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Abstract

In 2010, China's cement output was 1.9 gigatonnes, which accounted for 56% of world cement production. Total carbon dioxide (CO_2) emissions from Chinese cement production could therefore exceed 1.2 gigatonnes. The magnitude of emissions from this single industrial sector in one country underscores the need to understand the uncertainty of current estimates of cement emissions in China. This paper compares several methodologies for calculating CO_2 emissions from cement production, including the three main components of emissions: direct emissions from the calcination process for clinker production, direct emissions from fossil fuel combustion and indirect emissions from electricity consumption. This paper examines in detail the differences between common methodologies for each emission component, and considers their effect on total emissions. We then evaluate the overall level of uncertainty implied by the differences among methodologies according to recommendations of the Joint Committee for Guides in Metrology. We find a relative uncertainty in China's cement-related emissions in the range of 10 to 18 percent. This result highlights the importance of understanding and refining methods of estimating emissions in this important industrial sector.

Keywords: ***Cement industry; CO_2 emissions; Uncertainty***

1. Introduction

With the rapid growth of gross domestic product (GDP) and urbanization, China's cement output has increased rapidly since the 1980s. Figure 1 shows China's GDP and cement output from 1980 to 2010. In 1985, China became the world's largest cement producer (CCA, 2010). In 2010, China produced 1.87 gigatonnes (Gt) of cement, accounting for 56% of global cement production (CEMBUREAU, 2011; Ma, 2011). In 2011, China's cement output further increased to 2.09 Gt, up more than 200 million metric tons (Mt) from 2010 (MIIT, 2012).

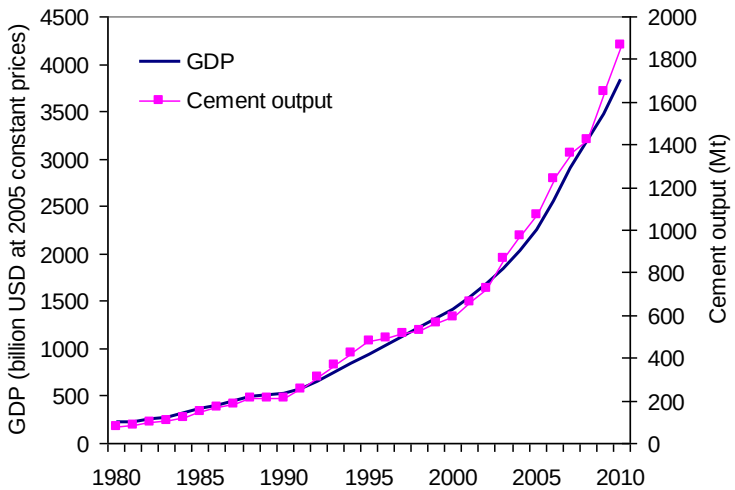

Fig. 1. China's gross domestic product (GDP) and cement output, 1980-2010

Source: CCA, 2010, 2011; CEMBUREAU, 2011; Digital Cement, 2011; Ma, 2011; NBS, 2010b, 2011. Calculations by authors.

Cement production emits carbon dioxide (CO_2) both directly and indirectly (CSI, 2005; Worrell et al., 2001). The direct CO_2 emissions mainly include the CO_2 emissions from chemical reactions in the cement production process (mainly from limestone calcination) and the CO_2 emissions from fossil fuel use for cement production (CSI, 2005, 2011; Worrell et al., 2001). Indirect CO_2 emissions result mainly from electricity consumption for cement production, or more specifically, from "external production of electricity consumed by cement producers" (CSI, 2011). Direct CO_2 emissions from fossil fuel combustion and indirect CO_2 emissions from electricity consumption are usually considered as energy-related CO_2 emissions, while direct CO_2 emissions from the calcination process in cement making are usually called cement process CO_2 emissions.

Cement production is a major source of CO_2 emissions in China owing to the large volume produced (CCA, 2010, 2011; Gregg et al., 2008; PBL, 2008; Wang, 2008). Generally speaking, the CO_2 emissions intensity of China's cement production is high due to the large amount of outdated, inefficient production capacity and the coal-dominated energy mix. We note that China's cement industry has

significantly reduced CO_2 emissions intensity in recent years, although the total CO_2 emissions from cement production have increased because of the rapid growth of cement production during the same time period (Ke et al., 2012).

The estimation of the CO_2 emissions from China's cement production has attracted worldwide attention (Gregg et al., 2008; IEA, 2007; Ke et al., 2012; Li et al., 2011; PBL, 2008; Tong et al., 2010; Wang, 2008). However, we note that different studies give very different estimates, which raises the issues of discrepancies and uncertainties in the data (Afsah and Aller, 2010). This study aims to evaluate the different estimation methodologies and estimate CO_2 emissions from China's cement production in a systematic manner as well as to better understand the uncertainties in the various estimation methodologies.

2. Process CO_2 emissions from cement production

2.1. Overview

Cement process CO_2 emissions mainly come from calcination of calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) in the raw meal for clinker production, which can be expressed by the following chemical equations (Worrell et al., 2001):

$$\mathrm{CaCO_3} \rightarrow \mathrm{CaO} + \mathrm{CO_2}$$

$$\mathrm{MgCO_3} \rightarrow \mathrm{MgO} + \mathrm{CO_2}$$

where CaO denotes calcium oxide and MgO denotes magnesium oxide. CaO is the main content of clinker.

Using the relative formula mass M_r, we can rewrite the above chemical equations according to the law of conservation of matter:

$$M_r(\mathrm{CaCO_3}) = M_r(\mathrm{CaO}) + M_r(\mathrm{CO_2})$$

$$M_r(\mathrm{MgCO_3}) = M_r(\mathrm{MgO}) + M_r(\mathrm{CO_2})$$

where:

$$M_r(\mathrm{CaCO_3}) = 100.09$$

$$M_r(\mathrm{MgCO_3}) = 84.31$$

$$M_r(\mathrm{CaO}) = 56.08$$

$$M_r(\mathrm{MgO}) = 40.30$$

$$M_r(\mathrm{CO_2}) = 44.01$$

Calculations based on the above equations show that the calcination of 1 tonne (t) of $CaCO_3$ emits about 0.44 t of CO_2, and the calcination of 1 t of $MgCO_3$ emits about 0.52 t of CO_2.

Generally speaking, there are two types of widely-accepted and often-used calculation methods for estimating the process CO_2 emissions from cement production: the input (raw materials, or raw meal in particular) method and the output (clinker is preferred) method (CSI, 2005, 2011). Some rough estimation methods are also used in the absence of relevant data or for convenience.

The input method calculates calcination CO_2 emissions based on the volume and carbonate content of the raw materials consumed for cement production (CSI, 2005, 2011). The raw meal-based input method is often used in the United States and Japan (CSI, 2005). The clinker-based output method calculates calcination CO_2 emissions based on the volume and composition of clinker produced plus discarded dust and CO_2 emissions from organic carbon in raw materials (CSI, 2005). The clinker-based output method has been adopted by the Intergovernmental Panel on Climate Change (IPCC) as the Tier 2 method for national greenhouse gas inventory calculations (IPCC, 2006), while the IPCC Tier 1 method estimates clinker production from cement production data (IPCC, 2006). The IPCC 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 (CSI, 2011). The raw meal-based input methods are already successfully used in practice and seem to be more practical than the IPCC Tier 3 methodology (CSI, 2011). Both the input method and the output method are included in the Cement Sustainability Initiative (CSI) Cement CO_2 and Energy Protocol Version 3 (CSI, 2011). As the calcination equations show, the input and output methods are equivalent in theory (CSI, 2011).

Because China has primarily adopted the clinker-based output method, we further discuss its calculation methodology. The calcination CO_2 emission factor (t CO_2 per t clinker production) can be calculated based on the measured calcium oxide (CaO) and magnesium oxide (MgO) content of the clinker (Wang, 2009):

$$CC = \alpha \times \frac{M_r(\mathrm{CO_2})}{M_r(\mathrm{CaO})} + \beta \times \frac{M_r(\mathrm{CO_2})}{M_r(\mathrm{MgO})}$$

where *CC* represents the calcination emission factor; α and β is the share of CaO and MgO content in clinker, respectively; $M_r(CO_2)$, $M_r(CaO)$ and $M_r(MgO)$ are the relative formula mass of CO_2, CaO, and MgO, respectively (Wang, 2009).

The emission factor should be corrected if significant quantities of CaO and MgO in the clinker originated from the non-carbonate sources (CSI, 2005), such as in the case where calcium silicates or fly ash are used as raw materials entering the kiln (CSI, 2005).

According to the IPCC (2006) and CSI (2005), CO_2 emissions from bypass dust or cement kiln dust (CKD) leaving the kiln systems should be calculated separately, taking into consideration the degree of calcination of the dust (CSI, 2005). The IPCC (2006) does not distinguish bypass dust and cement kiln dust, while CSI (2005) proposes different calculation methods for bypass dust and cement kiln dust.

Besides inorganic carbonates, the raw materials used for clinker making usually contain a small amount of organic carbon (CSI, 2005; Wang, 2009). Most of the organic carbon is converted to CO_2 during pyro-

processing of the raw meal (CSI, 2005). The CO_2 emissions from organic carbon in raw materials should also be taken into consideration to ensure the completeness of the inventory (CSI, 2005; Wang, 2009).

Table 1 shows China's clinker and cement output in 2005-2011, which will be used for estimating CO_2 emissions.

Table 1. China's clinker and cement production in 2005-2011.

Source: CBMF and QEASCBM, 2012; CCA, 2008, 2009, 2010, 2011; Digital Cement, 2011; MIIT, 2012; Zhou, 2011.

Item	2005	2006	2007	2008	2009	2010	2011
Clinker production (Mt)	779	873	957	977	1084	1152 [a]	1307 [a]
Cement production (Mt)	1069	1236	1361	1420	1649	1868 [a]	2085 [a]
Clinker-to-cement ratio (%)	73	71	70	69	66	62 [a]	63 [a]

[a] *Preliminary data.*

2.2. Estimation based on the IPCC Tier 1 and Tier 2 method

The IPCC Tier 1 method estimates clinker production from the use of cement production data (IPCC, 2006). Specifically, the IPCC Tier 1 method estimates clinker production based on production data of each type of cement and its clinker-to-cement ratio and then uses the default clinker emission factor with correction for discarded dust to estimate the CO_2 emissions from cement production (IPCC, 2006). The IPCC Tier 2 method suggests calculating the CO_2 emissions from the calcination process based on the CaO content in the clinker produced (IPCC, 2006). In the absence of specific data, IPCC suggests using a default CO_2 emission factor of 510 kilograms (kg) per t clinker produced which corresponds to a default CaO content in clinker of 65%, and incorporating a 2% correction factor for discarded dust. The IPCC methodology and default emission factor are widely accepted; the U.S. Geological Survey (USGS, 2010) and Energy Information Administration (EIA, 2008) follow the IPCC methodology and use the default emission factor to estimate CO_2 emissions from cement production. China has adopted the revised 1996 IPCC Guidelines for its national greenhouse gas inventory calculations. Based on China's clinker production data shown in Table 1, process CO_2 emissions from China's cement production in 2005-2007 are calculated using the IPCC Tier 2 method and the default CO_2 emission factor and are shown in Table 2. Specifically, the CO_2 emissions from clinker production are calculated by multiplying the clinker production by the default CO_2 emission factor for clinker production (without discarded dust correction), the CO_2 emissions from discarded dust are calculated by multiplying the CO_2 emissions from clinker production by correction factor for discarded dust. Total CO_2 emissions are the sum of CO_2 emissions from clinker production and CO_2 emissions from discarded dust.

Table 2. Comparison of estimates of process CO_2 emissions and CO_2 emission factors.

Source: Boden et al., 2011; CCA, 2008, 2009, 2010, 2011; CSI, 2005, 2011; IPCC, 2006; JRC and PBL, 2011; Wang, 2006, 2008. Calculations by authors.

Method	Item	2005	2006	2007
IPCC Tier 2	Estimated process CO_2 emissions (Mt)	405.2	454.3	497.7
	Default emission factor (kg CO2/ t clinker) [a]	520	520	520
CSI clinker-based	Estimated process CO_2 emissions (Mt)	426.0	477.6	523.2
	Assumed emission factor (kg CO2/ t clinker) [b]	547	547	547
EDGAR	Estimated process CO_2 emissions (Mt) [c]	416.9	482.3	530.9
	Implied emission factor (kg CO2/ t cement) [d]	390	390	390
CDIAC cement-based	Estimated process CO_2 emissions (Mt) [e]	533.0	616.8	678.8
	Implied emission factor (kg CO2/ t cement) [f]	499	499	499
Wang cement-based	Estimated process CO_2 emissions (Mt) [g]	454.3	525.3	578.5
	Assumed emission factor (kg CO2/ t cement)	425	425	425

[a] *Default clinker emission factor with correction for discarded dust (IPCC, 2006).*

[b] *Estimated according to CSI recommended clinker emission factor and default corrections for discarded dust and total organic carbon (CSI, 2005).*

[c] *Estimated by EDGAR (JRC and PBL, 2011).*

[d] *Calculated according to the estimate of EDGAR (JRC and PBL, 2011) and cement production data (CCA, 2010).*

[e] *Estimated by CDIAC (Boden et al., 2011).*

[f] *Calculated according to the estimate of CDIAC (Boden et al., 2011) and cement production data (CCA, 2010).*

[g] *Calculated according to the emission factor adopted by Wang (2006, 2008) and cement production data (CCA, 2010).*

2.3. Estimation using the CSI clinker-based output method

CSI (2005) finds the IPCC Tier 1 and Tier 2 default emission factor to be an underestimate as it does not include the CO_2 emissions from the calcination of $MgCO_3$. CSI (2005) thus suggests calculating CO_2 emissions from the calcination process based on the CaO and MgO content in the clinker. In the absence of specific data, a default emission factor of 525 kg CO_2 per t clinker is recommended by CSI (2005), corresponding to the IPCC Tier 1 and Tier 2 default emission factor with correction for calcination of $MgCO_3$. CSI (2005) also points out that higher default emission factors suggested by other countries or organizations may also be due to the inclusion of emissions from the calcination of $MgCO_3$.

CSI (2005) suggests that bypass dust and CKD should be calculated separately. Because bypass dust is usually fully calcined, CSI (2005) thus recommends that emissions related to bypass dust should be estimated using the emission factor for clinker. Because CKD is usually not fully calcined, CSI (2005) recommends that the emission factor for CKD should be determined based on the emission factor for clinker and the calcination rate of the CKD. In the absence of specific data, CSI (2005) also recommends the 2% correction factor should be used by noting that this default may be an underestimate in cases where significant amounts of dust leave the kiln system. Because the contribution of organic carbon to

overall emissions is usually small, in the absence of specific data, CSI (2005) recommends a simplified calculation method which multiplies clinker production with the default raw meal-to-clinker ratio of 1.55 and default total organic carbon (TOC) content in raw meal of 2 kg carbon per t raw meal. Table 2 lists the process CO_2 emissions from China's cement production in 2005-2007 calculated using the CSI clinker-based output method and defaults. Total process CO_2 emissions are the sum of CO_2 emissions from clinker production (without discarded dust correction) and CO_2 emissions from discarded dust and TOC.

2.4. Estimates by the Emission Database for Global Atmospheric Research

The Emission Database for Global Atmospheric Research (EDGAR) is a joint project of the European Commission Joint Research Centre (JRC) and the Netherlands Environmental Assessment Agency (PBL). EDGAR develops and maintains databases of global emissions of greenhouse gases and air pollutants by country (JRC and PBL, 2011). EDGAR is referenced by the PBL for its world CO_2 emissions report (PBL, 2008). Table 2 lists EDGAR's estimate of process CO_2 emissions from China's cement production in 2005-2007 (JRC and PBL, 2011).

2.5. Estimates by the Carbon Dioxide Information Analysis Center

The Carbon Dioxide Information Analysis Center (CDIAC) (2011) at Oak Ridge National Laboratory (ORNL) publishes its estimates of regional carbon emissions from fossil fuel burning and cement production annually. CDIAC (Boden et al., 2011) estimated China's process carbon emissions from cement production to be 145.4 Mt of carbon in 2005, 168.2 Mt of carbon in 2006 and 185.1 Mt of carbon in 2007. Table 2 lists the CO_2 equivalent process emissions, which are calculated by multiplying the carbon emissions by a factor of 3.667 (Boden et al., 2011). This calculation shows an implied emission factor of about 0.5 t CO_2 per t of cement in CDIAC's estimate of China's process emissions from cement production. Unlike many developed countries such as the United States (Bhatty et al. 2004), China's cement output is very large, but the majority of cement production is low grade cement usually associated with a low clinker-to-cement ratio. As seen in Table 1, China's clinker-to-cement ratio has decreased significantly in recent years: from 73% in 2005 to 70% in 2007, and further to about 62% in 2010 and 2011 (Digital Cement, 2011; MIIT, 2012). Because process emissions from cement production come mainly from the calcination process for clinker making, a lower clinker-to-cement ratio generally results in a lower emission factor for cement production, in terms of CO_2 emissions per unit of cement produced. Compared to the results from the clinker-based method recommended by IPCC and CSI, CDIAC's emission factor is clearly high. We note that CDIAC's relatively higher emission factor is equivalent to the assumption of a high clinker-to-cement ratio, which may overestimate the process CO_2 emissions from China's cement production.

2.6. Estimation based on the emission factor adopted by Wang

Wang (2008, 2009, 2011) was the primary researcher contributing to the development of Chinese industrial and national standards for calculating CO_2 emissions from cement production. The national standard is also the basis for the Chinese environmental standard for low-carbon cement labeling (MEP, 2011). Based on a number of statistical analyses, Wang (2006, 2008) adopted an emission factor of 0.425 t CO_2 per t cement to roughly estimate the process emissions from China's cement production in 2005 and 2007. This is a rough estimation method as it applies a default emission factor to cement output directly, not taking into consideration the content of clinker and the clinker-to-cement ratio. Because of its simplicity and convenience, this default emission factor was also used by other China-specific studies, e.g. TUC (2008) and ERI (2010). Based on this default emission factor and China's cement output, the process emissions from China's cement production can be estimated and the results are listed in Table 2. It should be noted that the systematic calculation methodology proposed by Wang in support of the industrial and national standard on cement production emissions calculation generally follows the IPCC guidelines and CSI methodology, with some China-specific modifications (CSI, 2005; Wang, 2009, 2011).

3. Direct CO_2 emissions from fossil fuel use

3.1. Estimation of direct CO_2 emissions from fossil fuel use

Cement production is very energy intensive and consumes a large amount of fuel[1] (CCA, 2011; Worrell et al., 2001). Combustion of fossil fuels, including conventional fossil fuels (such as coal) and alternative fossil fuels (or fossil wastes), results in a large amount of direct CO_2 emissions. The CO_2 emissions from fossil fuel combustion are calculated based on the fuel used and the fuel CO_2 emission factor. More specifically, the total CO_2 emissions from fossil fuel combustion, denoted as CE_{ff}, can be calculated using the formula:

$$CE_{ff} = \sum_{i=1}^{nfc} (FC_i \times EF_i)$$

where FC_i denotes the total heat value of the *i*th type of fossil fuel used for cement production, in units of terajoule (TJ); EF_i is the emission factor of the *i*th type of fossil fuel, in units of t CO_2 per TJ; *nfc* represents the number of total types of fossil fuel used for cement production.

Based on the estimation of final energy consumption and fuel mix of China's cement production, Ke et al. (2012) estimated that the CO_2 emissions from fossil fuel combustion were 347.8 Mt in 2005, 381.2 Mt in 2006 and 393.3 Mt in 2007, calculated using the IPCC default CO_2 emission factors for fossil fuels combustion (IPCC, 2006).

[1] Fuel use for cement production is largely in calcination, i.e. in clinker production.

The sources of uncertainty in estimation of CO_2 emission from fossil fuels use mainly arise from the energy statistics (fuel use and heating value) and emission factors used. Due to a large amount of inefficient cement kilns, mainly vertical shaft kilns (VSK), China's cement production is very energy intensive. In 2000, the energy-efficient new suspension preheating and precalcining (NSP) process[2] accounted for only 10% of the Chinese cement production (Zhou, 2011). As shown in Table 3, the share of NSP process of China's cement production increased to 39% in 2005 and 54% in 2007. The share of NSP process cement production reached 86% in 2011 (CBMF and QEASCBM, 2012).

Because the NSP process is much more efficient than the VSK process (CCA, 2011; QEASCBM, 2011; Zhou, 2007), the rapid increase in the share of the NSP process resulted in a significant reduction in energy intensity of China's cement production (CCA, 2011; QEASCBM, 2011; Zhou, 2007), which thus reduced the CO_2 emission intensity. Based on the energy statistics and energy intensity analysis of the NSP process and VSK cement production (CCA, 2011; QEASCBM, 2011; Zhou, 2007), we separately estimated the energy consumption and CO_2 emissions for China's NSP process and VSK cement production for 2005-2007, using the IPCC default CO_2 emission factors for fossil fuels combustion (IPCC, 2006). As the results in Table 3 show, the NSP process cement production technology significantly contributed to the reduction of emissions intensity.

Table 3. Estimating CO_2 emissions from fossil fuel use by cement production technology.

Source: CCA, 2008, 2009, 2010, 2011; QEASCBM, 2011; Zhou, 2007. Calculations by authors.

Item	2005	2006	2007
Share of NSP process cement production (%) [a]	39	46	54
Energy intensity of NSP process cement production (GJ/t cement) [b]	3.2	3.1	3.0
Energy intensity of VSK cement production (GJ/t cement) [b]	3.9	3.8	3.7
CO_2 from NSP process cement production (Mt) [b]	113.7	147.3	186.5
CO_2 from VSK cement production (Mt) [b]	226.9	224.5	209.3
Total CO_2 emissions from fossil fuel use (Mt)	340.5	371.8	395.8

[a] *CCA, 2008, 2009, 2010, 2011; QEASCBM, 2011.*

[b] *Estimated by the authors according to the energy statistics and energy intensity analysis of different cement production technologies (CCA, 2011; QEASCBM, 2011, Zhou, 2007). The clinker-to-cement ratio was 73% in 2005, 71% in 2006, and 70% in 2007 (CCA, 2011).*

The IPCC default emission factors are recommended in the absence of country-specific data. IPCC (2006) provides the lower and upper limits of the 95% confidence interval for the effective CO_2 emission factors for fuel combustion. For example, for "other bituminous coal" which is widely used in China, the lower and upper limit of the 95% confidence interval is 89.5 and 99.7 t CO_2 per TJ, respectively.

[2] The term "new dry process" is used in China to refer to the new suspension preheating and precalcining (NSP) process cement production technology.

3.2. Estimation based on the emission factor adopted by Wang

Wang (2006, 2008) adopted an emission factor of 0.390 t CO_2 per t of cement to roughly estimate the CO_2 emissions from fossil fuel use for China's cement production in 2005 and 2007. Applying this emission factor to the period 2005-2007 gives the CO_2 emissions from fossil fuel use for China's cement production as 416.9 Mt in 2005, 482.1 Mt in 2006, and 530.9 Mt in 2007.

This method is simple and convenient but it may overestimate CO_2 emissions from fossil fuel use because this fixed emission factor did not take into account the significant energy efficiency improvement of China's cement industry after 2005 (CCA, 2011; Ke et al., 2012; QEASCBM, 2011; Zhou, 2007). For example, calculations show that the average fuel intensity of China's cement production decreased from 3.44 GJ per t cement in 2005 to 3.05 GJ per t cement in 2007 (Ke et al., 2012). This shows that updated energy statistics are very important for estimating CO_2 emissions from fossil fuel use.

4. Indirect CO_2 emissions from electricity consumption

4.1. Estimation of the indirect CO_2 emissions from electricity consumption

Cement production consumes a large amount of electricity for raw materials preparation, cement grinding, and powering other electrical equipment. Fossil-fuel based electricity production directly emits a large amount of CO_2, while consumption of electricity is considered as emitting CO_2 indirectly. We note that the analysis of indirect emissions from electricity consumption evaluates the indirect impact of the cement industry on regional or national emissions. For regional or national CO_2 accounting, the CO_2 emissions from external electricity generation consumed by the cement industry are usually allocated to the power industry. Double-counting should be avoided in CO_2 emissions accounting and reporting (CSI, 2005, 2011).

The electricity used for cement production is mainly purchased from the grid (external electricity production), but some Chinese cement plants use waste heat recovery (WHR) power generation technologies to self-generate electricity. WHR power generation can typically provide 25-33% of a cement plant's electricity demand for cement production (Zeng, 2009). The adoption and utilization of WHR power generation technologies have been rising rapidly since 2000 due to four primary reasons (Zeng, 2009): (1) The Chinese industrial electricity tariff is high and self-generation can have significant economic benefit; (2) WHR power generation effectively uses waste heat and avoids large amount of fuel consumption for electricity production; (3) WHR power generation can be eligible for Clean Development Mechanism (CDM) projects; (4) the Chinese government has actively promoted WHR power generation, including granting financial incentives for its adoption, as a major energy savings and emissions reduction policy for the cement industry.

Because WHR power generation recovers the energy in waste heat and does not consume additional fossil fuels, WHR power generation effectively reduces the total energy consumption and CO_2 emissions. Therefore, when estimating indirect emissions from electricity consumption, the electricity consumed from WHR power generation should be excluded (i.e., only externally produced electricity consumed by cement production should be taken into account).

For simplicity, we estimate CO_2 emissions from electricity production according to the national average emission factor for China's power sector. Fossil fuel-fired thermal power, hydro, and nuclear power account for most of the electricity production in China. Fossil fuel-fired thermal power contributes more than 80% of the total electricity production and coal is the main fossil fuel for thermal power (NBS, 2010a). Table 4 shows a summary of China's power industry and the average national emission factor. Hydro, nuclear power, and other renewable power generation sources are assumed to be carbon neutral. According to CSI (2005, 2011), electricity transmission and distribution (T&D) losses should be excluded in the calculation of indirect CO_2 emissions from electricity consumption because electricity T&D losses are usually attributed to the power industry for national CO_2 emissions accounting. It can be argued, however, that the emissions from T&D losses should be allocated to the cement industry and not the power industry since the demand for the electricity to produce cement is based on the demand for cement.

Table 4. Chinese national average grid emission factor.

Source: NBS, 2010a, 2010b; SERC, 2009. Calculations by authors.

Item	2005	2006	2007
Total electricity production (TWh)	2500	2866	3282
Thermal power production (TWh)	2047	2370	2723
National average grid emission factor (kg CO_2/kWh) [a]	0.834	0.836	0.813

[a] *Calculated by authors. Hydro, nuclear, and other renewable power generation sources are assumed to be carbon neutral. Electricity transmission and distribution (T&D) losses are excluded (CSI, 2005, 2011).*

Indirect CO_2 emissions from consumption of externally produced electricity, denoted as CE_e, are estimated as follows:

$$CE_e = EC_e \times EF_{grid} = (EC_t - EC_w) \times EF_{grid}$$

where EC_e denotes externally produced electricity consumed by cement production (kWh); EC_t denotes total electricity consumed for cement production (kWh); EC_w denotes the electricity produced by WHR (kWh); EF_{grid} is the national average emission factor.

Because the grid emission factor is determined by the power industry, the cement industry's indirect emission from consumption of externally-produced electricity reflects the combined effects of emission intensity of the power industry and electricity consumption of the cement industry. Therefore, sources of uncertainty in the estimation of indirect emissions arise from both uncertainty in the estimation of

the grid emission factors and uncertainty in the estimation of the cement industry's consumption of externally-produced electricity.

Because WHR power generation increased rapidly after 2005 and installed capacity totaled 4786 megawatts (MW) by 2010 (Zuo and Yang, 2011), WHR power generation is becoming increasingly important in accounting for China's energy consumption and CO_2 emissions. WHR power generation can be estimated based on installed capacity or electricity generation per unit of clinker production (Zeng, 2009). We use two estimates of WHR power generation from Zeng (2009) to estimate indirect CO_2 emissions. The first estimate, denoted as EGW1, is based on installed capacity and an assumption of 7000 hours of annual operation (Zeng, 2009). The second estimate, denoted as EGW2, is based on clinker production capacity and an assumption of 36 kWh electricity per t of clinker production. The second estimate (i.e., EGW2) is conservative in assuming only 30% of the incremental clinker production capacity could be used in the installation year since 2006[3] (Zeng, 2009).

The total electricity consumption data are taken from Ke et al. (2012). Table 5 shows the indirect CO_2 emissions from consumption of externally-produced electricity in 2005-2007.

Table 5. Indirect CO_2 emissions from consumption of externally-produced electricity in 2005-2007.

Source: Ke et al., 2012; Zeng, 2009. Calculations by authors.

Item	2005	2006	2007
Total electricity consumption (TWh) [a]	105.5	118.3	127.7
Electricity produced by WHR: EGW1 (TWh) [b]	0.4	1.6	4.3
Electricity produced by WHR: EGW2 (TWh) [c]	0.4	0.7	2.3
Electricity from external power generation: EGW1 (TWh) [d]	105.1	116.7	123.4
Electricity from external power generation: EGW2 (TWh) [e]	105.1	117.6	125.4
Indirect CO_2 emissions: EGW1 (Mt CO_2) [f]	87.6	97.5	100.3
Indirect CO_2 emissions: EGW2 (Mt CO_2) [g]	87.6	98.2	101.9

[a] *Estimated by Ke et al. (2012).*

[b] *Estimated by Zeng (2009).*

[c] *Estimated by the authors according to Zeng (2009).*

[d] *Calculated by subtracting the electricity produced by WHR (EGW1 estimate) from the total electricity consumption.*

[e] *Calculated by subtracting the electricity produced by WHR (EGW2 estimate) from the total electricity consumption.*

[f] *Estimated according to the electricity from external power generation (EGW1 estimate).*

[g] *Estimated according to the electricity from external power generation (EGW2 estimate).*

[3] WHR power generation capacity has increased rapidly since 2006 (Zeng, 2009). The total installed capacity from 1997 to 2005 was only 63 MW, while the new installed capacity was 160 MW in 2006 and 388 MW in 2007 (Zeng, 2009).

4.2. Estimations based on default emission factors

Wang (2008) adopted an emission factor of 0.07 t CO_2 per t of cement to roughly estimate the indirect CO_2 emissions from electricity consumption in 2007. Applying this emission factor to the period of 2005-2007 gives indirect CO_2 emissions from electricity consumption of 74.8 Mt in 2005, 86.5 Mt in 2006, 95.3 Mt in 2007. We denote this estimation as ICE1. Wang (2009) also suggested that the cement industry was an electricity consumer and an indirect emission factor of 0.302 kg CO_2 per kWh electricity could be used, although the Chinese national average emission factor was about 0.8 kg CO_2 per kWh electricity in 2007. In the Chinese environmental standard for low-carbon cement labeling (MEP, 2011), a default emission factor of 0.86 kg CO_2 per kWh electricity is recommended when the relevant data are not available. Applying the emission factor of 0.86 kg CO_2 per kWh electricity to the period 2005-2007 gives the indirect CO_2 emissions from consumption of externally-produced electricity of 90.3 Mt in 2005, 100.4 Mt in 2006 and 106.1 Mt in 2007, where the electricity from external power generation data are taken from EGW1 calculation in Table 5. We denote this method as ICE2 and note that this method may overestimate the indirect emissions given the decreasing trend of the national average emission factor. The calculations here demonstrate the importance of clearly defining the CO_2 accounting and reporting boundaries and the selection of the emission factors.

5. Analysis of the discrepancies and uncertainties

For comparison, the estimation results for different methodologies are listed in Tables 6-8.

Table 6. Process CO_2 emissions from cement production.

Source: CCA, 2008, 2009, 2010; CSI, 2005, 2011; IPCC, 2006; JRC and PBL, 2011. Calculations by authors.

Item	2005	2006	2007
IPCC Tier 2 method (Mt)	405.2	454.3	497.7
CSI clinker-based output method (Mt)	426.0	477.6	523.2
Estimates by EDGAR (Mt) [a]	416.9	482.3	530.9
Estimates by CDIAC (Mt) [b]	533.0	616.8	678.8
Estimation using emission factor from Wang (Mt) [c]	454.3	525.3	578.5
d_1 : Maximum – Minimum (Mt)	127.8	162.5	181.1
m_1 : (Maximum + Minimum) / 2 (Mt)	469.1	535.5	588.2

[a] *Estimated by EDGAR (JRC and PBL, 2011).*

[b] *Estimated by CDIAC (Boden et al., 2011).*

[c] *Calculated by using the emission factor adopted by Wang (2006, 2008).*

Table 7. Direct CO_2 emissions from fossil fuel use.

Item	2005	2006	2007
LBNL estimation 1 (Mt) [a]	347.8	381.2	393.3
LBNL estimation 2 (Mt) [b]	340.5	371.8	395.8
Estimation using Wang's emission factor (Mt) [c]	416.9	482.1	530.9
d_2 : Maximum – Minimum (Mt)	76.4	110.3	137.6
m_2 : (Maximum + Minimum) / 2 (Mt)	378.7	426.9	462.1

[a] *Estimated by Ke et al. (2012).*

[b] *Estimated by the authors according to energy statistics and energy intensity analysis of different cement production technologies (CCA, 2011; QEASCBM, 2011; Zhou, 2007).*

[c] *Calculated by using the emission factor adopted by Wang (2006, 2008).*

Table 8. Indirect CO_2 emissions from electricity consumption.

Item	2005	2006	2007
EGW1 estimation (Mt)	87.6	97.5	100.3
EGW2 estimation (Mt)	87.6	98.2	101.9
ICE1 estimation (Mt) [a]	74.8	86.5	95.3
ICE2 estimation (Mt) [b]	90.3	100.4	106.1
d_3 : Maximum – Minimum (Mt)	15.5	13.9	10.8
m_3 : (Maximum + Minimum) / 2 (Mt)	82.6	93.5	100.7

[a] *Calculated by using the emission factor adopted by Wang (2008).*

[b] *Calculated by using the default emission factor adopted by MEP (2011).*

As Table 6 shows, the IPCC Tier 2 method (IPCC, 2006) with default emission factors gives the lowest estimate for process CO_2 emissions from cement production, while CDIAC (Boden et al., 2011) gives the highest estimate. We note that the IPCC Tier 2 method (IPCC, 2006) and the CSI clinker-based output method (CSI, 2005, 2011) estimates are very close and consistent. As pointed out by IPCC (2006), it is not consistent with good practice to estimate the CO_2 emissions directly using a fixed cement-based emission factor.

Table 7 shows that for CO_2 emissions from fossil fuel use, LBNL estimation 1 and estimation 2 are close, while the estimation based on the emission factor adopted by Wang (2006, 2008) results in much higher values. As previously pointed out, the main reason that the emission factor adopted by Wang (2006, 2008) gives a much higher result is due to the higher fuel intensity assumption and not taking into account the changes in energy intensity of cement production in China in recent years.

Table 8 shows that the estimation based on the emission factor adopted by Wang (2008) gives the lowest estimate for indirect CO_2 emissions from electricity consumption, while the estimation using the default emission factor adopted by MEP (2011) gives the highest estimate.

Given the large discrepancies between the different methodologies, we are interested in the uncertainty of the estimates in this study. To evaluate the uncertainty of the estimates, we adopt the methodologies and recommendations of the Joint Committee for Guides in Metrology (JCGM) for measurement data (JCGM, 2010).

We make the following assumptions:
(1) The different estimates are not obtained from repeated observations and the Type B standard uncertainty is evaluated by "scientific judgment using the relevant information available" (JCGM, 2010).
(2) A uniform or rectangular distribution is assumed for different estimates of process CO_2 emissions from cement production, direct CO_2 emissions from fossil fuel use and indirect CO_2 emissions from electricity consumption, due to the absence of specific information of probability distribution.
(3) The upper and lower limits are assumed to be maximum and minimum estimates of process CO_2 emissions from cement production, direct CO_2 emissions from fossil fuel use and indirect CO_2 emissions from electricity consumption, respectively. More specifically, if the maximum and minimum estimates of process CO_2 emissions from cement production by different methodologies are denoted as $a_+^{(c)}$ and $a_-^{(c)}$, then the probability that the actual process CO_2 emissions from cement production lie within the interval $a_+^{(c)}$ to $a_-^{(c)}$ is assumed to be equal to one (the probability that the actual CO_2 emissions from cement production lie outside this interval is essentially zero). Similarly, it can be assumed that the actual direct CO_2 emissions from fossil fuel use and indirect CO_2 emissions electricity consumption lie within the intervals $a_+^{(f)}$ to $a_-^{(f)}$ and $a_+^{(e)}$ to $a_-^{(e)}$, respectively, where $a_+^{(f)}$ and $a_-^{(f)}$ denote the maximum and minimum estimates of direct CO_2 emissions from fossil fuel use by different methodologies and $a_+^{(e)}$ to $a_-^{(e)}$ denote the maximum and minimum estimates of indirect CO_2 emissions from electricity consumption by different methodologies. With these assumptions, the midpoint of the interval determined by different methodologies can be taken as the expected value for the actual CO_2 emissions, or more specifically, the midpoints $(a_+^{(c)} + a_-^{(c)})/2$, $(a_+^{(f)} + a_-^{(f)})/2$ and $(a_+^{(e)} + a_-^{(e)})/2$ can be taken as the expected value of the process CO_2 emissions from cement production, direct CO_2 emissions from fossil fuel use and indirect CO_2 emissions from electricity consumption, respectively.
(4) The process CO_2 emissions from cement production, direct CO_2 emissions from fossil fuel use and indirect CO_2 emissions from electricity consumption are assumed to be uncorrelated.

Given the above assumptions, the variances associated with the midpoint estimates can be calculated using the follow formulas (JCGM, 2010):

$$u_c^2 = (a_+^{(c)} - a_-^{(c)})^2 / 12,$$

$$u_f^2 = (a_+^{(f)} - a_-^{(f)})^2 / 12,$$

$$u_e^2 = (a_+^{(e)} - a_-^{(e)})^2 / 12,$$

where u_c^2, u_f^2 and u_e^2 denote the variance associated with the midpoint estimates of process CO_2 emissions from cement production, direct CO_2 emissions from fossil fuel use and indirect CO_2 emissions from electricity consumption, respectively.

The Type B standard uncertainty can be calculated as (JCGM, 2010):

$u_c = \sqrt{(a_+^{(c)} - a_-^{(c)})^2 / 12}$,

$u_f = \sqrt{(a_+^{(f)} - a_-^{(f)})^2 / 12}$,

$u_e = \sqrt{(a_+^{(e)} - a_-^{(e)})^2 / 12}$,

Total CO_2 emissions from cement industry c_t are expressed as:

$c_t = f(c_c, c_f, c_e) = c_c + c_f + c_e$,

where c_c, c_f and c_e denote the process CO_2 emissions from cement production, direct CO_2 emissions from fossil fuel use and indirect CO_2 emissions from electricity consumption, respectively.

The expected value of the total CO_2 emissions from cement industry can be taken as

$c_t^{(m)} = f(c_c^{(m)}, c_f^{(m)}, c_e^{(m)}) = c_c^{(m)} + c_f^{(m)} + c_e^{(m)}$,

where $c_c^{(m)}$, $c_f^{(m)}$, and $c_e^{(m)}$ denote the midpoint estimates of the process CO_2 emissions from cement production, direct CO_2 emissions from fossil fuel use and indirect CO_2 emissions from electricity consumption, respectively.

The associated combined variance of the total CO_2 emissions can be calculated as

$$u_t^2 = \left(\frac{\partial f}{\partial c_c}\right)^2 u_c^2 + \left(\frac{\partial f}{\partial c_f}\right)^2 u_f^2 + \left(\frac{\partial f}{\partial c_e}\right)^2 u_e^2 = u_c^2 + u_f^2 + u_e^2,$$

The combined standard uncertainty is then the positive square root of u_t^2, i.e.

$u_t = \sqrt{u_c^2 + u_f^2 + u_e^2}$.

The expanded uncertainty, which is denoted by U_t, is obtained by multiplying the combined standard uncertainty u_t by the coverage factor k which is generally in the range 2 to 3 (JCGM, 2010):

$U_t = ku_t$,

The relative expanded uncertainty is defined as (JCGM, 2010):

$$U_t^{(rel)} = \frac{ku_t}{c_t^{(m)}} \times 100\%$$

According to the assumptions and methodology described above, we calculate the standard uncertainty of the midpoint estimates of process CO_2 emissions from cement production, direct CO_2 emissions from fossil fuel use and indirect CO_2 emissions from electricity consumption. Combined standard uncertainty and expanded uncertainty of the estimate of the total CO_2 emissions from China's cement production are shown in Table 9. We also list the estimate by Ke et al. (2012) in Table 9 as a reference for total CO_2 emissions.

Table 9. Uncertainty of the estimates of the total CO_2 emissions from China's cement production.

Item	2005	2006	2007
Standard uncertainty u_c (Mt)	37	47	53
Standard uncertainty u_f (Mt)	23	32	40
Standard uncertainty u_e (Mt)	4.5	4.1	3.2
LBNL estimate (Mt) [a]	861.4	956.3	1016.8
Midpoint estimate (Mt) [b]	930.4	1055.9	1151.0
Combined standard uncertainty u_t (Mt)	44	57	66
Expanded uncertainty U_t (k=2) (Mt)	87	120	140
Expanded uncertainty U_t (k=3) (Mt)	130	180	200
Relative expanded uncertainty $U_t^{(rel)}$ (k=2) (%)	10	11	12
Relative expanded uncertainty $U_t^{(rel)}$ (k=3) (%)	14	17	18

[a] *Estimated by Ke et al. (2012).*

[b] *Calculated according to the estimates analyzed in this study.*

As Table 9 shows, the relative uncertainty of the estimates of the CO_2 emissions from China's cement production is in the range of 10% to 18%, which accords with the estimation by Gregg et al. (2008). We emphasize that the uncertainty estimated in this section reflects the discrepancies between different methodologies.

6. Discussion and conclusions

Cement production has received worldwide attention as one of the main sources of anthropogenic CO_2 emissions. China has been the largest cement producer in the world since 1985 and currently accounts for about 50% of the world cement production. Cement production emits more CO_2 than any other industrial sector in China, when process emissions are taken into account. Table 10 shows the estimate of CO_2 emissions from China's cement production and its share in China's total fossil fuel emissions. As Table 10 shows, the cement industry accounts for 13% to 14% of China's total fossil-fuel emissions, if we take CDIAC's estimates of total fossil-fuel emissions (Boden et al., 2011) as a reference.

Because process CO_2 emissions from cement production are generally determined by the chemical reactions in the cement production process and are difficult to reduce significantly in short term, the Chinese government has focused on increasing energy efficiency, including phasing out inefficient cement production capacity and promoting the more energy-efficient NSP process for cement production (NDRC, 2009; Ze, 2010). Statistics show that the energy efficiency of China's cement industry has improved significantly (CCA, 2011; QEASCBM, 2011; Zeng, 2010), which in turn has reduced the direct CO_2 emissions from fossil fuel use for cement production. This significant energy efficiency improvement is very important for the reduction of CO_2 emission intensity, as the Chinese cement output will not likely decrease in the near future (Gao, 2010; Ke et al., 2012; MIIT, 2012).

Table 10. Share of CO_2 emissions from China's cement production in China's total fossil fuel emissions.

Source: CDIAC, 2011; Ke et al., 2012. Calculations by authors.

Item	2005	2006	2007
Estimation of direct CO_2 emissions from China's cement production ce_d (Mt) [a]	773.8	858.8	916.5
Estimation of total CO_2 emissions from China's cement production ce_t (Mt) [a]	861.4	956.3	1016.8
Midpoint estimation of total CO_2 emissions from China's cement production ce_m (Mt) [b]	930.4	1055.9	1151.0
CDIAC's estimate of China's total fossil fuel emissions e_t (Mt) [c]	5790.0	6414.5	6791.8
ce_d / e_t (%)	13.4	13.4	13.5
ce_t / e_t (%)	14.9	14.9	15.0
ce_m / e_t (%)	16.1	16.5	16.9

[a] *Estimated by Ke et al. (2012).*

[b] *Calculated according to the estimates analyzed in this study.*

[c] *Estimated by CDIAC (Boden et al., 2011).*

From the regional and national perspective, a reliable estimate of the CO_2 emissions from cement production is important for evaluating the current situation and potential emissions reductions, making proper decisions and policies, and adopting suitable measures to reduce total CO_2 emissions. Our estimate shows that the direct CO_2 emission intensity of China's cement production (including fossil-fuel combustion emissions and process emissions) decreased from 0.724 t CO_2 per t cement in 2005 to 0.625 t CO_2 per t cement in 2009, and total CO_2 emission intensity (including fossil-fuel combustion emissions, process emissions, and indirect emissions from external electricity production) decreased from 0.806 t CO_2 per t cement in 2005 to 0.683 t CO_2 per t cement in 2009 (Ke et al., 2012). China's cement production soared to 1.9 Gt in 2010, implying that total CO_2 emissions from cement production could exceed 1.2 Gt if the total CO_2 emission intensity in 2009 (i.e., 0.683 t CO_2 per t of cement) is applied. However, given a relative uncertainty in the range of 10% to 18%, the estimated CO_2 emissions from China's cement industry in 2010 could be lower than 1.1 Gt or higher than 1.4 Gt, a difference of more than 0.3 Gt.

China has announced that it will reduce its carbon intensity, i.e. CO_2 emissions per unit of GDP, by 40-45% over the 2005 level by 2020 (Fu et al., 2009). We note that the National Bureau of Statistics has revised China's energy consumption data for 1996-2008 (NBS, 2010a), which resulted in a higher 2005 base level for this commitment. For the manufacture of non-metallic mineral products sub-sector, to which the cement industry belongs, final energy consumption in 2005 was revised upward by 14.5%. Assuming China's cement production remains at a high level until 2020 (Gao, 2010; Ke et al., 2012), the cement industry will be a critical sector to focus on for China to meet the national 40-45% carbon intensity reduction target. More reliable estimates of the CO_2 emissions from China's cement production and their uncertainty analysis are thus very important.

Given the analyses conducted in this study, we conclude with the following remarks:
(1) The IPCC Guidelines for National Greenhouse Gas Inventories and CSI Cement CO_2 and Energy Protocol should be followed for estimating CO_2 emissions from cement production. As shown in this

study, the IPCC Guidelines for National Greenhouse Gas Inventories and CSI Cement CO_2 and Energy Protocol are based on rigorous and scientific analysis and can provide comprehensive and reliable calculation results.

(2) Up-to-date statistics and analyses of raw materials inputs and clinker production and country-specific emission factors are preferred for estimating the process CO_2 emissions from cement production. It is not consistent with good practice to estimate CO_2 emissions by directly applying a fixed cement-based emission factor. CSI defaults are recommended for estimating process CO_2 emissions from cement production in the absence of relevant and specific data.

(3) Country-specific and up-to-date energy statistics and emission factors are preferred for estimating CO_2 emissions from fuel combustion for cement production. IPCC default emission factors for fossil fuel combustion are recommended in the absence of relevant and specific data.

(4) The estimation of indirect CO_2 emissions of cement production is used to analyze the impact of the cement industry on regional and national CO_2 emissions. For CO_2 emissions accounting, indirect CO_2 emissions from consumption of externally-produced electricity are allocated to the power industry and double-counting should be avoided.

(5) The magnitude of CO_2 emissions from a single industrial sector in China underscores the need to further evaluate the current estimates of cement CO_2 emissions in that country.

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References

Afsah, S., Aller, M., 2010. CO2 Discrepancies between Top Data Reporters Create a Quandary for Policy Analysis. < http://www.co2scorecard.org/home/researchitem/17 >

Bhatty, J.I., Miller, F.M., Kosmatka, S.H., 2004. Innovations in Portland Cement Manufacturing. Portland Cement Association, Skokie.

Boden, T.A., Marland, G., Andres, R.J., 2011. People's Republic of China Fossil-Fuel CO2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA. doi 10.3334/CDIAC/00001_V2011. < http://cdiac.ornl.gov/trends/emis/tre_prc.html >

CBMF (China Building Materials Federation's Department of Information), QEASCBM (Quantitative Economics and Audit Society of China Building Materials), 2012. Statistical analysis of 2011 Chinese cement production and capacity. China Cement (3), 10-12.

CCA (China Cement Association), 2008. China Cement Almanac 2007. China Building Materials Industry Publishing House, Beijing.

CCA (China Cement Association), 2009. China Cement Almanac 2008. Jiangsu People's Publishing House, Nanjing.

CCA (China Cement Association), 2010. China Cement Almanac 2009. Jiangsu People's Publishing House, Nanjing.

CCA (China Cement Association), 2011. China Cement Almanac 2010. Jiangsu People's Publishing House, Nanjing.

CDIAC (Carbon Dioxide Information Analysis Center), 2011. Fossil-Fuel CO2 Emissions. < http://cdiac.esd.ornl.gov/trends/emis/meth_reg.html >

CEMBUREAU (European Cement Association), 2011. Activity Report 2010. < http://www.cembureau.eu/sites/default/files/Activity_Report_2010.pdf >.

CSI (Cement Sustainability Initiative), 2005. CO2 Accounting and Reporting Standard for the Cement Industry, Version 2.0. < http://www.wbcsdcement.org >.

CSI (Cement Sustainability Initiative), 2011. CO2 and Energy Accounting and Reporting Standard for the Cement Industry, Version 3.0. < http://www.wbcsdcement.org/pdf/tf1_co2%20protocol%20v3.pdf >.

Digital Cement, 2011. China's Cement and Clinker Output in 2010. < http://www.dcement.com/Article/201101/94655.html >.

EIA (Energy Information Administration), 2008. Documentation for Emissions of Greenhouse Gases in the United States 2006, Energy Information Administration, Department of Energy, Washington, D.C., USA. < http://www.eia.doe.gov/oiaf/1605/ggrpt/documentation/pdf/0638(2006).pdf >

ERI (Energy Research Institute of the NDRC, China), 2010. Guidebook for the Financing of Energy Efficiency and Renewable Energy Projects. China Environmental Science Press, Beijing.

Fu J., Li J., Sun X., 2009. China Targets Massive 40-45% Carbon Cut. < http://www2.chinadaily.com.cn/china/2009-11/27/content_9060284.htm >

Gao, C., 2010. Prospect of China's Cement Production Capacity Control. China Building Materials News, No. 5602. < http://www.zgjcbw.com/ac/pageDetail.jc?pkCnt=44920&cntype=1 >

Gregg, J.S., Andres, R.J., Marland, G., 2008. China: Emissions pattern of the world leader in CO2 emissions from fossil fuel consumption and cement production. Geophysical Research Letter 35. (L08806).

IEA (International Energy Agency), 2007. Tracking Industrial Energy Efficiency and CO2 Emissions. IEA, Paris.

IPCC (Intergovernmental Panel on Climate Change), 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. < http://www.ipcc-nggip.iges.or.jp/public/2006gl/ >

JCGM (Joint Committee for Guides in Metrology), 2010. JCGM 100:2008 Evaluation of Measurement Data – Guide to the Expression of Uncertainty in Measurement. < http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf >

JRC (European Commission's Joint Research Centre), PBL (Netherlands Environmental Assessment Agency), 2011. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2. < http://edgar.jrc.ec.europa.eu/index.php >

Ke, J., Zheng, N., Fridley, D., Price, L., Zhou, N., 2012. Potential energy savings and CO2 emissions reduction of China's cement industry. Energy Policy 45, 739-751.

Li, X., Shi, J.P., Lv, S.Z., Wang, H.B., 2011. CO2 emissions from the Chinese cement industry and methods to reduce them. Acta Scientiae Circumstantiae 31(5), 1115-1120.

Ma, J., 2011. China's Economy in Good Shape in 2010. < http://www.stats.gov.cn/tjfx/jdfx/t20110120_402699441.htm >.

MEP (Ministry of Environmental Protection of PR China), 2011. Chinese Environmental Standard: Technical Requirement for Environmental Labeling Products – Low Carbon Cement (Public Consultation Draft). < http://www.mep.gov.cn/gkml/hbb/bgth/201112/W020111208396803765230.pdf >

MIIT (Ministry of Industry and Information Technology), 2012. Status of Cement Industry in 2011 and the Industry's Development Outlook for 2012. < http://www.miit.gov.cn/n11293472/n11293832/n11294132/n12858402/n12858582/14481348.html >

NBS (National Bureau of Statistics), 2010a. China Energy Statistical Yearbook 2009. China Statistics Press, Beijing.

NBS (National Bureau of Statistics), 2010b. China Statistical Yearbook 2010. China Statistics Press, Beijing.

NBS (National Bureau of Statistics), 2011. China Statistical Yearbook 2011. China Statistics Press, Beijing.

NDRC (National Development and Reform Commission), 2009. Notice on Suggestions of Restraining Excess Capacity and Redundant Construction in Certain Sectors and Guiding Their Healthy Development. < http://www.sdpc.gov.cn/zcfb/zcfbqt/2010qt/t20100513_346554.htm >

PBL (Netherlands Environmental Assessment Agency), 2008. Global CO2 Emissions: Increase Continued in 2007. < http://www.pbl.nl/en/publications/2008/GlobalCO2emissionsthrough2007 >

QEASCBM (Quantitative Economics and Audit Society of China Building Materials), 2011. Cement industry structure adjustment and energy consumption in the "Eleventh Five-Year Plan" period. China Cement (1), 30-35.

SERC (State Electricity Regulatory Commission), 2009. 2008 Power Industry Energy Savings and Emissions Reduction Bulletin. < http://www.serc.gov.cn/zwgk/scjg/200911/t20091102_12268.htm >.

Tong, H., Cui, Y., Qu, W., Liu, Y., 2010. System dynamic scenarios analysis of CO2 emissions of China's cement industry. China Soft Science (3), 40-50.

TUC (Tsinghua University of China), 2008. Assisting Developing Country Climate Negotiators through Analysis and Dialogue: Report of Energy Saving and CO2 Emission Reduction Analysis in China Cement Industry. <http://www.ccap.org/docs/resources/694/China%20Cement%20Sector%20Case%20Study.pdf>.

USGS (U.S. Geological Survey), 2010. 2008 Minerals Yearbook: Cement [Advance Release]. < http://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2008-cemen.pdf >

Wang, L., 2006. Discussion of CO2 emission reduction in Chinese cement industry. China Cement (4), 34-36.

Wang, L., 2008. Further discussion of CO2 emission reduction in Chinese cement industry. China Cement (2), 36-39.

Wang, L., 2009. Calculation of carbon dioxide emissions. China Cement (11), 21-22.

Wang, L., 2011. Review of the calculation method of CO2 emissions of cement production. China Cement (8), 52-55.

Worrell, E., Price, L., Martin, N., Hendriks, C., Ozawa Meida, L., 2001. Carbon dioxide emissions from the global cement industry. Annual Reviews of Energy & the Environment 26 (8), 303-329.

Ze, X., 2010. Review of the Development of China Cement Industry. China Economic Herald, August 3.

Zeng, X., 2009. Development report of cement industry waste heat power generation. China Cement (10), 18-23.

Zeng, X., 2010. Cement industry fully launches energy efficiency benchmark. China Cement (4), 25-27.

Zhou, H., 2007. Study on energy consumption of Chinese cement industry in 2006. China Cement (10), 26-29.

Zhou, H., 2011. Change of cement industry in the "Eleventh Five-Year" period. China Cement (4), 16-19.

Zuo, Z., Yang, M., 2011. Thoughts on energy conservation of China cement industry during the "Twelfth Five Years Plan". China Cement (7), 10-12.