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Factory-level measurements on CO_2 emission factors of cement production in China

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ABSTRACT

Cement is a primary component of concrete and is consumed extensively for construction and transportation infrastructures worldwide. Cement is largely produced and consumed locally but has global impact in terms of both energy consumption and greenhouse gas emissions. China is both the largest producer of cement and the biggest emitter of CO_2 emissions in the world. It has been widely recognized that uncertainties of China's CO_2 emissions were poorly quantified and clear discrepancies can be identified among different sources. These discrepancies arise from many uncertainties, including system boundary and statistical standards, availability of production data (especially for the clinker and cement outputs), and emission factors. We argue that the emission factors (*EFs*, either default values or adjusted ones) are the most important here and highlight the importance of clearly defining the CO_2 accounting and reporting boundaries for determining the emission factors. We therefore developed a factory-level measurement for different types of clinker and cement production, primarily using onsite surveys and sampling, with the objective of distinguishing process-, combustion- and electricity-related emission factors on a factory level. It is a bottom-up CO_2 emission inventory for China using the uniform formula and calculators and the first time factory-level sampling method (BFSM) based on three tiers of production lines, provincial and national integrations. Our results indicate that China's carbon emissions from cement production might be overestimated in the previous estimates because they overlooked the technology transition from the wet process to the dry process, differences in lime content and clinker-to-cement ratios, raw materials and fuels substitutions, and usages of blend additives.

Contents

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1. Introduction

Cement products are considered to be the second most-consumed substance on Earth after water [1]. This is because cement is the primary component of concrete and is consumed extensively for construction and transportation infrastructures worldwide. Cement is largely produced and consumed locally within 300 km due to its various use in construction, while is has global impact as an important barometer for general socio-economic activities. Globally, more than 150 countries produce cement and/or clinker. Cement production of the world is growing by 2.5% annually, and is expected to rise from 2.3 gigatonnes (Gt) in 2005 to 3.5 Gt by 2020 [2] then 3.7–4.4 Gt by 2050 [3]. World cement demand was about 2.3 Gt in 2005, with China accounting for more than 1 Gt (47% of total). The expected demand for 2020 and 2050 will increase in general but might decrease in parts of countries worldwide. The demand for cement per capita follows a bell curve pattern as shown in Fig. 1. Some developing and emerging countries during their high growth phase consume a large quantity of cement because of their needs for infrastructure, while transiting and developed countries will definitely follow a decrease trend for cement demand.

China is both the largest producer of cement and the biggest emitter of CO_2 emissions in the world. In 2010, the world's total cement production is about 3.3 Gt [5] and is expected to be 3.69–4.4 Gt by 2050 [1]. Fig. 2 shows the historical cement output from 1978 to 2010. It is observed that China has been the biggest cement producer in the world since 1985 and produced 1.88 Gt of cement in 2010, accounting for 56% of global cement output [6]. China's demand for cement in the next 5–10 years (probably during years of 2014–2018) will reach at its peak point.

The cement production is both energy and emission intensive. The production of each ton of cement requires about 60–130 kg/t of fuel and 110 kWh/t of electricity [7], emitting around 700 $kgCO_2/t$ in Western Europe and 900–935 $kgCO_2/t$ in China, India and the US [8]. Cement production is a key source of CO_2 emission, due in part to process-related emissions resulting from the direct release of CO_2 during the calcination of limestone. Other main sources result from the significant reliance on fossil fuels mainly like coal and petroleum coke to fuel the kilns and electricity consumption for cement production. Those indirect emissions are generally accounted for elsewhere [9]. It has been reported that about 3.4% in 2000 and 5% in 2006 of global CO_2 emissions and 18% of industrial greenhouse gases (GHGs) came from the cement industry, of which about 50% of emissions come from process-related activity, 40% from direct energy-related combustion, and 5–10% from indirect energy-related electricity use [10].

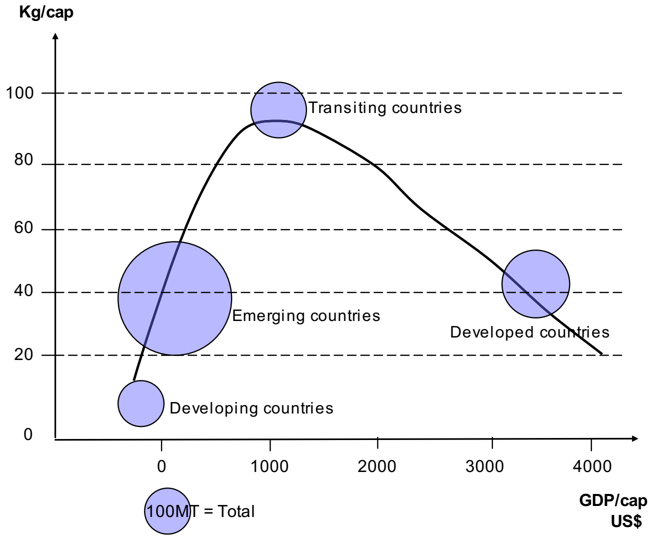

Fig. 1. Relationship between cement consumption and per capita GDP..
Source: Modified from [4]

It has been widely recognized that uncertainties of China's CO_2 emissions were poorly quantified and clear discrepancies exist among previous estimates [11–16]. Gu et al. [17]estimated China's CO_2 emissions from cement production reached 1 billion tons in 2008, accounting for more than 17.85% of the total GHG emissions in the industrial sector. But according to the date of estimation by Carbon Dioxide Information Analysis Center [18], China's CO_2 emissions from cement production is 0.89 billion tons, accounting to around 10.85% of the total emission in China. Worrell et al. [19] estimated the CO_2 emissions factor from China's cement was 883 kg/t cement, in which 415 and 467 kg come from the calcining process and energy emissions respectively. Boden et al. [20] made their efforts to calculate GHG emissions of China's cement industry, and estimated that 496–507 kg CO_2 was from process emissions. 499 kg CO_2/t was used by CDIAC [11] to estimate China's cement production emission. Wang [21] adopted an emission factor of 425 kg CO_2/t cement to roughly estimate the process of emissions from China's cement production in 2005 and 2007 and many scholars [14,22–24] estimated China's cement emission based on the default value, not considering China's reality. We note that different studies give very different estimations. Generally speaking, estimates of China's CO_2 emissions as a part of global studies are much higher than estimates made from domestic studies because some parameters used in global studies does not fit the real situation of Chinese cement industry. Due to lack of country-specific measurements, a general approach to estimate CO_2 emissions from clinker production was given by IPCC Guidelines [25], which suggests to multiply product of activity levels such as the amount of clinker production by the clinker emission factors (*EFs*). Although the calculation is quite easy, we note that different studies on China's emissions from cement production provide various estimates, which raises the issues of data discrepancies and uncertainties [26].

The above discrepancies can be explored from three folds as follows. First, the calculation boundary and statistical standard are different. Some studies [20,25,27] only calculated the raw meal calcination emission without considering the fuel combustion emissions, and others [19,28,29] calculated both but had no electricity-related emissions. Second, it is difficult to get the activity data, especially for the clinker and cement outputs. The third is the uncertainty of emission factors, in which international calculation methods only refer to all kinds of default values. The first two issues are simple. This is because once the calculation boundary is determined it is easy to distinguish the direct and indirect emissions from the process of cement production; and the data of clinker and cement output for years can be obtained from authoritative Department of Statistics, for instance the data promulgated by China Cement Association, National Bureau of Statistics, and others. Consequently, it is the key issue to calculate and confirm the emission factors (*EFs*, either default values or adjusted ones).

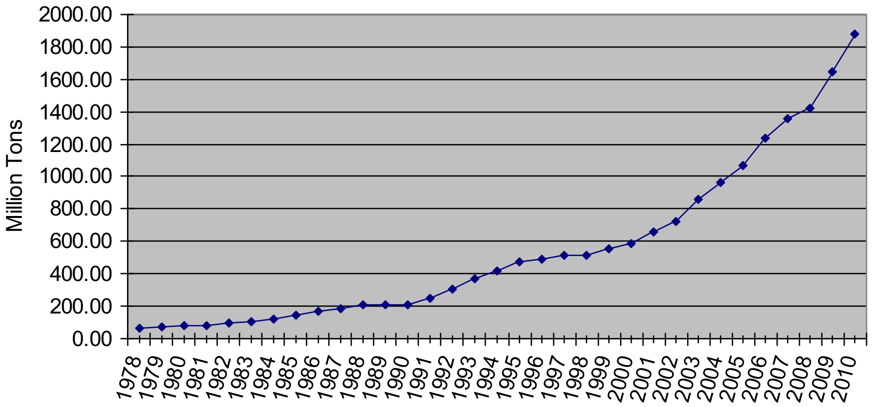

Fig. 2. Total cement production of China: 1978–2010.

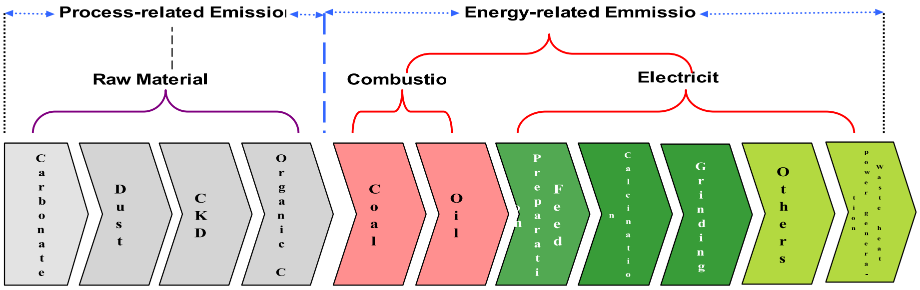

Fig. 3. Types of emissions from cement production

In this paper, we distinguish the overall emission factors of cement production into three types, that is, the process-related emission factors (EF_p), the combustion-related emission factors (EF_c), and the electricity-related emission factors (EF_e). Such a decomposition measurement can clearly identify the emission sources and easily compare national contribution of emissions. It can also improve the foundation for CO_2 reduction and mitigation policies because it reveals different factors during the full life cycle of the cement production process.

This paper is organized as follows. Section 2 provides a brief introduction to the cement production process and identifies some major issues of various emission calculations; Section 3 describes different estimation methods for cement production emission used in China; Section 4 provides four different cases studied on the measurements of emission factors in China; and Section 5 concludes our findings and analyses.

2. Cement production process

As generally known, a cement production process can be divided into three main stages, after mining and quarrying. First, kiln feeds are prepared. Limestone and calcium, silicon, aluminum and iron oxides are crushed and then milled into raw meals. All feed materials including carbonates, dust, cement kiln dust (CKD) and organic carbon can emit CO_2 once they are sent into the kiln. Second, clinker is produced in a kiln by pyro-processing the feed materials. Whilst kilns are fueled by various types of energy from traditional fossil fuels like coal and oil to alternative waste fuels. Third, cooled clinkers are ground and mixed with a small amount of gypsum for Portland cement or with a greater quantity of lime for masonry cement.

In order to analyze the relative contribution of factors influencing emissions in the cement plant, the total CO_2 emissions can be considered as the sum of emissions released from the raw material process, fuels combustion and electricity consumption (Fig. 3), using the equation as bellow:

$$\begin{aligned}\text{Total } CO_2 \text{ emissions} = {} & \text{Process} - \text{related emissions} \\ & + \text{Combustion} - \text{related emissions} \\ & + \text{Electricity} - \text{related emissions}\end{aligned} \tag{1}$$

where each emission implies as given below:

- **Process-related emissions:** raw materials (calcium oxide and other minerals such as silicon, aluminum and iron oxide) drying, pyro-processing; CKD and organic carbon also produce parts of emissions.
- **Combustion-related emissions:** coal, petroleum coke, liquid and solid waste fuels, natural gas, other new waste streams (wood, carpets, plastics, paint residue and sewage sludge etc.).
- **Electricity-related emissions:** motors, fans and blowers for whirling a kiln, drying, heating, grinding of materials, feeds or clinkers.

The process-related emissions are generally considered as direct emissions from cement production, while the combustion- and electricity-related emissions are normally taken account into the emissions from energy use. This differentiation is useful to understand different estimations on CO_2 emission from cement production. In general, about half to half of the CO_2 is emitted from the calcination process and fossil fuels combustion respectively as shown in Table 1 for the U.S. case.

The sources of uncertainties in estimations of combustion-related emissions mainly arise from energy data (fuel use and heating value) and emission factors used. The use of a large amount of inefficient shaft kilns for cement production of China in the 1990s (Table 2) led to high fuel requirements and subsequently CO_2 emissions. More recently, the energy-efficient new suspension preheating and pre-calcining (NSP) process has been widely introduced in China particularly since the year 2006 (Table 3).

Table 1
Share of combustion-and process-related CO_2 emissions from historic U.S. cement manufacturing.
Source: modified from [30].

	1994	1995	1996	1997	1998	1999	2000	2001
Combustion-related CO_2(%)	45.9	46.0	46.0	45.6	45.6	47.4	47.0	46.1
Process-related CO_2(%)	54.1	54.0	54.0	54.4	54.4	52.6	53.0	53.9
Total CO_2(%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 2
Numbers and percentages of kilns in China by process in 1990 and 1995 [31].

Types		**Number (kilns)**		**Percentage (%)**	
		1990	**1995**	**1990**	**1995**
Shaft Kilns	Mechanized shaft kilns	2333	7904	55.8	84.0
	Ordinary shaft Kilns	1171	347	28.0	3.7
	Other shaft kilns	140		3.3	0.0
	Subtotal	3644	8251	87.1	87.7
Rotary Kilns	Dry hollow Kilns	227	421	5.4	4.5
	Dry kilns with waste heat power generation	49	88	1.2	0.9
	Cyclone preheater kilns	24	348	0.6	3.7
	Hollow preheater kilns	51		1.2	0.0
	New suspension preheater kilns (NSP)	22	86	0.5	0.9
	Wet kilns	147	199	3.5	2.1
	Lepol kilns	18	19	0.4	0.2
	Subtotal	538	1161	12.9	12.3
Total		4182	9412	100.0	100.0

Table 3
NSP Kilns of China from 1983–2010 [32].

Years	Kilns **Number**	**Average scale (t/day)**	**Percentages of kilns with over 4000 t/day**
1983	1	4000	100.00
1985	4	2750	72.73
1990	27	1522	29.20
1995	68	1514	15.54
2000	136	1627	24.58
2001	173	1589	19.79
2002	239	1649	21.42
2003	339	1803	23.82
2004	502	2078	30.88
2005	612	2266	37.94
2006	695	2378	41.04
2007	797	2465	42.34
2008	924	2669	48.72
2009	1091	2851	52.74
2010	1304	3002	56.57

Table 3 also illustrates that the average capacity of NSP kilns has increased over time, along with an increase in total production of clinker and cement and energy consumption (Fig. 4). The technology transitions either from the wet to the dry process or from the shaft to rotary kilns coincided with a decrease in the total number of kilns. Although the total energy consumption of cement production in China has increased from 2005 to 2010 (Fig. 4), the NSP dry process has much lower fuel intensity than that of the shaft and other processes (Fig. 5).

Process-related emissions have been more fully characterized than combustion-and electricity-related emissions worldwide as the nature of the IPCC Guidelines and the way industrial sector emissions are separately estimated [30]. Other factors that may result in estimation differences include (1) specific type of clinker and cement produced and clinker-to-cement ratios; (2) availability of statistic data and factors at national or regional levels; and (3) different methodologies. Their consequent impacts on China's CO_2 emissions from cement production are discussed below.

3. Methodology

As discussed above, the key to understand the discrepancies and uncertainties of emission estimates on China's cement production lies in the choice of different emission factors. We highlight the importance of clearly defining the CO_2 accounting and reporting boundaries and the determining of emission factors. This study attempted to develop a factory-level measurement for different types of clinker and cement production, primarily using onsite surveys and sampling, with the objective of distinguishing process-, combustion- and electricity-related emission factors on a factory level.

3.1. A simple and fast estimation method

For simplicity, some rough methods are widely accepted and often used for estimating CO_2 emissions. Basically, the process-related emissions mainly come from calcinations of calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) in the feed meal for clinker production, which could be expressed by the following stoichiometric equations:

$$CaCO_3(+950\ ^{\circ}C) \rightarrow CaO + CO_2\uparrow$$

$$CaCO_3(+950\ ^{\circ}C) \rightarrow CaO + CO_2\uparrow$$

where CaO and MgO denote calcium oxide and magnesium oxide, respectively. CaO is the main content of clinker. According to the law of conservation of matter, each mole of CaO remained in the clinker emits one mole of CO_2. As a result, the clinker emission

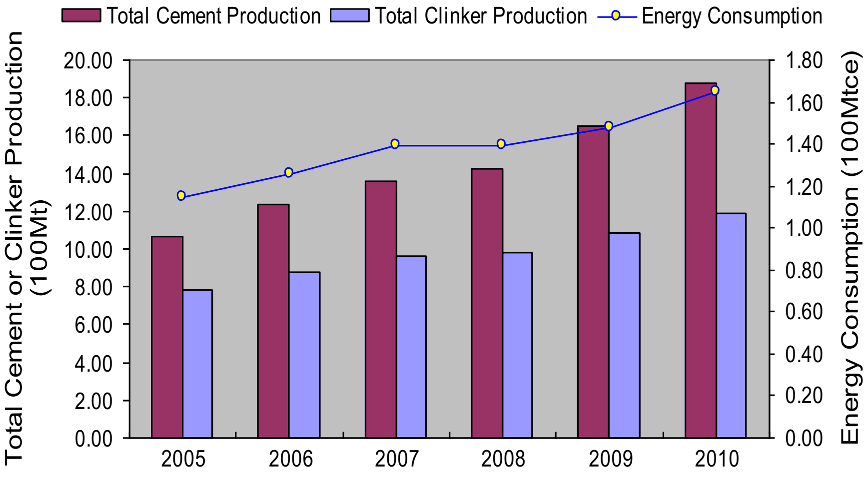

Fig. 4. Energy consumption and productions of clinker and cement of China.

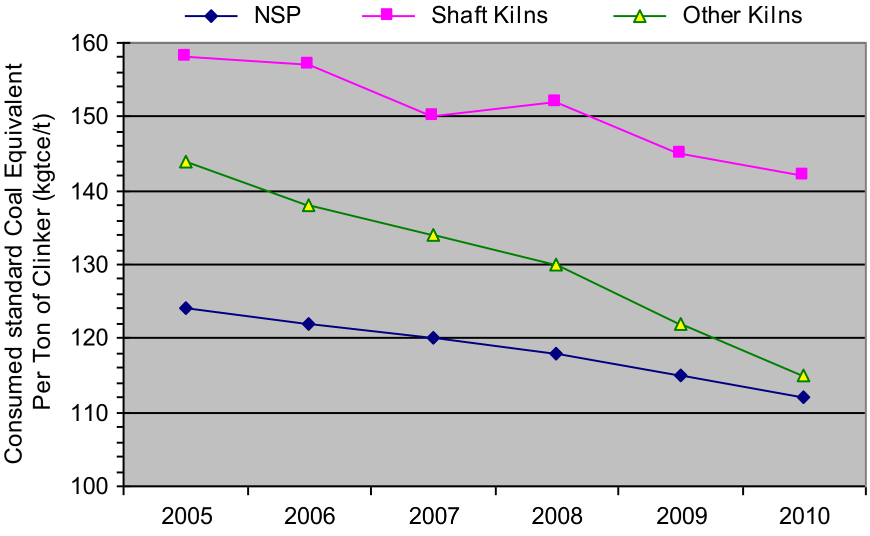

Fig. 5. Standard coal equivalent consumption of different types of kilns.

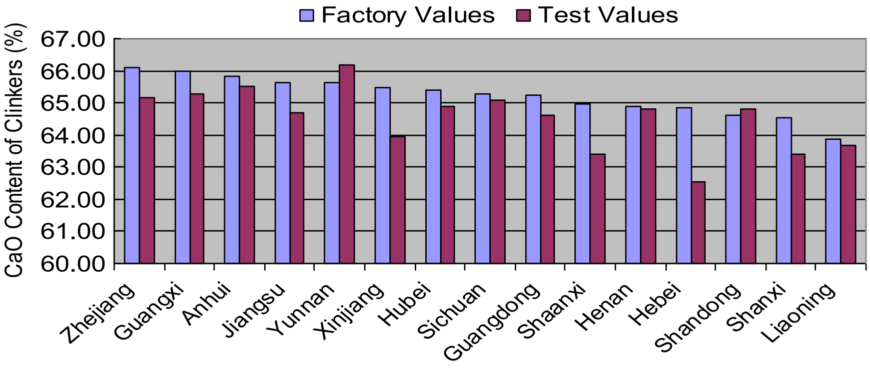

Fig. 6. Differences of CaO content at provincial level of China.
Source: self tested by authors in 2012.

factor is the product of the fraction of lime in the clinker multiplied by the ratio of the relative mass of CO_2 released per unit of lime as below:

$$\begin{aligned} EF_{clinker} &= \text{Fraction CaO}(44.01\ g/\text{mole } CO_2/56.08\ g/\text{mole CaO}) \\ &= \text{Fraction CaO} \times 0.785 \end{aligned}$$

The CaO content can vary from country to country. Thus, the Tier 1 of the IPCC Guideline recommends the default value for the fraction of lime in the clinker could be 64.6% [33], then the clinker emission factor is $0.646 \times 0.785 = 0.5071$. The IPCC also recommends that the above factor should be adjusted by the emission of the lost cement kiln dust (CKD) with around 2–6%, which represents additional CO_2 emissions not accounted for in the clinker emissions estimate. As a result, the above $EF_{clinker}$ should be at least $0.5071 \times 1.02 = 0.5172$. Likewise, according to our sampling over 15 provinces or regions of China in 2012 (Fig. 6),

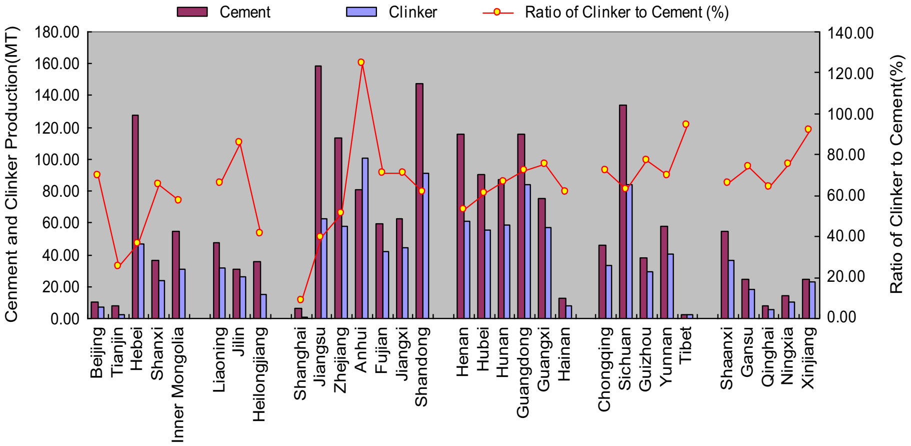

Fig. 7. Differences of provincial cement and clinker production of China.

the average CaO content of China is 64.19%, thus the Chinese $EF_{clinker}$ should be at least $0.6419 \times 0.785 \times 1.02 = 0.5140$.

China's cement industry has its own complexity and specialty. It had a large amount of backward kilns such as shaft and wet process in the past. Its clinker-to-cement ratios is low on average, with a number as 63.14% in 2010. These ratios differ a lot at province or region levels (Fig. 7). The high values in some provinces partially reflect the fact that these provinces exported much more clinkers outside; on the contrary, the low values are as a result of the grinding only facilities in some provinces.

In addition, the IPCC default emission factor might be an underestimate as stated by Cement Sustainability Initiative [34] because it does not include the CO_2 emissions from the calcination of $MgCO_3$. In the absence of specific data, CSI (2005) thus recommends a default emission factor of 0.525 t CO_2/t clinker with correction for calcination of $MgCO_3$, and 0.547 t CO_2/t clinker with the default raw meal-to-clinker ratio 1.55 and default total organic carbon (TOC) content in raw meal of 2 kg carbon/t raw meal [14]. Other process-related emission factors recommend by EDGAR [35] and CDIAC [36] are 0.390 t CO_2/t cement and 0.499 t CO_2/t cement, respectively.

Wang [21,37] also adopted 0.425 t CO_2/t cement as the Chinese process-related CO_2 emission factor, not taking into account for the content of clinker and the clinker-to-cement ratio [14]. This is clearly lower than those of other estimates mentioned above, which excludes the emissions from the calcinations of $MgCO_3$. We will discuss the calculation method of the process-related emission factor below, which should be corrected by emissions from the non-carbonate sources such as calcium silicates or fly ash, bypass dust or CKD and organic carbon [34].

Regarding the combustion-related and electricity-related emission factors, the common best practice is the usage of the IPCC default values for fossil fuels combustion in the absence of country-specific data [38], which provides the lower and upper limits of 95% confidence interval for the effective fuel combustion emission factors. As a simple and convenient way, Wang [21,37] recommended the combustion-related emission factor of 0.390 t CO_2/t cement and the electricity-related emission factor of 0.07 t CO_2/t cement, respectively. This method may result in overestimations on CO_2 emissions from fuel and electricity use because this fixed emission factors did not take into account the effects of types of cement production processes, fuels used, energy efficiency improvement, and difference of regional electricity grid in China.

The electricity-related emissions of cement production are generally accounted in the power industry. CSI [34,39] also states that double-counting should be avoided in CO_2 accounting and reporting. The electricity consumed for cement production is mainly purchased from the external grid but some Chinese cement plants have been adopting new power generation technologies by waste heat recovery (WHR) to self-generate electricity since 2000, which effectively reduce the total energy consumption and CO_2 emissions. As a result, the electricity consumed from WHR power generation should be excluded from the electricity-related emission factors.

Climate Change Division of the National Development and Reform Commission (NDRC) of China [40] issued the 2012 baseline emission factors for regional power grids in China. They recommend the highest electricity-related emission factor as 1.0935 tCO_2/MWh electricity in the Northeastern China and the lowest as 0.8244 t CO_2/MWh electricity in the Eastern China. Wherever more specific data are not available the default emission factors of these referenced grids were used, for example, 0.9913 t CO_2/MWh electricity for the Northwestern China, 0.9344 t CO_2/MWh electricity for the Southern China, 0.9944 t CO_2/MWh electricity for the Central China, and 1.0021 t CO_2/MWh electricity for the Northern China [41].

3.2. The IPCC three tiers method

The IPCC methodology and default emission factors are widely accepted and cited. Three tiers methods for the process-related emission factors of cement production are recommended by the IPCC [38]. The Tier 1 method uses the default emission factor of 0.510 t CO_2/t clinker produced, which is based on the fraction of lime in clinker, or 64.6% and incorporating a 2% correction factor for discarded dust. The Tier 2 method is based on the average lime concentration in clinker by collecting data on clinker production and lime fraction by type. The difference of both methods is expected to be small. The Tier 3 method is a comprehensive method based on raw material inputs but may not be practical for many cement facilities due to its extensive data requirements [39]. The CSI also states that either the input (raw materials or raw meal) method or the output (clinker is preferred) method is equivalent in theory.

For the case of China, there is no previously published China-specific emission factor and most studies had to rely on global default values. This may ignore distinctive characteristics of a number of major emission processes in China. As a result, Zhao et al. [15] summarized and compiled a list of China's emission factors with uniform probability distributions, including the global default emission factors of two databases from IPCC [38] and U.S. Energy Information Administration [42].

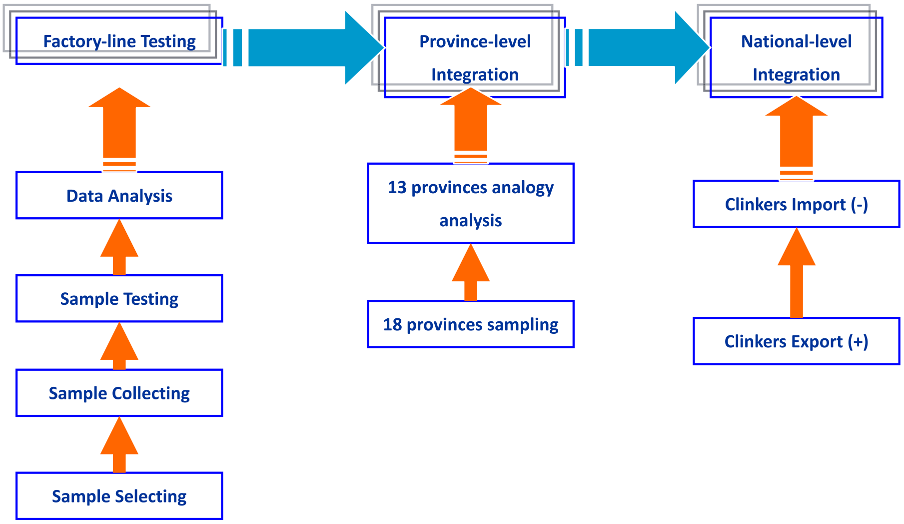

Fig. 8. Three tiers of integrated estimating method.

3.3. *A bottom-up factory-level sampling method (BFSM)*

Our current studies provide some domestic measurements based on large amount of onsite samplings on factory-level cement production lines. It is a bottom-up CO_2 emission inventory for China and the first time factory-level sampling method (BFSM) based on three tiers of production lines, provincial and national integrations (Fig. 8).

The cement production in China can be divided into three main types of processes, including new suspension pre-heaters or pre-calciners (NSP) kilns, shaft kilns and other rotary kilns (including wet kilns, lepol kilns, hollow kilns) which have different specific energy consumption. Clinker production in the NSP kiln and shaft kiln process and the cement grinding process are shown in Fig. 9a, b and c, respectively.

The NSP kiln process has emerged to be the major technology of cement production in China since 2006, comprising 12.3% in total kilns of China before 1995 but more than 85% in 2012. The shaft kiln process accounted 87.0% of all kilns in China before 1995 and has been largely shut down since 2005 to a level of less than 10% in 2012. Grinding stations consume some amount of electricity for external clinker and cement addictive grinding. Thus there only indirect CO_2 emissions are emitted.

Some specific types of cement, including rapid hardening high strength cement, expansive cement, self-stressing cement, hydraulic cement, oil wells cement, decorative cement and others, are produced by the NSP and shaft kilns thus aggregated as one type for our CO_2 emission factor measurements. They accounted for a very small percentage in total cement output of China.

All clinker can be mixed with a small quantity of gypsum to produce Portland cement with a share of more than 95% in all types of cement but this process did not emit CO_2. About 5% of masonry cement is produced by the mixture of clinker and a large amount of lime, and the corresponding CO_2 is accounted in the lime producing sector.

We proposed a BFSM approach in our study from the three tiers of integration framework to estimate China's CO_2 emission factors from the cement production. It follows the IPCC tier 3 and incorporated a large amount of factory-level sample measurements over the 18 major cement producing provinces and/or regions of China.[1] We start with all the production-lines' CO_2 emission factors calculation, including sample selecting, collecting, testing, and production line data analyzing. Then we integrate each province-level CO_2 emission factor by comparing the 18 surveyed provinces and/or region with the rest of the other 13 similar ones. Finally, a national average CO_2 emission factor is calculated by considering the weight of each province's cement output and their clinker imports and outputs (Fig. 8).

The CO_2 emission factors for all production lines are calculated using a uniform formula and calculators,[2] which include the process-related, combustion-related, and electricity-related emissions. The process-related CO_2 emission factor includes the emissions from calcinations of carbonates, non-carbonates like bypass dust or CKD and organic carbon, which is expressed by the equation:

$$EF_{prc} = R_1 + R_2 + R_3 \tag{2}$$

where:

EF_{prc}: the CO_2 emission factor of carbonates calcinations (t CO_2/t clinker);
R_1: emission factor from calcinations of carbonates in the raw meal (t CO_2/t clinker);
R_2: emission factor from calcinations of parts of carbonates in the kiln exhaust dust (t CO_2/t clinker);
R_3: emission factor from calcinations of parts of carbonates in the kiln bypass dust (t CO_2/t clinker).

The calcinations CO_2 emission factor (R_1) is calculated based on the measured calcium oxide (CaO) and magnesium oxide (MgO) content of the clinker as bellow:

$$R_1 = C_c \frac{44}{56} + C_m \frac{44}{40} \tag{3}$$

in which

C_c: the share of CaO content in the clinker, %;
C_m: the share of MgO content in the clinker, %;
44/56: the conversion of the relative formula mass of CO_2 and CaO;
44/40: the conversion of the relative formula mass of CO_2 and MgO.

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[1] All data set of this study in Excel format can be available for any replication purposes.

[2] All estimations in the study are obtained by our self-developed Excel-based calculators.

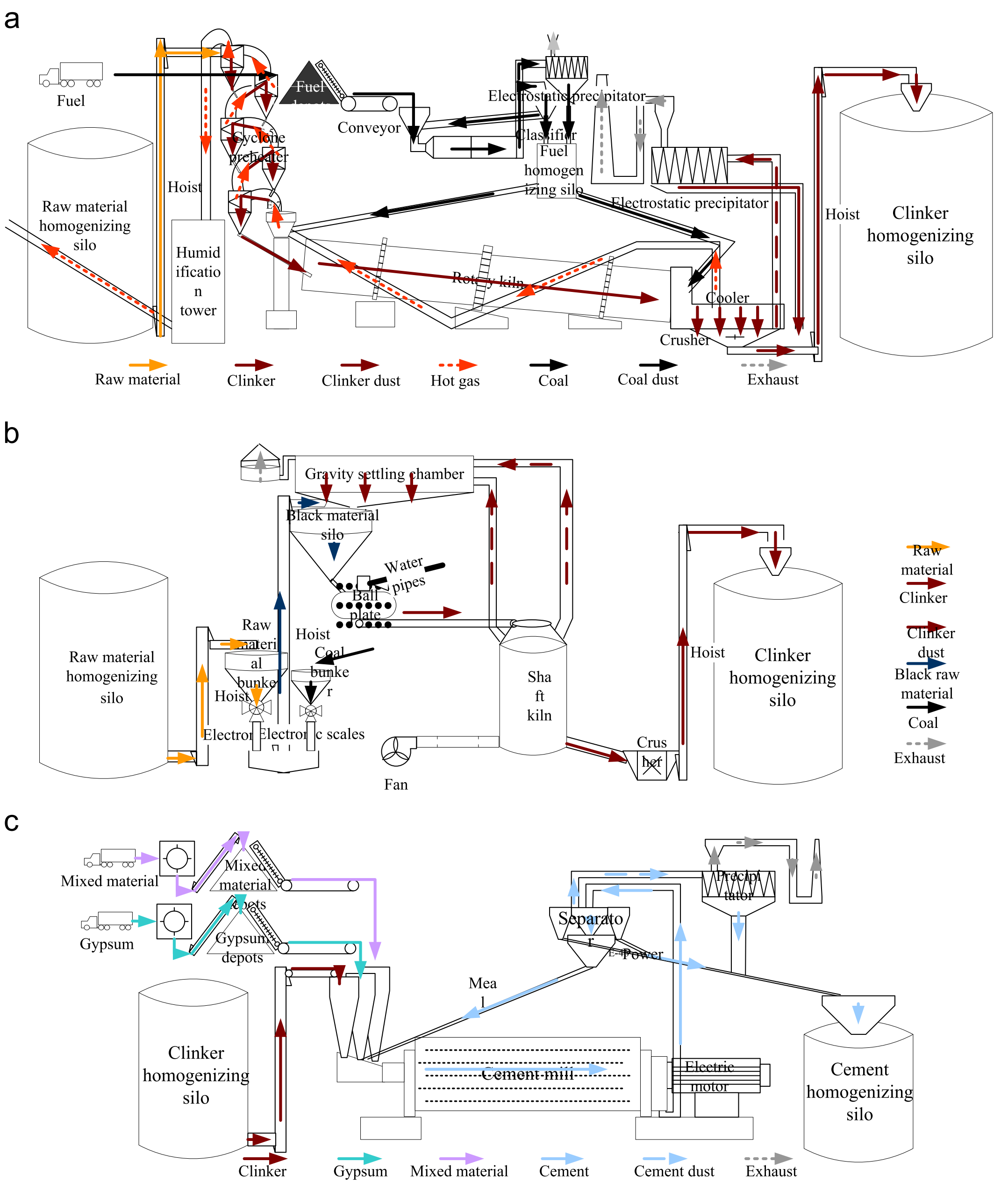

Fig. 9. Main types of cement production process in China.

If alternative materials (like carbide slag or steel slag and others) are used, the formula is then replaced by

$$R_1 = \frac{R_c}{(1-L_c)F_c} \tag{4}$$

in which

R_c: content of CO_2 in the raw meal (%);
L_c: loss on ignition (LOI, %);
F_c: conversion factor of coal ash in clinker blends. If data are unavailable, the default value is set as 1.04.

The emission factor from calcinations of parts of carbonates in the kiln exhaust dust (R_2) is calculated using the formula:

$$R_2 = \frac{R_1 \times U_e}{1000} \tag{5}$$

in which

U_e: dust emission per unit clinker in the kiln exhaust (kg/t). If there are no measured data, the default value is set as 0.15 (kg/t clinker).

The emission factor from calcinations of parts of carbonates in the kiln bypass dust (R_3) is calculated using the formula:

$$R_3 = \frac{Q_d \times B_e}{1000} \tag{6}$$

in which

Q_d: the amount of bypass dust in the klin (kg/t clinker);
B_e: the emission factor of bypass exhaust dust (kg/t clinker), which is calculated using the formula

$$B_e = R_1\left(1 - \frac{R_b}{L_c}\right) \tag{7}$$

in which

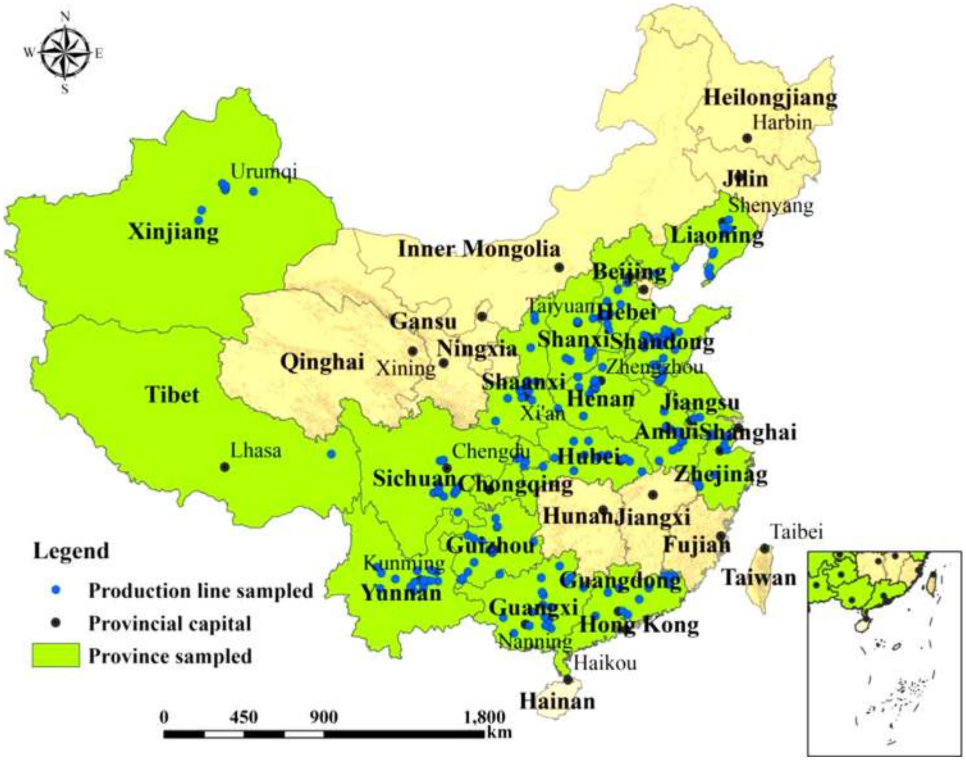

Fig.10. Spatial distribution of samples collected for cement production lines.

R_b: LOI of bypass exhaust dust (%).

The CO_2 emission factor of non-carbonates in the raw meal is calculated by the following formula:

$$E_{pro} = r_a \times R_o \times \frac{44}{12} \tag{8}$$

in which

r_a: the raw meal-to-clinker ratio. If there are no measured data, it is set as 1.52 (the default value);

R_o: the carbon content in the raw meal (%). If there are no measured data, it is set as 0.1–0.3% (in dry, the default value), in which the maximum value is used for the additives of coal gangue and fly ash with high content of carbon; otherwise, the default value is set as the minimum one;

44/12: the conversion of the relative formula mass of CO_2 and C.

As for the combustion-related emission factors, we follow the common best practice by using the IPCC default values for fossil fuels; while for electricity-related emission factors, we use electricity consumptions at production lines and distinguish the baseline emission factors for different regional power grids in China [41].

4. Preliminary measurements on CO_2 emission factors of four cases at factory-level cement production in China

4.1. Field sample collections and four case descriptions

By the end of 2012, we have finished sampling of 289 cement production lines over 18 provinces in China (Fig. 10). Limestone, clay, shale, fly ash, coal, raw meal, clinker and cement were collected from various points by a stainless steel spatula. 685 samples of 144 NSP kiln production lines were collected in 16 provinces. 314 samples of 67 shaft kiln production lines in 13 provinces and 378 samples of 78 special cement and/or grinding stations production lines in 15 provinces were also surveyed respectively (Table 4).

We take four typical examples as follows to demonstrate our calculation procedure (Table 5). Case A is a typical NSP production line with a daily capacity of 5000 t or 1.844 million tons per year of clinker and 1.95 million tons per year of cement. Case C is a typical shaft kiln for specific type of cement production with a daily capacity of 500 t or 120,000 t per year of clinker and 200,000 t per year of cement, while case B is also a shaft kiln for specific type of cement (aluminates) production with a daily capacity of 300 t per day or 80,000 t per year of clinker and 40,000 t per year of cement. The last case D is only grinding station with a capacity of 700,000 t per year of cement. Coal and electricity consumption data for each production line are also collected as shown at the bottom rows in Table 5.

The chemical composition of raw materials and fuels for clinkers and percentage mixture for cements differ greatly by process and cement type. Case A is a large-scale NSP process with 83.12% of lime for cement production (Table 6). Case C is a small-scale shaft kiln with 71% of lime and 9% of coal ash for cement production (Table 8). The case B is a typical process with the mixture of 45% of lime and 55% of bauxite into aluminates cement (Table 7). For Case D, only electricity use data were collected.

4.2. Results of the CO_2 emission factor of the four cases

All results of the CO_2 emission factors of the four cases are listed in Table 9.

For the clinker production, the process-related emission factor accounts for 62% (or 522.84 kg CO_2/t clinker) of total emissions in Case A and 56% (or 472.11 kg CO_2/t) in Case C, comparing to the lowest level of 25% (or 252.95 kg CO_2/t) in Case B (Fig. 11). This is because limestone is a major raw material used in the raw meal in

Table 4
List of surveyed provinces and production lines for different production processes.

Province	NSP Group	Samples	Shaft kilns Group	Samples	Special cements and grinding only Group	Samples	Total Group	Samples
Liaoning	7	41			5	31	12	72
Sichuan	10	54	3	18	4	20	17	92
Xinjiang	6	35	2	10	6	20	14	65
Shandong	12	58	10	58	8	35	30	151
Zhejiang	8	32			4	14	12	46
Jiangsu	8	25			3	9	11	34
Chongqing	1	6	3	12			4	18
Tibet			1	7			1	7
Henan	10	51			7	34	17	85
Guizhou			18	55			18	55
Shanxi	8	34	3	15	6	37	17	86
Hebei	11	43			6	36	17	79
Shaanxi	9	55	4	28	6	37	19	120
Hubei	8	35	4	20	6	33	18	88
Anhui	14	59	3	17	2	9	19	85
Guangdong	11	60	5	19	4	13	20	92
Guangxi	10	50	7	38	5	16	22	104
Yunnan	11	47	4	17	6	34	21	98
Total	144	685	67	314	78	378	289	1377

Table 5
Factory-level data of the cases A, B, C and D.

Items	Units	Case A	Case B	Case C	Case D
Case details	Scale daily (t/d)	5000	300	500	
	clinker(10,000 t/a)	184.4	8	12	
	Cement(10,000 t/a)	195	4	20	70
Real coal consumption yearly	10,000 t	25.6	2.4	1.89	
Real electricity consumption yearly of above	10,000 kWh	20251.5	970	1436	2702.62
Electricity for feed preparation	10,000 kWh	5886.39	400	408	
Electricity for clinker calcination	10,000 kWh	6114.31	300	228	
Electricity for cement grinding	10,000 kWh	8250.82	200	700	2206.22
Electricity for other processing	10,000 kWh		70	100	496.40
Power generation of waste heat recovery	10,000 kWh	6500			

Table 6
Chemical composition of raw materials and fuels and their percentage for case A (%).

Name	LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Percentage (%)
Limestone	41.53	4.13	0.71	0.29	52.17	0.65		83.12
Sand rock	3.33	85.07	6.98	1.71	0.36	0.48		6.84
Powder coal ash	4.89	52.42	24.85	5.83	5.42	1.42	2.26	10.04
Raw material	36.23	13.31	3.03	2.15	43.49	0.87		
Coal powder		55.22	28.25	6.73	4.13	1.06	1.43	
Clinker	0.25	21.93	5.34	3.38	66.15	1.33		

Table 8
Chemical composition of raw materials and fuels and their percentage for case C (%).

Name	LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Percentage (%)
Limestone	42.6	1.98	0.74	0.51	52.37	1.25	71
Gangue	17.59	51.67	18.46	5.63	2.27	2.23	13.5
Iron ore	0.41	23.23	3.7	21.19	40.8	8.31	5
Fluorite							1.5
Raw material	38.51	12.06	3.81	2.32	39.4	1.79	
Coal ash							9
Clinker	0.29	20.04	6.07	3.88	64.61	2.67	

Table 7
Chemical composition of raw materials and fuels and their percentage for case B (%).

Name	LOI	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Percentage (%)
Lime	41.70	1.50	1.00	0.80	54.00	0.65	45.00
Bauxite		5.80	72.50	1.80			55.00
Raw material	26.20	5.60	39.20	1.49	24.20	0.40	
Fuel coal ash							
Clinker	0.40	7.90	51.80	2.06	32.80	0.65	
Cement	0.30	7.50	50.80	2.10	34.50	0.65	

Case A and Case C, but in Case B a small quantity of lime (45% as shown in Table 7) is used. It can be generally argued that both the NSP and shaft kiln process are dominated by the process-related emission at a level of more than 50% in total. We also found that the direct emission factors of the NSP kilns are higher than those of the shaft kiln processes which are very high in the combustion-related emission factors (for example, 640.41 kg CO_2/t clinker as shown in Table 9) due to the difference in technology and fuel consumption. The total emission factors of the NSP (for example, 834.56 kg CO_2/t for Case A) are a little lower than those of the shaft kiln processes (846.61 kg CO_2/t for Case C) because the former have consumed less electricity and are higher in economy of scale than the latter. Case D shows that the grinding only process has very small amount of electricity-related emissions (38.61 kg CO_2/t cement as shown in Table 9).

For the cement production, the carbon dioxide intensity of per unit cement depends on the clinker-to-cement ratio, clinker-producing technology, grinding efficiency and others. Our case

Table 9
Calculations results of the CO_2 emission factors of cases A, B, C and D. (Unit: kg CO_2/t clinker or cement).

Products	Factors	Case A	Case B	Case C	Case D
Clinker	1) Direct emission factor	803.85	893.36	786.49	
	Process-related emission factor	522.84	252.95	472.11	
	Combustion-related emission factor	281.00	640.41	314.38	
	2) Indirect emission factor	30.72	113.22	60.13	38.61
	Electricity-related emission factor	30.72	113.22	60.13	38.61
	3) Emission factor	834.56	1006.59	846.61	38.61
Cement	Emission factor	753.53 (P.O.52.5) 606.73 (P.O.42.5)	1071.94 (aluminates)	516.88 (P.O. 32.5)	

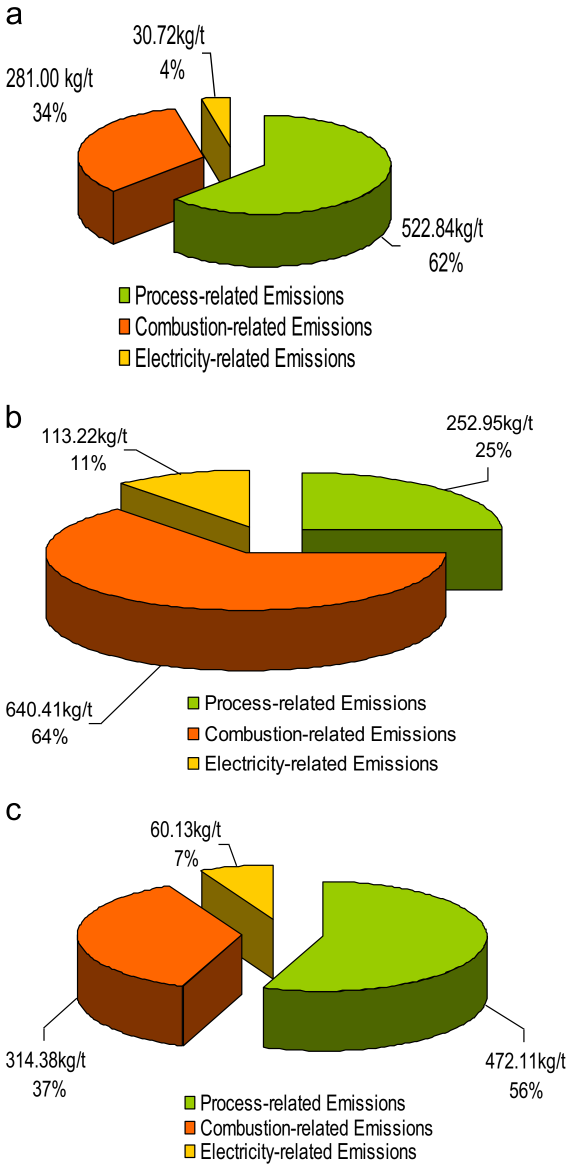

Fig.11. Shares of CO_2 emission factors of clinker production for cases A, B, C (kg CO_2/t, %).

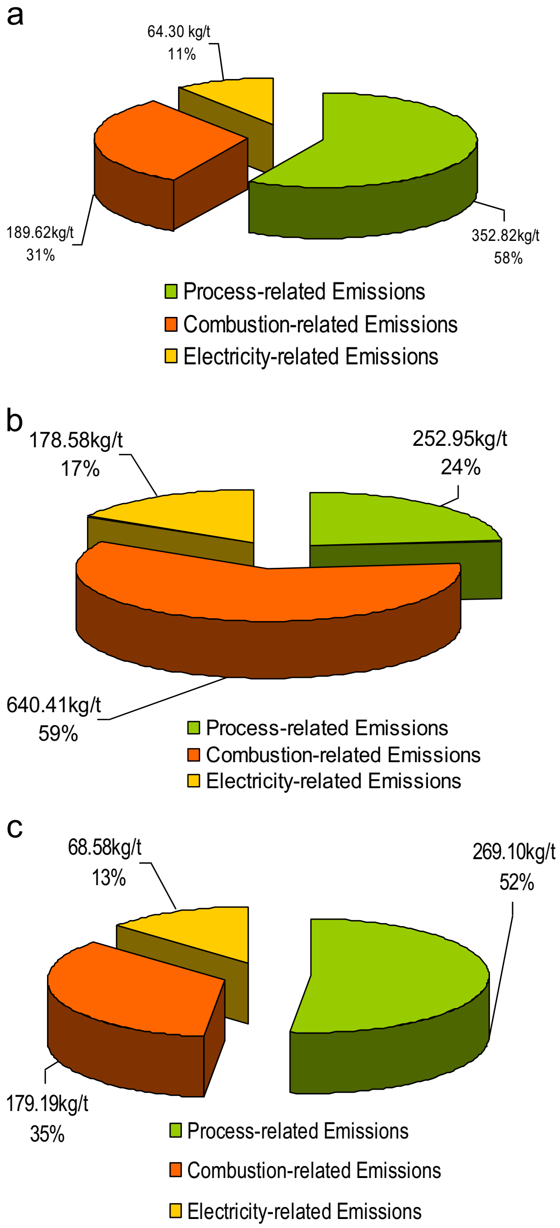

Fig.12. Shares of CO_2 emission factors of cement production for cases A, B, C (kg CO_2/t, %).

studies indicate that the shares of process-related emission factors account for 58% for the P.O.42.5 cement in Case A and 52% for the P.O. 32.5 cement in Case C, whilst only 24% for the aluminates cement in Case B (Fig. 12). This implies that the higher label cement has relatively higher emission factors than the lower label cement. We also found that specific types of cement emit more CO_2 than ordinary ones, because their raw meals are dominated by limes. Similarly, both the NSP process and the shaft kiln process are dominated by the process-related emissions with an overall share of more than 50% in total. Differing from the clinker production, the NSP cements have relatively higher total emission factors (for example, 753.53 kg CO_2/t for the P.O.52.5 cement or

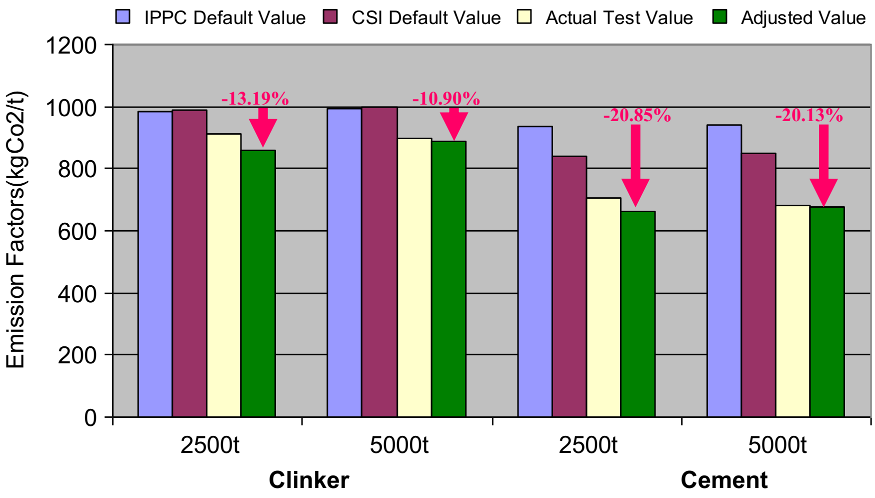

Fig. 13. Differences of our tests on clinker and cement emission factors with IPCC and CSI default values.

606.73 kg CO_2/t for the P.O.42.5 cement in Case A) than the shaft kiln cements (516.88 kg CO_2/t for the P.O. 32.5 cement in Case C).

4.3. Discrepancies of our measurements with IPCC and CSI default values

It is stated by the CO_2 Scorecard Group [26] that substantial discrepancies among the top publicly available global databases of CO_2 emissions may result in a real dilemma for policy analysis and a problem for mitigating human-induced climate change. Our studies further reveal considerable discrepancies exist among various domestic and international public data sources for the total emissions and factors of China's cement production.

To compare our CO_2 emission factors with the IPCC and CSI's default values, we selected two examples in China with a daily capacity of 2500 t and 5000 t for clinker and cement production (Fig. 13). It can be found that the differences of clinker emission factors between our results and the IPCC default values fall in the range of 10.90–13.19%, and higher uncertainty range of 20.13–20.85% for cement production.

These findings are not surprising. Previous expert opinions suggested an uncertainty of 15–20% for China's emissions data, which is highly different from the estimates of around 3–5% for the U.S. [43]. A closer comparison of our results with other estimates from EDGAR/PBL and BP for CO_2 emissions from cement production also reveals such a discrepancy. While perfectly consistent estimates of CO_2 emissions are almost unattainable, more bottom-up empirical measurements on emission factors for cement production of China will be definitely helpful in global emission estimates, climate change dialogs, governmental decision-making on the emission reduction, and industry emission accounting, reporting and action implementing.

5. Conclusions

Cement production is a local presence but has global significant impact. It is also an energy and emission intensive industry. The demand for cement per capita follows a bell curve pattern, which implies that emerging countries including China are expected to consume a large quantity of cement because of their needs for infrastructure during the high growth phase. China's demand for cement may reach at its peak in the next 5 years, whilst its CO_2 emissions will be continually increasing.

Previous estimates may have largely overestimated emissions from China's cement industry. These discrepancies come mainly from different calculation standards, classification and usages of default values, methodologies in general, and specific features of China's cement production and its technology and policy changes.

Our comparisons in this study portrayed that simply using emission factor and some default values is a quick and easy way to rough cross-country estimates but is not accurate enough in an individual country or enterprise context for policy making, performance examination, and diplomacy negotiation. A better approach should be based on the factory-level and facility-specific sampling and examining. Our bottom-up factory-level sampling method (BFSM) is only a first step. More disaggregated classifications for emission sources and spatial scales are a necessary next step and will be done in the near future.

Our case studies indicate that China's emissions from cement production might be overestimated in the previous studies because they overlooked technology transition from the wet process to the dry process, differences in lime content and clinker-to-cement ratios, raw materials and fuels substitutions, and usages of blend additives. Future work will need to address challenges from data confidentiality, comprehensiveness, consistency, and accuracy.

Acknowledgments

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