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An inventory of primary air pollutants and CO₂ emissions from cement production in China, 1990–2020

Yu Lei a,b, Qiang Zhang c, Chris Nielsen b, Kebin He a,*

a State Key Joint Laboratory of Environment Simulation and Pollution Control, Department of Environmental Science and Engineering, Tsinghua University, Beijing 100084, China
b School of Engineering and Applied Science, Harvard University, Cambridge, MA 02138, USA
c Center for Earth System Science, Tsinghua University, Beijing 100084, China

**Abstract**

Direct emissions of air pollutants from the cement industry in China were estimated by developing a technology-based methodology using information on the proportion of cement produced from different types of kilns and the emission standards for the Chinese cement industry. Historical emissions of sulfur dioxide (SO₂), nitrogen oxides (NOₓ), carbon monoxide (CO), particulate matter (PM) and carbon dioxide (CO₂) were estimated for the years 1990–2008, and future emissions were projected up to 2020 based on current energy-related and emission control policies. Compared with the historical high (4.36 Tg of PM₂.₅, 7.16 Tg of PM₁₀ and 10.44 Tg of TSP in 1997), PM emissions are predicted to drop substantially by 2020, despite the expected tripling of cement production. Certain other air pollutant emissions, such as CO and SO₂, are also predicted to decrease with the progressive closure of shaft kilns. NOₓ emissions, however, could increase because of the promotion of precalciner kilns and the rapid increase of cement production. CO₂ emissions from the cement industry account for approximately one eighth of China’s national CO₂ emissions. Our analysis indicates that it is possible to reduce CO₂ emissions from this industry by approximately 12.8% if advanced energy-related technologies are implemented. These technologies will bring co-benefits in reducing other air pollutants as well.

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1. Introduction

China is the largest cement producing and consuming country in the world. Cement production in China was 1.39 billion metric tons in 2008 (CMIIT, 2009), which accounted for 50% of the world’s production (USGS, 2009). Enormous quantities of air pollutants are emitted from cement production, including SO₂, NOₓ, CO, and PM, and result in significant regional and global environmental problems. In China, the cement industry has been identified as an important source of pollution. For example, it is the largest source of PM emissions, accounting for 40% of PM emissions from all industrial sources (CEYEC, 2001) and 27% of total national PM emissions (Zhang et al., 2007a). Cement production also releases large amounts of CO₂ from both fuel combustion and the chemical process producing clinker, where calcium carbonate (CaCO₃) is calcined and reacted with silica-bearing minerals. According to the National Greenhouse Gas Inventory of China (NDRC, 2004), cement production contributed 57% of CO₂ process emissions (distinct from combustion emissions) from China’s industrial sources in 1994.

There are two main kiln types in China: shaft kilns and rotary kilns. With higher productivity and efficiency, rotary kilns have dominated the cement industry in Western countries since the middle of the 20th century. Starting in the 1980s in China, however, small but easy-to-construct shaft kilns were built all over the country to meet the rapidly increasing demands of the construction industry. By the mid-1990s, they accounted for 80% of production (Lei, 2004). The extremely rapid increase in the number of shaft kilns resulted in poor operating practices within the Chinese cement industry. There were more than 7000 cement plants in China in 1997 (Zhou, 2003), most of them small and releasing high emissions. At the end of the 1990s, China began to restrict construction of new shaft kilns and instead promoted precalciner kilns, which are the most advanced rotary cement kilns. Consequently, the production from precalciner kilns increased very rapidly and by 2008 they accounted for more than 60% of cement production (CMIIT, 2009).

Since China’s cement industry is an important emission source of several types of air pollutants, the systematic and reliable estimation of its emissions is essential for atmospheric modeling and
air pollution policy-making. From the perspective of criteria air pollutants, existing emission inventories for China usually treat the cement industry as a part of the industrial sector, roughly estimating its emissions based on coal consumption (Streets et al., 2003; Ohara et al., 2007). These emission inventories, however, are not capable of providing to the atmospheric modeling community reliable emission trends of China’s cement industry. Moreover, there are shortcomings in future emission estimates because the effects from technology replacement and emission control measures were not taken into account. From the perspective of greenhouse gas (GHG) emissions, there have been some estimates made at a national level (He and Yuan, 2005; Liu et al., 2009; NDRC, 2004; Zhu, 2000) or as a part of a global analysis (Boden et al., 1995, 2009; WBCSD, 2002; Worrell et al., 2001). Most of these studies, however, have focused on a specific year and are not able to reflect changes in emissions due to technology replacement and energy efficiency improvement in China’s cement industry. Our previous studies have addressed concerns over the technology-based emission estimates from the cement industry for specific air pollutants, such as PM (Lei et al., 2008) and NOx (Zhang et al., 2009), however, a historical trend of emissions from China’s cement industry is still missing. In this work, we developed a historical emission inventory of major air pollutants from China’s cement industry for the period 1990–2008 to explore the effects of recent regulations and technologies on these emissions, and we predict future emissions up to 2020 in light of existing and possible future regulations.

2. Methodology and data

2.1. Bottom-up methodology

The emission inventory developed here includes four gaseous air pollutants (SO2, NOx, CO and CO2) and PM in three different size ranges: PM2.5 (particulates with diameter less than 2.5 µm), PM10 (particulates with diameter less than 10 µm) and TSP (total suspended particulates). Only direct emissions from cement production were considered in this inventory. The indirect emissions, such as which from power consumption during manufacture and the transportation of raw materials and end products are not included. Kilns are the major source of most air pollutants in the cement production process. In this study, cement kilns are classified into three groups: shaft kilns, precalciner kilns, and other rotary kilns.

Emissions from the cement industry of each province in China were calculated based on province-level cement outputs and emission factors (EFs), and then summed to give estimates at a national level. The approaches used for estimating emissions of different pollutants are listed in Table 1. The burning of fuel in the kilns is the sole source of SO2, NOx and CO emissions. The emissions of these pollutants were estimated based on coal consumption as almost all cement kilns in China use coal as fuel. In addition to fuel combustion, calcination of carbonate such as limestone is the other important source of CO2 emissions, which we calculated separately in our analysis. PM emissions were more complicated to estimate because: (1) besides kiln emissions, there are several other emission sources such as quarrying and crushing, raw material storage, grinding and blending, and packaging and loading; and (2) abatement efficiency varies a lot between the different PM emission control technologies. Taking the multiple sources and control technologies into account, a dynamic methodology was developed to estimate the inter-annual emissions of PM.

2.2. Activity rates

Total cement production by province from 1990 is available from the China Statistical Yearbook (NBS, 1991–2008). A breakdown of national cement production by kiln type was estimated from the historical capacity of precalciner kilns and other rotary kilns (Kong, 2005; Lei, 2004; Zeng, 2004), as shown in Fig. 1. There are no statistical data for clinker production or coal consumption for the cement industry in China as a whole. We therefore estimated these by using typical clinker to cement ratios and energy efficiency data of the Chinese cement industry.

In general, cement is produced by mixing auxiliary materials with milled clinker. In China in the 1990s, the national average clinker to cement ratio varied within the range 0.701–0.738 (Zhou, 2003) and so for this study we used a value of 0.72. The energy efficiency of China’s cement industry has improved considerably in last two decades. The average energy intensity of the whole industry dropped from 5.27 MJ tonne\(^{-1}\)-clinker in 1990 (Liu et al., 1995) to 4.77 MJ tonne\(^{-1}\)-clinker in 1998 (Zhou, 2003). And the current energy efficiency of China’s precalciner kilns is around 3.51 MJ tonne\(^{-1}\)-clinker, a value that is recommended as the basic level for clean production of cement (MEP, 2009). Based on this information, the historical energy efficiency of different kiln types was interpolated, which enabled coal consumption to be calculated, as shown in Table 2.

2.3. Emission factors (EFs)

SO2 mainly comes from the oxidation of sulfur in coal. In precalciner kilns, approximately 70% of SO2 is absorbed by reaction with calcium oxide (CaO) (Liu, 2006), while much less is absorbed in other rotary kilns and in shaft kilns (Su et al., 1998). Utilization of

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Combustion</th>
<th>Calcination</th>
<th>Other sources</th>
<th>Equation for emissions estimation(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO2</td>
<td>√</td>
<td>—</td>
<td>—</td>
<td>(E_i = \sum CC_{i,m} \times EF_{m})</td>
</tr>
<tr>
<td>NOx</td>
<td>√</td>
<td>—</td>
<td>—</td>
<td>(E_i = \sum CC_{i,m} \times EF_{m})</td>
</tr>
<tr>
<td>CO</td>
<td>√</td>
<td>—</td>
<td>—</td>
<td>(E_i = \sum CC_{i,m} \times EF_{m})</td>
</tr>
<tr>
<td>CO2</td>
<td>√</td>
<td>√</td>
<td>—</td>
<td>(E_i = \sum CC_{i,m} \times EF_{m} + \sum CP_{i,j} \times EFC)</td>
</tr>
<tr>
<td>PM</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>(E_{ij} = \sum P_{i,m,j} \times EF_{m} + \sum C_{m,n,j} \times (1 - \eta_{m}))</td>
</tr>
</tbody>
</table>

\(^a\) \(i, j, m\) and \(n\) represent the province, year, type of kiln or emission source and type of PM control technology respectively; \(\gamma\) represents the three size categories of PM: PM2.5, PM > 2.5 µm but < 10 µm (PM2.5–10); PM > 10 µm (PM > 10); \(EF_i\) is the total emissions; \(CC\) is the coal consumption; \(CP\) denotes the clinker production; \(P\) is the cement production; \(EF\) is the emission factors from coal combustion; \(EFC\) denotes the emission factor of CO2 from calcination during clinker production; \(\eta\) is the final emission factor of PM; \(EFR\) is the unabated emission factor of PM prior to the effect of PM control devices; \(F_i\) is the fraction of all PM in size range \(y\) with \(\sum F_i = 1\); \(C_{m,n,j}\) is the penetration rate of the PM control technology; \(n\) with \(\sum C_{m,n,j} = 1\); \(\eta\) is the PM removal efficiency of the control technology.
baghouse filters, as required with new precalciner kilns, can further reduce SO₂ emissions. Assuming that SO₂ absorption is 80% for the entire precalciner kiln process and 30% for other types of kilns (Liu, 2006), we estimated SO₂ emissions by province using a mass balance approach and based on the average sulfur content of coal in each province (Liu, 1998).

Generation of NOₓ and CO is highly dependent on temperature and oxygen availability. Compared to shaft kilns, rotary kilns produce much more NOₓ and less CO because of their higher operation temperature and stable ventilation. Based on local test results, our previous studies have estimated the EFs of NOₓ (Zhang et al., 2007b) and CO (Streets et al., 2006) from different types of kilns in China. These EFs were used in this study, and the average NOₓ and CO EFs of the cement industry as a whole were calculated based on the historical balance of kiln type, as listed in Table 3.

CO₂ EFs were given in quite a few studies estimating CO₂ emissions from the cement industry in China (Boden et al., 1995; Cui and Liu, 2008; He and Yuan, 2005; NDRC, 2004; Wang, 2009; Worrell et al., 2001; Zhu, 2000). In this work, we used CO₂ EFs from the study by Cui and Liu (2008) who followed the approach recommended by the International Panel on Climate Change (IPCC, 2006) and calculated the EFs based on the typical practices of the cement industry in China. Their estimates of the CO₂ EFs were 0.55 kg kg⁻¹ clinker from the calcining process, and 1.94 kg kg⁻¹ coal from coal combustion. The CO₂ EFs from different published works are compared in Sect. 3.3 to assess the reliability of our CO₂ emission estimates.

The EFs of PM is dependent on both the characteristics of unabated emissions from the overall production process and the effectiveness of PM emission control devices. Our previous study (Lei et al., 2008) reviewed prior research and calculated the unabated PM EFs for different types of kilns and other emission sources, such as quarrying, crushing and other mechanic processes, as summarized in Table 4.

PM control devices can reduce PM emissions by 10–99.9%, depending on the type of control technology employed and the size distribution of PM in the raw flue gas (Lei et al., 2008). Although more efficient PM control technologies require higher investment and have higher operational costs, improving emission standards is driving the promotion of these technologies within the industry. The standard value for the PM concentration in kiln flue gas dropped from 800 to 50 mg m⁻³ in 20 years, according to progressive editions of the air pollutant emission standards for the cement industry (SEPA, 1985, 1996b, 2004). Based on the PM concentration requirements of the three successive emission standards, penetration rates of the different PM control technologies in newly built cement plants are estimated for four periods: before 1985, 1985–1996, 1997–2004, and after 2004. Although the emission standards published in 1996 and 2004 allow 3–10 years for existing plants to reduce their PM emission rates, reduction is not likely to be significant in existing plants as there are few measures to enforce the standard. In this work, we assume that all plants retrofit their whole production line every 15 years, and in doing so meet the present standards for new plants. We then calculate the penetration rates of PM control technologies across the cement industry for the period 1990–2008, and estimate the corresponding PM EFs, as shown in Fig. 2. Over the 18-year period, the EF of TSP from the cement industry dropped by 88%, from 27.93 g kg⁻¹ to 3.31 g kg⁻¹. The reduction in PM₁₀ and PM₂.₅ EFs is also considerable: 18.08–2.53 g kg⁻¹ and 10.65–1.61 g kg⁻¹, respectively.

3. Results and discussion

3.1. Emissions from 1990 to 2008

Fig. 3 and Table 5 show emissions of gaseous air pollutants and PM from China’s cement industry for the period 1990–2008. The emissions in 2005 are also compared with China’s total emissions from all anthropogenic sources in Table 5. The cement industry is a major source of PM in China, contributing more than a quarter of PM₂.₅ and PM₁₀ in 2005. As a significant contributor to GHG emissions in China, the cement industry produces approximately one eighth of China’s total anthropogenic CO₂ emissions. The
cement industry is also very important from the perspectives of China’s SO2, NOx and CO emissions, contributing approximately 5.1%, 6.4% and 7.7% of national anthropogenic emissions in 2005, respectively.

Emissions of SO2 increased from 0.42 Tg in 1990 to 1.39 Tg in 2007, then dropped to 1.21 Tg in 2008 (a reduction of 12.6%). The decline in SO2 emissions in 2008 is attributed to two factors. First, the global economic recession suppressed the construction industry and saw the annual rate of increase in cement production drop from 10% in the previous year to 2% in 2008. Second, nationwide replacement of shaft kilns with precalciner kilns from 2007 to 2008 led to a 20% of reduction in cement production from shaft kilns, which emit several times more SO2 per mass unit of cement.

The trend observed for CO emissions is similar to that of SO2. In contrast, NOx emissions increased much faster than any other pollutant. During the 1990s, NOx emissions doubled, and the 2000 emissions were three times higher by 2008. With the recent rapid expansion of precalciner kilns in China, the average annual increase in NOx emissions from the cement industry from 2003 to 2008 was over 220 Gg. This accounts for about 20% of the incremental NOx emissions seen for China as a whole according to the INTEX-B emission inventory (Zhang et al., 2009). As awareness grows of China’s increasing NOx emissions and its consequences for ozone pollution and acidification (Zhao et al., 2009), policies to combat acid rain pollution will inevitably have to specifically address the cement industry.

Emissions of CO2 increased 5.8 times, from 153 Tg in 1990 to 892 Tg in 2008. The proportion of CO2 emissions from fuel combustion compared to that from calcination of carbonates decreased from 46.0% in 1990 to 38.6% in 2008, representing improved energy efficiency in the cement industry. Our estimates of CO2 emissions are lower than the results delivered by some researchers such as Boden et al. (2009), Liu et al. (2009) and Worrell et al. (2001). The main reasons of the differences are discussed in Section 3.3.

Emissions of PM rose rapidly from 1990 to 1995, when cement production developed with an average annual increase of 17.8%. In the second half of the 1990s, expansion of China’s cement industry slowed and the new emissions standard released in 1996 promoted the application of electrostatic precipitators (ESPs) in shaft kilns, resulting in an industry-wide decrease in PM emissions. After 2000, although the average annual increase in cement production was greater than 12%, PM emissions gradually decreased due to the replacement of shaft kilns by precalciner kilns and the application of high-performance PM removal technology, especially after 2004. Over the whole period, PM emissions reached a peak in 1997, with 4.36 Tg of PM2.5, 7.16 Tg of PM10 and 10.44 Tg of TSP.

3.2. Spatial distribution of emissions

The spatial distribution of emissions changed year-by-year. Using 2005 as a base year, cement production from 5294 plants was collected from the China Cement Association (CCA), including the capacity of 612 clinker production lines installed with precalciner kilns. These plants accounted for almost all precalciner kilns and more than 95% of cement production in China in that year. The location of these plants and production lines is determined at county-level from cement plant registration information (CCA, 2006). Thus emissions of PM2.5, SO2 and NOx from the cement industry in 2005 are mapped onto an 18° × 18° grid of China, as shown in Fig. 4.

In different ways, the distribution of PM2.5, SO2 and NOx emissions reflect regional operational differences and kiln combinations within China, a point illustrated by the following examples. The grid cells indicating high PM2.5 emissions show a greater

---

**Table 4**

<table>
<thead>
<tr>
<th>Kilns</th>
<th>Total PM</th>
<th>PM2.5</th>
<th>PM2.5-10</th>
<th>PM10-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precalcer kilns</td>
<td>105</td>
<td>18.9</td>
<td>25.2</td>
<td>60.9</td>
</tr>
<tr>
<td>Other rotary kilns</td>
<td>98</td>
<td>14.0</td>
<td>21.0</td>
<td>63.0</td>
</tr>
<tr>
<td>Shaft kilns</td>
<td>30</td>
<td>3.3</td>
<td>6.0</td>
<td>20.7</td>
</tr>
<tr>
<td>Other sources</td>
<td>140</td>
<td>9.5</td>
<td>23.8</td>
<td>107.7</td>
</tr>
</tbody>
</table>

Fig. 2. PM emission factors (g kg\(^{-1}\) cement) for all cement producing processes in China’s cement industry for the years 1990–2008. Bars represent the penetration rate of PM control technologies within the industry (BAG: baghouse filter; ESP: electrostatic precipitator; WET: wet scrubber; CYC: cyclone), and line represents the net emission factor of TSP.

Fig. 3. Emissions of air pollutants (top panel, PM; bottom panel, SO2, NOx, CO, CO2) from China’s cement industry from 1990 to 2008.
concentration in north China. The provinces of Shandong, Hebei and Henan account for 31.5% of total PM2.5 emissions. By consuming coal with much higher sulfur content than other provinces, Sichuan has the second highest provincial emissions of SO2 after Shandong. Shandong, Zhejiang, Jiangsu and Anhui are the largest contributors to NOx emissions, which is due to a number of clinker-producing centers using large precalciner kilns in these provinces. The highest PM2.5, SO2 and NOx emissions are all located in the same grid cell in Shandong province, where the city of Zaozhuang is found.

3.3. Comparison of CO2 emissions with other studies

Some studies have been conducted to quantify CO2 emissions from cement production in China, but few of them have observed the effects of developments in technology on CO2 emissions in China. We compare our estimates with some results from other studies in Table 6. All CO2 emission estimates were converted to CO2 EFs in the comparison.

Generally speaking, estimates of China’s CO2 emissions as a part of global studies (e.g., WBCSD, 2002; Boden et al., 2009) are much higher than estimates made from domestic studies because some parameters used in global studies don’t fit the real situation of Chinese cement industry. For example, a higher clinker to cement ratio was used in global studies (83–100%) than in domestic ones (72–75%). Higher energy intensity was assumed in global studies as well, which led to higher EFs of CO2 from energy consumption. The other factor leading to higher results in global studies is that indirect CO2 emissions from electricity consumption are usually included in those analyses. The national average electricity intensity of China’s cement industry is 110–115 kWh/tonne cement (Liu et al., 1995; MEP, 2009). Therefore electricity consumption during cement production leads to additional indirect CO2 emissions of 0.102–0.107 kg CO2/kg cement.

Our estimates of CO2 emissions are generally comparable with most domestic studies. However, the recent studies by Cui and Liu (2008) and Wang (2009) indicate much lower values of CO2 emission than our study, as their estimations were based on the working practices of advanced precalciner cement plants. These lower EFs indicate that China’s cement industry shows promising potential to reduce CO2 emissions.

4. Future emissions and mitigation potential

Since emissions from China’s national cement industry contribute significant levels of several air pollutants, accurate emission projections are necessary to inform Chinese national strategies on air pollution control and GHG mitigation. In this study, the future emissions from the cement industry for the period 2010–2020 were estimated, and the potential of mitigation technologies to reduce the emission is analyzed.

4.1. Emissions projection

Cement production in China exceeded 1.63 billion metric tons in 2009, and the available statistical data show another 19% increase in the first 5 months of 2010 (http://www.stats.gov.cn/tjjs/, in comparison with the same period of 2009. Expert opinion from the CCA indicates that cement production may reach approximately 1.8 billion tons in 2010 (personal communication), but projecting as far ahead as 2020 reveals large differences between the available predictions: the Chinese Academy for Environmental Planning predicted production to be 2.1 billion metric tons based on future investment in fixed assets; Ho and Jorgenson (2007) modeled China’s economy with a computable general equilibrium (CGE) economic model that included 33 production sectors and one household sector, and predicted production to be 1.7 billion metric tons in 2020; Wei and Yagita (2007) coupled cement production with future rates of urbanization and building area and predicted production to be 1.2 billion metric tons by the same date. Considering the large uncertainties involved in predicting the development of China’s cement industry over the next 10 years, our emission projections are based on these three studies’ predictions of cement production by 2020, representing scenarios of high, medium and low production, respectively.

The key technological features of the cement industry are projected based on the existing policies on industry structure (NDRC, 2006), energy saving (MEP, 2009) and emission control (SEPA, 2004). Assuming no new policy will come into effect before 2020, future EFs of air pollutants from the cement industry were estimated using the same methodology described in Sect. 2, as listed in Table 7. Generally speaking, the continued replacement of shaft kilns by precalciner kilns will lead to a decrease in both coal intensity and in CO2 EFs. Higher penetration of precalciner kilns will also result in a decrease in SO2 and CO EFs, and an increase in NOx EFs. PM EFs are predicted to fall with the progressive construction of new cement plants which meet the requirement of the latest emission standards.

According to our estimates (Table 8), the emissions of SO2, CO and PM from China’s cement industry will decrease in all of the three scenarios; however, emissions of NOx and CO2 will increase until 2020 in the high-production scenario. Emissions of NOx will be considerable, compared with SO2 and PM emissions. The ratio of NOx to SO2 will increase from 2.07 in 2010 to 3.14 in 2020, indicating that greater focus should be given to NOx emission control in order to prevent pollution from acid rain. The differences in CO2 emissions between 2010, 2015 and 2020 are less than those of other pollutants. This is because under current policies the EF of CO2 will
However, as CO₂ emissions mitigation is of serious concern, more policies should be considered to reduce CO₂ EFs from China’s cement industry.

4.2. Potential for CO₂ mitigation

Several studies have addressed potential reductions in CO₂ emissions from China’s cement industry. The World Business Council for Sustainable Development (WBCSD, 2009a) has summarized the recent studies and pinpointed four areas of technology for the reduction of CO₂ emissions: thermal and electric efficiency, alternative fuels, clinker substitution, and carbon capture and storage (CCS). Following the technology roadmap laid out by WBCSD (2009a), we analyzed the potential for CO₂ mitigation by China’s cement industry in 2020, as listed in Table 9. Thermal efficiency could be improved by replacing small shaft kilns by large precalciner kilns. On a global level, top 10% advanced kilns can currently operate at a average thermal efficiency of 3.10 MJ kg⁻¹-clinker (MEP, 2009; WBCSD, 2009a), and although the clinker to cement ratio in China is already lower than the global average (WBCSD, 2009b; Worrell et al., 2001), the predicted increase of power plants and iron and steel plants will increase the availability of by-products which can be used as substitutes for clinker. It is estimated that the clinker to cement ratio could drop to 65% (CCA, personal communication). A few cement plants in China have begun to use solid waste as a fuel in kilns as a substitute for coal. WBCSD (2009a) projected that the share of alternative fuel in clinker fuel use in Asia could increase at an annual rate of 0.6%.

Our analysis indicates that the potential for CO₂ mitigation by clinker substitution is likely to be much larger than that possible by improvements in thermal efficiency and from the use of alternative fuels. If these three technologies are implemented together, CO₂ emissions from cement production could be reduced by 12.8% by 2020. Using the mid-level scenario of predicted increase in cement production, mitigation of CO₂ emissions will be 130 Tg of CO₂, equivalent to the emissions of CO₂ from the usage of 67 Tg of coal.

Fig. 4. Emissions of PM₂.₅, SO₂ and NOₓ from the cement industry in China plotted on an 18° × 18° grid; provincial boundaries are shown. (a) PM₂.₅; (b) SO₂; (c) NOₓ.

<table>
<thead>
<tr>
<th>Year</th>
<th>Proportion of precalciner kilns (%)</th>
<th>Coal intensity (MJ kg⁻¹-clinker)</th>
<th>Clinker to cement ratio</th>
<th>SO₂ EF (kg kg⁻¹ coal consumed)</th>
<th>NOₓ EF (kg kg⁻¹ coal consumed)</th>
<th>CO EF (kg kg⁻¹ coal consumed)</th>
<th>CO₂ EF (kg kg⁻¹ cement)</th>
<th>PM₂.₅ EF (kg kg⁻¹ cement)</th>
<th>PM₁₀ EF (kg kg⁻¹ cement)</th>
<th>TSP EF (kg kg⁻¹ cement)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>2015</td>
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<td>2020</td>
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</tr>
</tbody>
</table>

**Table 6**

<table>
<thead>
<tr>
<th>Study</th>
<th>Energy consumption</th>
<th>Calcining process</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>0.248–0.336</td>
<td>0.395</td>
<td>0.643–0.731</td>
</tr>
<tr>
<td>Zhu, 2000</td>
<td>(0.467)</td>
<td>0.415</td>
<td>(0.883)</td>
</tr>
<tr>
<td>Worrell et al., 2001</td>
<td>–</td>
<td>–</td>
<td>(0.900–0.950)</td>
</tr>
<tr>
<td>WBCSD, 2002</td>
<td>–</td>
<td>0.374</td>
<td>–</td>
</tr>
<tr>
<td>NDRC, 2004</td>
<td>–</td>
<td>–</td>
<td>0.671–0.911</td>
</tr>
<tr>
<td>He and Yuan, 2005</td>
<td>0.168 (0.259)</td>
<td>0.395</td>
<td>0.563 (0.654)</td>
</tr>
<tr>
<td>Cui and Liu, 2008</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Boden et al., 2009</td>
<td>(0.226)</td>
<td>0.427</td>
<td>(0.653)</td>
</tr>
<tr>
<td>Wang, 2009</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

* The values in parentheses refer to EFs that include indirect CO₂ emission from power consumption.
* The lower value in the range is the EF in 2008, and the upper value is the EF in 1990.
* The lower value in the range is the EF in 1997, and the upper value is the EF in 1990.
* The EF is used to estimate CO₂ emission in 1994.
* The lower value in the range is the EF in 1995, and the upper value is the EF in 1990.
* The range represents the different EF values for different type of kilns.
4.3. Potential for emission control of other air pollutants

Current emission standards have promoted the use of advanced emission control technologies; however, the level of emission control in China’s cement industry is still lower than that of advanced countries. If state-of-the-art control technologies are used, there is potential to substantially further reduce the emission of air pollutants from the cement industry in China.

PM emissions have been the major focus of air pollution control from the cement industry for years. As of 2010, all new cement plants are required to meet an emission standard of 50 mg m\(^{-3}\) flue gas (SEPA, 2004), which equates to a PM EF for the whole production process of approximately 1 g kg\(^{-1}\) cement (CRAES, 2003). This emission level could be even lower, however, when baghouse filters replace PM control devices that are relatively inefficient. If all of China’s cement plants used baghouse filters in major production processes, the average PM EF could drop to 0.7 g kg\(^{-1}\) cement.

Deployment of baghouse filters will benefit SO\(_2\) emission control as well. However, emissions of NO\(_x\) would not be reduced unless selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR) technology is used. Although BREF documents state that NO\(_x\) emissions could be as low as 200–500 mg m\(^{-3}\) if the best available technologies (BAT) are used, actual NO\(_x\) emissions from most European cement plants using SNCR technology are 500–800 mg m\(^{-3}\) (Jiao, 2007). If China’s cement plants could reduce the average NO\(_x\) emission level to 500 mg m\(^{-3}\) in 2020, the corresponding NO\(_x\) EF would be 9.7 kg kg\(^{-1}\) coal.

The technologies used to mitigate CO\(_2\) emissions are also effective in reducing emissions of PM, SO\(_2\) and NO\(_x\). Based on mid-scenario emissions of these pollutants in 2020, we estimated the potential for emission reduction from each mitigation technology, as listed in Table 10. Our estimates indicate that there is the potential for China’s cement industry to reduce air pollutants substantially. Baghouse filters and SCR/SNCR technologies are likely to be the most effective in controlling PM and NO\(_x\) emissions, respectively, and technologies to abate CO\(_2\) emissions will also bring significant benefits in terms of SO\(_2\) emission control.

### Table 8
Future output and coal consumption of China’s cement industry, and associated emissions of air pollutants (Tg) for three production scenarios of high, medium and low cement production (see text for details).

<table>
<thead>
<tr>
<th></th>
<th>High</th>
<th>Medium</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement production</td>
<td>1800 2140</td>
<td>1800 1660</td>
<td>1800 1170</td>
</tr>
<tr>
<td>Coal consumption</td>
<td>222 234</td>
<td>222 184</td>
<td>222 130</td>
</tr>
<tr>
<td>SO(_2) emissions</td>
<td>1.29 1.04</td>
<td>1.29 0.81</td>
<td>1.29 0.57</td>
</tr>
<tr>
<td>NO(_x) emissions</td>
<td>2.67 2.83</td>
<td>2.67 2.54</td>
<td>2.67 1.79</td>
</tr>
<tr>
<td>CO emissions</td>
<td>11.51 7.79</td>
<td>11.51 6.04</td>
<td>11.51 4.26</td>
</tr>
<tr>
<td>CO(_2) emissions</td>
<td>1141 1305</td>
<td>1141 1013</td>
<td>1141 714</td>
</tr>
<tr>
<td>PM(_{2.5}) emissions</td>
<td>1.44 0.78</td>
<td>1.44 0.92</td>
<td>1.44 0.55</td>
</tr>
<tr>
<td>PM(_{10}) emissions</td>
<td>2.27 1.29</td>
<td>2.27 1.49</td>
<td>2.27 0.91</td>
</tr>
<tr>
<td>TSP emissions</td>
<td>2.79 2.08</td>
<td>2.79 1.61</td>
<td>2.79 1.13</td>
</tr>
</tbody>
</table>

### Table 9
Estimated emission reduction potential from major CO\(_2\) mitigation technologies in 2020.

<table>
<thead>
<tr>
<th>Technology category</th>
<th>Improvement of performance</th>
<th>CO(_2) reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal efficiency</td>
<td>Thermal intensity drops from 3.22 MJ kg(^{-1}) clinker to 3.10 MJ kg(^{-1}) clinker</td>
<td>1.3</td>
</tr>
<tr>
<td>Clinker substitution</td>
<td>Clinker to cement ratio drops from 72% to 65%</td>
<td>9.7</td>
</tr>
<tr>
<td>Alternative fuels</td>
<td>Share of alternative fuel increases by 6%</td>
<td>2.1</td>
</tr>
</tbody>
</table>

5. Conclusions

The cement industry plays an important role in emissions of many air pollutants in China. This study estimates the direct emissions of major air pollutants from cement production based on information on the development of production technologies and rising emission standards in China’s cement industry. Our analysis shows that with the replacement of old shaft kilns by precalciner kilns, there is an opportunity to reduce PM emissions through the implementation of stricter emission standards and the promotion of high-performance PM control technologies. Other air pollutants such as CO and SO\(_2\) will also decrease as shaft kilns are gradually retired. However, the promotion of precalciner kilns within China and a rapid increase in cement production has led to greatly increased NO\(_x\) emissions. Future NO\(_x\) emission could be reduced if SCR or SNCR technologies are introduced within the cement industry, although the cost of introduction is likely to be considerable.

Although energy-use efficiency in China’s cement industry has improved significantly in recent years, the industry still contributes approximately one eighth of the nation’s CO\(_2\) emissions. Our analysis indicates that it may be possible to reduce CO\(_2\) emissions by 12.8% by 2020 if advanced energy-related technologies are implemented, and that the substitution of clinker with other material is likely to be the most effective technology in this regard. These energy-related technologies are likely to bring additional benefits by reducing the emission other air pollutants as well.

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