5)	F_GRDB60	Triangular	B
Size Fraction	$PM_{2.5}$	PC	0.135 (0.12-0.15)	PC	Uniform	B
	$PM_{2.5}$	SK	0.11 (0.08-0.14)	SK	Uniform	B
	$PM_{2.5}$	OR	0.114 (0.08-0.15)	OR	Uniform	B
	$PM_{2.5}$	GRD	0.04 (0.01-0.07)	GRD	Uniform	B
	$PM_{2.5}$	Fugitive PC (≥4000 t)	0.1 (0.07-0.13)	F_PCL4000	Uniform	C
	$PM_{2.5}$	Fugitive PC (2000-4000 t)	0.1 (0.07-0.13)	F_PC2000_4000	Uniform	C
	$PM_{2.5}$	Fugitive PC (<2000 t)	0.1 (0.07-0.13)	F_PCB2000	Uniform	C
	$PM_{2.5}$	Fugitive SK	0.1 (0.07-0.13)	F_SK	Uniform	C
	$PM_{2.5}$	Fugitive OR	0.1 (0.07-0.13)	F_OR	Uniform	C

	$PM_{2.5}$	Fugitive Grinding ≥0.6 million tons/year	0.1 (0.07-0.13)	F_GRDL60	Uniform	C
	$PM_{2.5}$	Fugitive Grinding<0.6 million tons/year	0.1 (0.07-0.13)	F_GRDB60	Uniform	C
	PMcoarse	PC	0.219 (0.2-0.24)	PC	Uniform	B
	PMcoarse	SK	0.21 (0.18-0.24)	SK	Uniform	B
	PMcoarse	OR	0.205 (0.18-0.24)	OR	Uniform	B
	PMcoarse	GRD	0.12 (0.09-0.15)	GRD	Uniform	B
	PMcoarse	Fugitive PC (≥4000 t)	0.2 (0.16-0.24)	F_PCL4000	Uniform	C
	PMcoarse	Fugitive PC(2000-4000 t)	0.2 (0.16-0.24)	F_PC2000_4000	Uniform	C
	PMcoarse	Fugitive PC(<2000 t)	0.2 (0.16-0.24)	F_PCB2000	Uniform	C
	PMcoarse	Fugitive SK	0.2 (0.16-0.24)	F_SK	Uniform	C
	PMcoarse	Fugitive OR	0.2 (0.16-0.24)	F_OR	Uniform	C
	PMcoarse	Fugitive Grinding ≥0.6 million tons/year	0.2 (0.16-0.24)	F_GRDL60	Uniform	C
	PMcoarse	Fugitive Grinding<0.6 million tons/year	0.2 (0.16-0.24)	F_GRDB60	Uniform	C
sulfur content	SO_2				Normal [CV(1990)=20%, CV(2010)=5%)	B
sulfur retention	SO_2		25% (2.5%)		Normal	B
Sulfur absorption	SO_2	PC	80% (8%)	PC	Normal	C
Sulfur absorption	SO_2	SK	30% (3%)	SK	Normal	C
Sulfur absorption	SO_2	OR	30% (3%)	OR	Normal	C
CYC	$PM_{2.5}$		10% (5%-15%)		Triangular	B
WET	$PM_{2.5}$		50% (38%–62%)		Triangular	B
ESP	$PM_{2.5}$		93%		Lognormal (GSD: 1.0%)	B
ESP2	$PM_{2.5}$		96%		Lognormal (GSD: 1.0%)	B
BAG	$PM_{2.5}$		99% (98.7%– 99.4%)		Triangular	B
CYC	PMcoarse		70% (65%–73%)		Triangular	B
WET	PMcoarse		90% (85%–95%)		Triangular	B
ESP	PMcoarse		98%		Lognormal (GSD: 1.0%)	B
ESP2	PMcoarse		99%		Lognormal (GSD: 1.0%)	B
BAG	PMcoarse		99.5% (99.3%–99.7%)		Triangular	B
DeNOx	NO_x	PC		PC	Normal (CV=5%)	C
DeNOx	NO_x	SK		SK	Normal (CV=5%)	C
DeNOx	NO_x	OR		OR	Normal (CV=5%)	C

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

Table S3 Probability distributions of the unit-level emission estimation-related parameters of cement industry in China

Parameters		Value in 2000	Distribution in 2000	Value in 2015	Distribution in 2015
clinker production		85.6	CV (10%)	161.9	CV (5%)
coal consumption		14.9	CV (10%)	25.3	CV (5%)
Sulfur content		0.094	CV (10%)	0.093	CV (5%)
Control technology	Application of $DeNO_x$ devices	0.05	Yes-No	0.99	Yes-No
	Removal efficiency of $DeNO_x$ devices	0.25 (0-0.5)	Triangular	0.5 (0.45-0.55)	Triangular

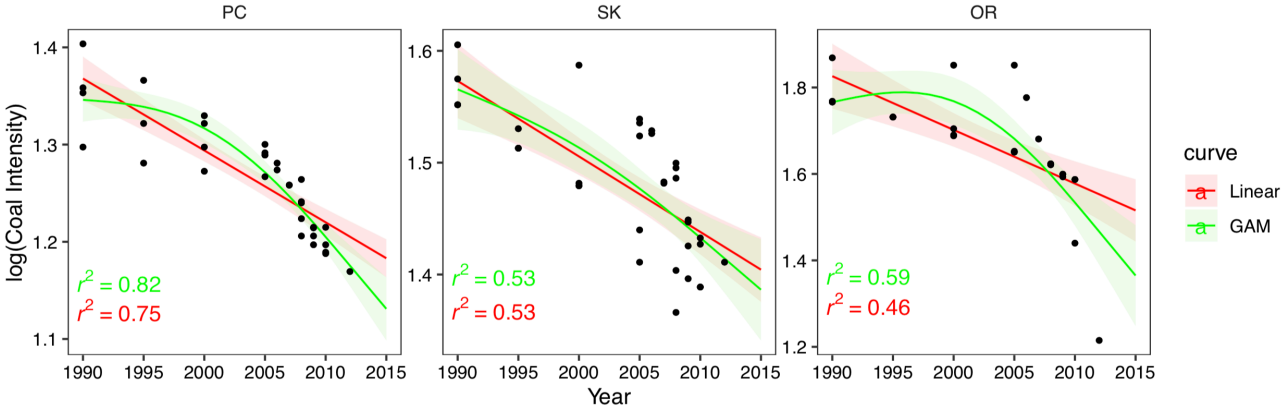

Figure S1 in Supporting Information: Regression of the logarithm of coal use intensity for different kiln types with linear and non-linear (GAM) method. The shadings illustrates the 95% confidential interval of the regression curves. The kiln types include precalciner kilns (PC), shaft kilns (SK) and the other rotary kilns (OR).

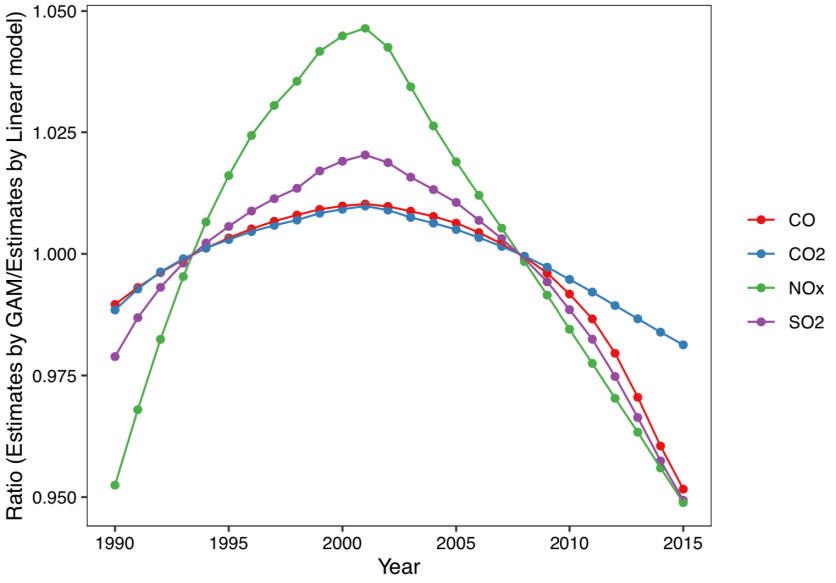

Figure S2 in Supporting Information: Emission ratio between the emission estimates through the coal use derived by GAM regression and the emission estimates through the coal use derived by the linear regression for CO_2, CO, NO_x, and SO_2.

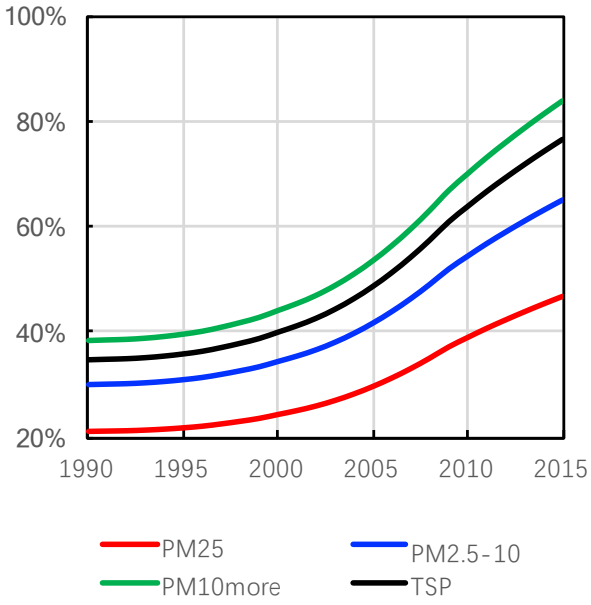

Figure S3 the average abatement rates of fugitive PM emissions during 1990-2015.

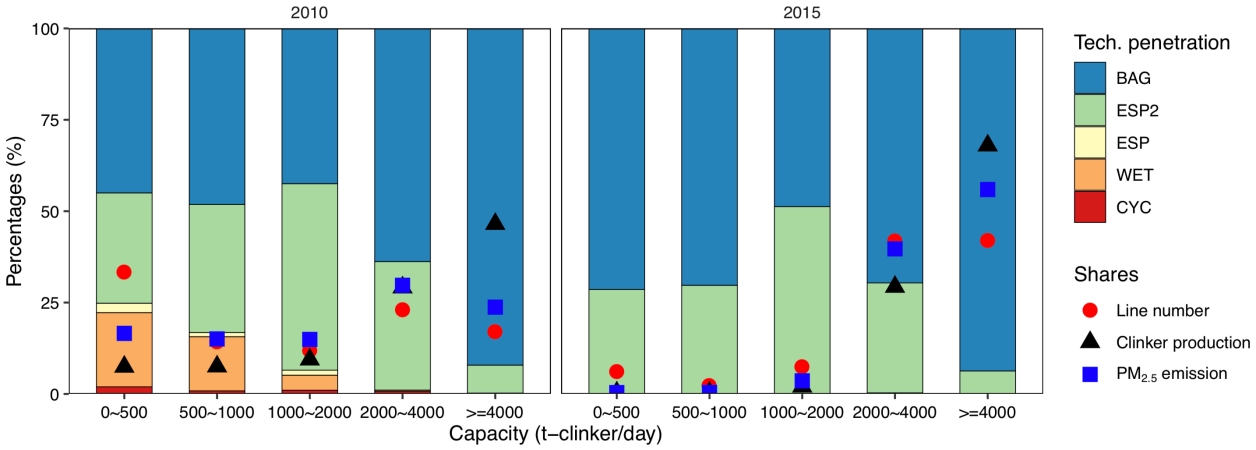

Figure S4 PM control technology penetration in production lines by different clinker production capacities, and share of different capacities to the number of production lines, clinker production, and $PM_{2.5}$ emissions in 2010 and 2015.