Supplementary information

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

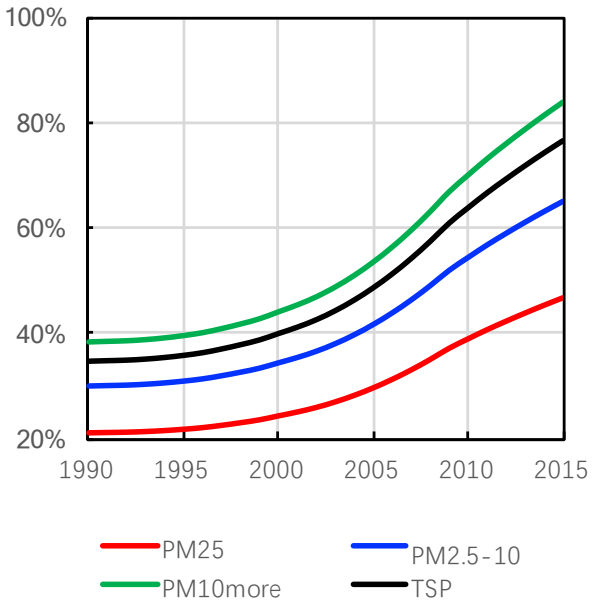

Fig. S1 the average abatement rates of fugitive PM emissions during 1990-2015.

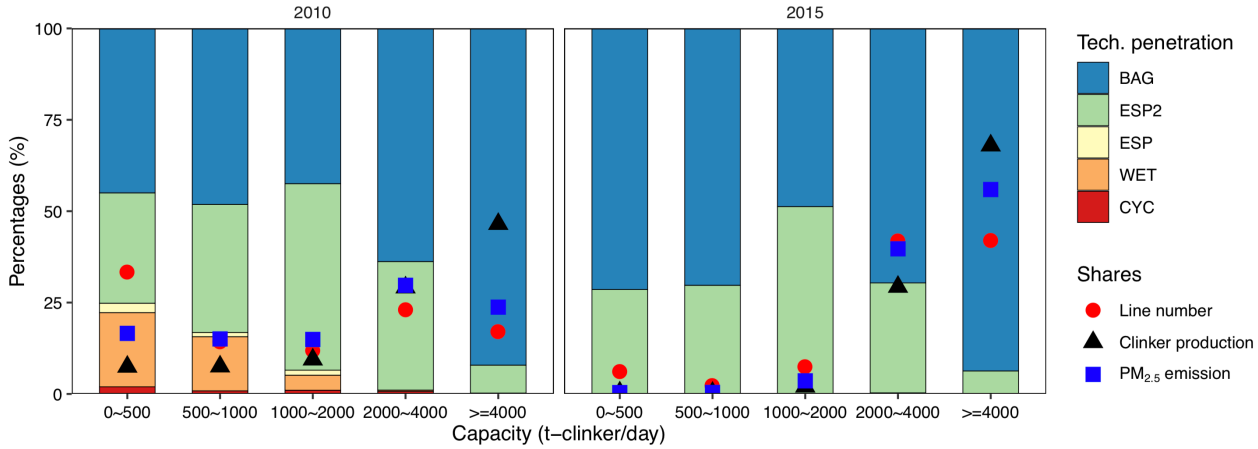

Fig. S2 PM control technology penetration in production lines by different clinker production capacities, and share of different capacities to the number of production lines, clinker production, and $PM_{2.5}$ emissions in 2010 and 2015.