

Peak cement-related CO₂ emissions and the changes in drivers in China

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Abstract

In order to fight against the climate change, China has set a series of emission reduction policies for super-emitting sectors. The cement industry is the major source of process-related emissions, and more attention should be paid to this industry. This study calculates the process-related, direct fossil fuel- and indirect electricity-related emissions from China's cement industry. The study finds that China's cement-related emissions peaked in 2014. The emissions are, for the first time, divided into seven parts based on the cement used in different new-building types. The provincial emission analysis finds that developed provinces outsourced their cement capacities to less-developed regions. This study then employs index decomposition analysis to explore the drivers of changes in China's cement-related emissions. The results show that economic growth was the primary driver of emission growth, while emission intensity and efficiency were two offsetting factors. The changes in the construction industry's structure and improvement in efficiency were the two major drivers that contributed to the decreased emissions since 2014.

Keywords: Cement industry; CO₂ emissions; Driving forces; Index decomposition analysis; China

1 Introduction

Being the largest CO₂ emitter and energy consumer ([Guan et al. 2009](#)), China is taking increasing responsibility for global climate actions. To reduce greenhouse gas (GHG) emissions in more effective and efficient ways, China has set a series of relevant strategies and specific policies targeting super-emitting sectors ([NDRC 2016c](#)), including power generation ([NDRC 2017](#)), coal mining ([NDRC 2016b](#)), and the iron and steel industry ([MIIT 2016](#)). Cement is one of the largest key sources of process-related emissions in China and worldwide. According to China's official GHG emission inventories from National Communications on Climate Change (as shown in Figure S1), process-related GHG emissions from the cement lime industry reached 157.78 million tons (Mt) (or 57% of the total process-related emissions) in 1994 ([NDRC 2004](#)), 411.57 Mt (or 72%) in 2005 ([NDRC 2013](#)), and 834.03 Mt (or 70%) in 2012 ([NDRC 2016a](#)). With such a large amount and rapid growth of GHG emissions, the cement industry has become a key sector in GHG emissions mitigation. Indeed, several policies have been proposed to reduce the energy consumption and emission intensity of the cement industry in China. In the latest 13th five-year plan for the cement industry, the government aims to achieve a 30% reduction of the air pollutant emissions of the cement industry in 2020 compared to the 2015 level (China Cement Association, CCA, ([2017](#)). The energy consumption per ton of clinker production should be kept under 105 kilograms (kg) coal equivalent in 2020, while those of 2015 amounted to 112 kg. With the efforts of the government, the process-related CO₂ emissions from China's cement industry peaked in 2014 ([Shan et al. 2018a](#)), maintaining the same trend as China's total emissions ([Guan et al. 2018](#)).

Accurately accounts of the cement-related emissions and understanding the driving forces of the changes in emissions is of considerable value, especially has practical significance for further emission reduction policymaking. [Oda et al. \(2018\)](#) developed a global high-spatial-resolution gridded CO₂ emissions data inventory including cement production as a part of nonpoint emission sources. [Sanal \(2018\)](#) evaluated the CO₂ emissions of different types' cement and discussed emission reduction capacities of cement replacement in concrete production. [Andrew \(2018\)](#) presented a new analysis of global process emissions from cement production, which were 30 % lower than those reported by the Global Carbon Project ([Le Quéré et al. 2015](#)). Apart from the carbon source function, [Xi et al. \(2016\)](#) found that carbonation of cement materials has offset 43% of CO₂ emissions from cement production from 1930 to 2013.

Previous studies have employed the Index Decomposition Analysis (IDA) - logarithmic mean Divisia index (LMDI) model to analyze the variations of carbon emissions. [Branger and Quirion \(2015\)](#) investigated the changes of CO₂ emissions in the European cement industry from 1990 to 2012 and found that most of the emission change (activity, clinker trade, thermal and electrical energy efficiency, and electricity decarbonization) could be attributed to the activity effect. When it comes to China,

Xu et al. (2012) got a similar result. They found that the activity effect (calcining process and electricity consumption) was the main driver of cement-related emissions increase while clinker share, structural shift, and kiln efficiency were main negative drivers. Wang et al. (2013) identified the main drivers that influence China's cement-related greenhouse gas emissions. Boqiang Lin (2016) found that the labor productivity was the major driving force to increase the cement-related CO₂ emissions from 1991 to 2010.

Despite that nearly all previous studies in emission accounts and analysis involved the cement process in the emission inventories, the emissions are usually calculated with the cement production (Shan et al. 2016b; Liu et al. 2015; Shan et al. 2018b). As the process-related CO₂ emissions are majorly produced alongside the clinker production, such a cement production-based calculation method is not accurate enough. It may overlook the regional diversity in the cement manufacturing technique and cement-clinker ratio. Therefore, some recent studies calculated the emissions with clinker's production (Cai et al. 2016).

Considering the regional diversity in China's cement manufacturing, this study first investigates the emissions from China and its regions' cement industry. This study examines the process-related CO₂ emissions (calculated based on the clinker productions), direct emissions from fossil fuel combustion, and indirect emissions induced by purchased electricity in the cement industry. The cement-related CO₂ emissions are divided into seven parts according to the cement demands of different new-building types for the first time. This study also describes the regional diversity in cement production and the cement production capacity shifts among the provinces.

This study then employs the LMDI method to break down the changes in China's cement-related CO₂ emissions into four drivers, including the construction industry's structure, emission intensity, efficiency, and economic growth. To the best of our knowledge, our study is the first to examine the factor of "construction industry's structure", which is measured by the cement used for different new-building types, in the analysis of the drivers of China's cement-related emissions. We particularly compared the changes in drivers before and after these emissions peaked in 2014.

Our study provides robust and transparent data support for further environmental evaluations and emission reduction/sustainable production policy making for the cement industry in China.

2 Methods and data sources

2.1 Cement production process and related emissions

Cement is normally produced in three steps, as shown in Figure 1 (Worrell et al. 2001). First, the limestone (primarily CaCO₃) is crushed and ground into raw meal. Then, the

raw meal is calcined in kilns to clinker. Finally, the clinker is ground together with additives (fly ash, pozzolana, gypsum, anhydrite, etc.) to form cement.

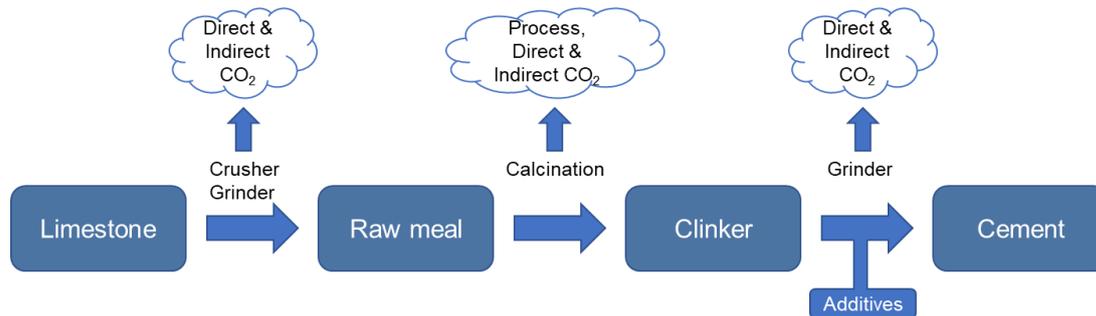


Figure 1 Cement production process and emission calculation

The crusher and grinder are physical reactions that do not emit any CO₂ during the process. In contrast, calcination is a chemical reaction, during which the process-related CO₂ may be emitted. The process-related emissions are the CO₂ emitted as a result of chemical reactions in the production process rather than the energy combusted by industry (Shan et al. 2016a). During the calcination of raw meal, the limestone is heated to lime (CaO) and CO₂; see Equation 1. The CO₂ emissions are process-related emissions during the cement production process.



Although the crushing and grinding processes do not emit process-related emissions, they consume abundant energy for power, such as coal and electricity. The CO₂ emitted during coal combustion and electricity generation is counted as direct emissions and indirect emissions, respectively (Liu 2016b). The indirect emissions are normally produced in power plants rather than the cement plants.

Overall, this study considers the process-related CO₂ emissions, direct CO₂ emissions from coal combustion, and indirect CO₂ emissions induced by electricity consumption in China's cement industry. We adopt the mass balance method recommended by the Intergovernmental Panel on Climate Change to account for the emissions (IPCC 2006).

2.2 Emission calculation

2.2.1 Process-related CO₂ emissions

The process-related CO₂ emissions during cement production can be estimated as the cement or clinker production timed by the related emission factors. As discussed above, most of the previous studies use the cement production to calculate the cement process-related emissions. These cement production-based emission accounts may overlook the regional diversity in the cement manufacturing process and cement-clinker ratio. Therefore, the present study calculates the process-related emissions based on clinker production to achieve more accurate emission accounts of the cement industry; see Equation 2 (IPCC 2006).

$$CE_{process} = AD_{clinker} \times EF_{clinker} \quad \text{Equation 2}$$

In the above equation, $AD_{clinker}$ refers to the clinker production, while $EF_{clinker}$ is the emission factor for clinker production, i.e., the CO₂ emitted during per unit production of clinker.

The emission factor for cement is collected from [Liu et al. \(2015\)](#), which is 0.4964 tons CO₂ per ton of clinker production.

2.2.2 Direct CO₂ emissions from coal combustion (coal-related CO₂ emissions)

The direct coal-related CO₂ emissions are estimated using Equation 3 ([IPCC 2006](#)).

$$CE_{coal} = AD_{coal} \times EF_{coal} = AD_{coal} \times NCV \times CC \times O \quad \text{Equation 3}$$

In the above equation, CE_{coal} is the direct coal-related CO₂ emissions in the cement production, AD_{coal} (activity data) refers to the coal consumption, and EF_{coal} is the emission factor of coal, which is made up of three components: NCV (net calorific value), CC (carbon content), and O (oxygenation efficiency). The parameters are collected from our previous study on China's coal quality based on an extensive investigation of 4243 coal mines ([Liu et al. 2015](#)). The NCV of coal is 20.60 PJ/mt, the CC is 26.32 tC/TJ ([Shan et al. 2018a](#)), and the O is 92%. The overall emission factor of coal (EF_{coal}) is 0.499 ton CO₂ emissions per ton of coal consumption.

2.2.3 Indirect CO₂ emissions from electricity consumption (electricity-related CO₂ emissions)

The indirect CO₂ emissions induced by purchased electricity consumption are calculated using Equation 2 ([IPCC 2006](#)).

$$CE_{ele} = AD_{ele} \times EF_{ele} \quad \text{Equation 4}$$

In the equation, CE_{ele} is the electricity-related CO₂ emissions in the cement production and AD_{ele} (activity data) refers to the electricity consumption, while EF_{ele} refers to the emission factor. This study uses the regional average electricity emission factors ([NDRC 2011](#)) for each province (see Table 1).

Table 1 Emission factors of electricity (NDRC 2011)

Regional grid	Provinces	EF_{ele} (kg/kwh)
North	Beijing, Tianjin, Hebei, Shanxi, Shandong, Inner Mongolia West	1.246
Northeast	Liaoning, Jilin, Heilongjiang, Inner Mongolia East	1.096
East	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian	0.928
Central China	Henan, Hubei, Hunan, Jiangxi, Sichuan, Chongqing	0.801
Northwest	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang	0.977
South	Guangdong, Guangxi, Yunnan, Guizhou	0.714
Hainan	Hainan	0.917

2.2.4 CO₂ emissions induced by domestic construction and exports

Cement is mainly used in the construction industry to build new-buildings. Therefore, the cement-related CO₂ emissions are closely associated with the new investment in the construction industry. In order to better analyze the CO₂ emissions, we split the total cement-related emissions into seven parts according to the cement demands of different domestic new-building types and export.

We firstly exclude the export-related emissions from the total amount. The export-related emissions are calculated based on the cement clinker export amount, which is collected from the CCA (2005-2014). The remaining CO₂ emissions are associated with domestic new-building's construction, which can be categorized into six types: residential, manufacturing, infrastructural, commercial, science-education-culture-health, and other buildings. We collect each new-building types' construction outputs from CCA (2005-2014) and calculate the respectively proportion of each type. We then divide the domestic emissions into six parts according to the proportion of each new-building type.

2.3 **Index decomposition analysis (IDA)**

Understanding the drivers leading to the cement-related CO₂ emission peak has practical importance for further emission reduction policymaking. Techniques available for conducting such analyses include structural decomposition analysis (SDA) (Rose and S. Casler 1996) and index decomposition analysis (IDA) (Ang 2004; Liu et al. 2012b), both of which have been extensively applied to quantify the socioeconomic driving factors of a dependent variations, such as energy consumption or CO₂ emissions (Dhakal 2009; Mi et al. 2017; Baležentis et al. 2011; Guan et al. 2018). SDAs enable us to capture both direct and indirect effects along the entire supply chain on the basis of input-output tables (Meng et al. 2018). This study focuses on the emissions from 1996-2016 and uses IDA because of two reasons. First, all the cement-related CO₂ emissions are from the sector of non-metallic products, only a small part of sectors in China's economy is involved in the supply chain. Second, the time-series input-output tables in China are not available. Thus, we use IDA to decompose the cement-related CO₂ emissions.

A variety of methods for IDA have been developed, most of which are versions of the Laspeyres index or Divisia index methods. Ang (2004) proposed a log mean Divisia index (LMDI) method based on the Divisia index. The LMDI method is the most preferred method, as it passes a number of basic tests for a good index number. The decomposition is perfect, which means that there is no residual term that other methods might produce. The LMDI method can also deal with zero values better than other methods (Ang and Liu 2007a; Ang and Liu 2007b). The LMDI method has the advantages of "*path independence, consistency in aggregation and easily interpreted results*" (Liu et al. 2012a; Meng et al. 2016). By using the LMDI method, previous

studies have explored the drivers of regional emission growth ([Guan et al. 2018](#); [Liu 2016a](#); [Zhang et al. 2016](#); [Chong et al. 2012](#); [Wang et al. 2014](#); [Liu et al. 2007](#)). This study, therefore, employs LMID to quantify the drivers of CO₂ emissions' changes in China's cement industry. Detailed methods are presented in the Supporting Information.

Four driving factors are defined in Equation 5 to explain the total changes in the cement-related CO₂ emissions: the construction industry's structure, emission intensity, efficiency, and fixed capital formation. The changes in each factor help quantify the change in CO₂ emissions from the cement's different usages, environmental effects, technological advancement, and economic growth aspects.

$$CE = \sum_i CE_i = \sum_i \frac{CE_i}{CE} \times \frac{CE}{P} \times \frac{P}{F} \times F = SIEF \quad \text{Equation 5}$$

In the above equation, CE is the total cement-related CO₂ emissions. CE_i are emissions induced by different new-building types, which reflects the construction industry's structure in China. We merge the seven types defined in the section 2.2.4 to three for a clear and concise decomposition analysis: residential and commercial buildings; infrastructural buildings, manufacturing buildings, science-education-culture-health buildings, exports and others. The building types merged together have similar characters. P is the cement production, and F represents the fixed capital formation in respective years.

The four different factors are:

- 1) $S_i = CE_i/CE$ (proportion of CO₂ emissions, in %) measures the share of CO₂ emitted from cement usage i , representing the construction industry's structural effect;
- 2) $I = CE/P$ (emission intensity, in ton/ton) measures the CO₂ emissions per unit of cement production, representing the environmental impacts in the cement production;
- 3) $E = P/F$ (input efficiency, in ton/Chinese yuan) measures the cement production per unit of fixed capital formation, representing the technological advancements in the cement production;
- 4) F (fixed capital formation, in Chinese yuan) stands for the economic growth.

2.4 Data sources

2.4.1 Cement and clinker production

National Bureau of Statistics [NBS \(2018\)](#) provides the national and provincial cement production from 1996 to 2016. The [CCA \(2005-2014\)](#) publishes the cement production of the country from 1996 to 2013, clinker productions for the country from 2002 to 2013, and the cement/clinker for the provinces from 2005 to 2012. We compare the national and provincial aggregated cement production of NBS and CCA. We find that the difference between the two sources is within $\pm 1\%$ (as shown in Table S1). This

demonstrates that the quality of China's cement statistics is relatively high. In order to achieve more accurate CO₂ emission accounts for China's cement industry, we integrate both NBS and CCA's data and obtain the cement and clinker production data.

At the national level:

- 1) The cement production from 1996 to 2013 are collected from CCA, and the data from 2014 to 2016 are collected from NBS. The clinker production from 2002 to 2013 are collected from CCA.
- 2) We then calculate China's clinker-to-cement ratios from 2002 to 2013. The clinker-to-cement ratio is calculated as the clinker production divided by the cement production.
- 3) China's clinker-to-cement ratios from 2014 to 2016 are estimated based on a linear regression of historical ratios and the years (2002 to 2013); the ratios from 1996 to 2001 are assumed to be the same as those in 2002.
- 4) The clinker production from 1996 to 2001 and 2014 to 2016 are estimated as the product of clinker-to-cement ratios and corresponding cement production volume.

At the provincial level:

- 1) The provincial cement and clinker production from 2005 to 2012 are collected from CCA, and their cement production from 1996 to 2004 and 2013 to 2016 are collected from NBS.
- 2) The clinker-to-cement ratios of every province from 2005 to 2012 are calculated based on the provinces' cement and clinker production volume.
- 3) The clinker-to-cement ratios of every province from 2002 to 2004 and 2013 are estimated with the country's overall ratios and the provinces' ratios. We assume the provinces have the same change rates in clinker-to-cement ratio as those at national level. For example, the 2004 provincial ratios are estimated as $Province_Ratio_{2004} = \frac{National_Ratio_{2004}}{National_Ratio_{2005}} \times Province_Ratio_{2005}$. Similarly, the 2013 provincial ratios are estimated based on 2012 provincial ratios and 2012 to 2013 national ratios.
- 4) The clinker-to-cement ratios of every province from 1996 to 2001 and 2014 to 2016 are considered the same as those in 2002 and 2013, assuming the ratios remain unchanged.
- 5) The clinker production of every province from 1996 to 2004 and 2013 to 2016 are estimated as the product of clinker-to-cement ratios and corresponding cement production volume.

The cement and clinker productions, and the clinker-to-cement ratios of China (for both the nation and provinces) are presented in Table S2, Table S3, and Table S4, respectively.

2.4.2 Coal and electricity consumptions

The CCA (2005-2014) published the total energy consumption and coal consumption of each province from 2005 to 2012. We estimate the provinces' energy consumption for the remaining years assuming that the energy intensities (per unit of cement production energy consumption) remain the same. The electricity consumption is estimated as the total energy consumption minus the coal consumption, as coal and electricity are the primary energies used in China's cement industry (CCA 2005-2014).

The coal and electricity consumption in China and each province's cement industry are presented in Table S5 and Table S6, respectively.

2.4.3 Other indexes used in IDA

The fixed capital formations of China are collected from the official database of NBS (2018) and are consistent with the latest published statistical yearbooks in China. We convert all the economic data to the 2002 constant price to eliminate the effects of price fluctuation. The cement and clinker exports are collected from CCA (2005-2014). The construction output of each new-building type are also collected from CCA (2005-2014). The indexes are listed in Table S7.

All the data and results can be download freely from the "China Emission Accounts and Datasets (CEADs)" at <http://www.ceads.net> for re-use.

3 Results and discussion

3.1 Emissions from China's cement industry

Figure 2 presents the overall CO₂ emissions from China's cement industry. The total cement-related CO₂ emissions in 2016 reached 1,019 Mt, accounting for 11.06% of China's total CO₂ emissions (9,217 Mt in 2016) (Shan et al. 2018a). The total cement-related CO₂ emissions in China peaked in 2014, at 1,093 Mt.

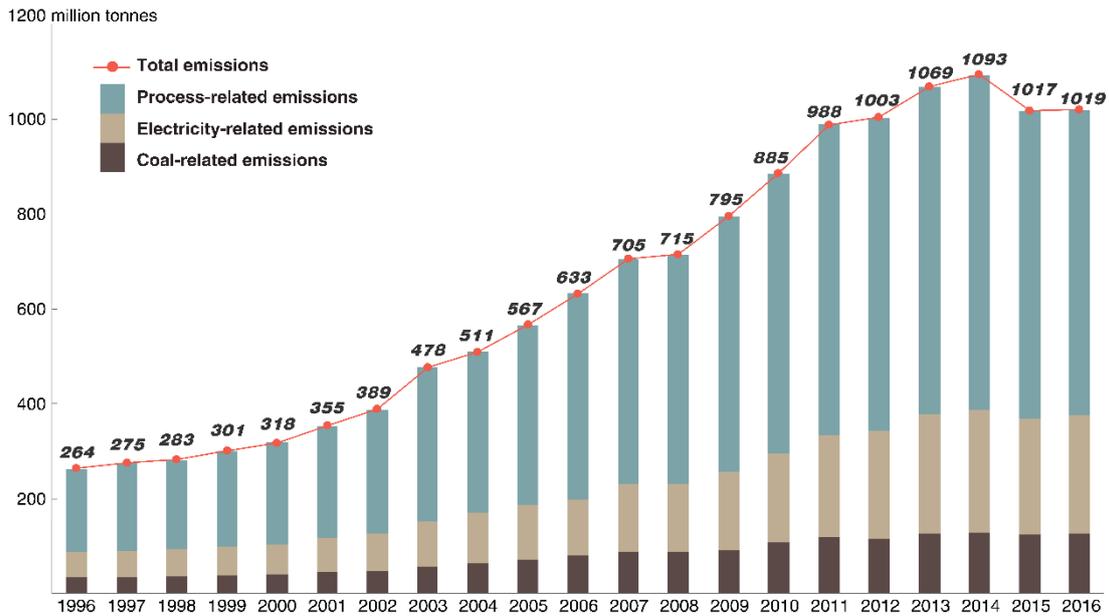


Figure 2 CO₂ emissions from China's cement industry

Before their peak in 2014, the cement-related emissions can be divided into three phases based on different growth characteristics. 1) Stable growth (1996 to 2002): The cement-related CO₂ emissions increased stably from 264 to 389 Mt during the period, with an average growth ratio of 6.6% per year. 2) Rapid growth (2002 to 2011): Stimulated by joining the WTO in 2002, China's cement production rapidly increased beginning in 2002. The cement-related CO₂ emissions surged as well. The average emission growth ratio reached 10.9% per year. The emission growth temporarily stagnated in 2008 due to the global financial crisis and the depressed cement market demand. 3) Slow growth (2011 to 2014): Beginning in 2012, the growth of cement-related emissions slowed (3.4% per year averagely) due to economic cooling.

The growth of cement-related CO₂ emissions was coupled with the trends of China's GDP growth (NBS 2018). This correlation can be explained by the relationships among the emissions, production/demand, and economic inputs in the cement industry: 1) the CO₂ emissions are calculated based on the clinker/cement production; 2) the cement is a building material that is not easy to preserve, and the plants normally produce cement based on the market demand or purchasing orders; and 3) cement demand is closely associated with the number of new-buildings, which is primarily stimulated by the country's fixed capital formation. In this way, it could be inferred that the cement-related CO₂ emissions were highly driven by the country's economic gains.

After the three increasing phases, China's cement-related emissions peaked in 2014. In 2015, the overall cement-related emissions appeared to decline for the first time. The emissions decreased by 76 Mt (or 7.5%) in one year. This decline was mainly

caused by a decrease in cement production. The total cement production decreased from 2,492 Mt in 2014 to 2,359 in 2015.

By investigating the detailed emission mix, we find that the process-related CO₂ emissions were the primary source of cement-related emissions in China, accounting for 63.1% in 2016. The coal- and electricity-related emissions accounted for the remaining 12.3% and 21.6%, respectively. The shares of emissions caused by different sources have changed slightly over the past 20 years. The process-related emissions decreased from 67.0% in 1996 to 63.1% in 2016 (with an average value of 66.1%), while the emissions induced by purchased electricity consumption increased from 20.2% in 1996 to 24.4% in 2016 (with an average value of 21.6%). The coal-related emissions remained stable at approximately 12.3% over the 20-year study period. As we use the same emission factor for emission accounts over years, the unchanged emission mix implies that the energy intensity (energy consumption per units of cement production) has not changed greatly, i.e., the energy efficiency and utilization technology in China’s cement production remained at the same level during the past 20 years.

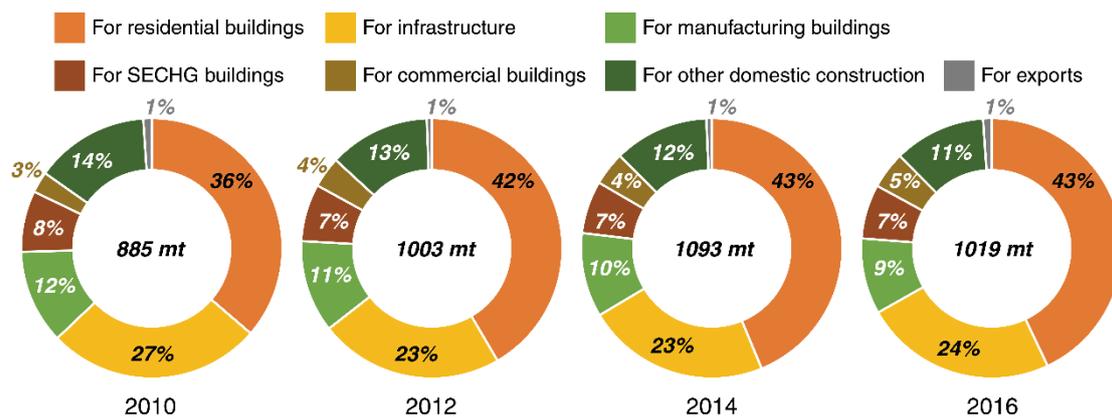


Figure 3 Cement-related CO₂ emissions by new-building types
 Note: SECHG is short for science-education-culture-health-government.

Figure 3 presents the CO₂ emissions induced by the cement consumption in each new-building type in selected study years. The results show that the emissions induced by cement produced for different new-building types remain stable over time, implying a relatively stable structure in China’s construction industry. Residential buildings are the major contributors to the cement-related emissions, accounting for approximately 40%, followed by infrastructure (approximately 25%) and the manufacturing plants (approximately 10%). Science-education-culture-health-government (SECHG) and commercial buildings emitted approximately 7% and 4% of total emissions, respectively. The emissions induced by the cement export accounted for only 1% of the total emissions due to the small export volume. Cement is expensive for long-distance transport due to its short shelf life and high density. It is much more cost-effective to self-produce cement. China exports less than 10 Mt of cement and clinker

to Africa and the USA/EU every year, a very small proportion of the 2,410 Mt cement and 1,295 Mt clinker produced.

This study also calculates the emission intensity of cement production. The emission intensity is defined as CO₂ emissions per unit of cement production. We find that the emission intensity of the cement production slightly decreased during the past two decades from 0.54 (in 1996) to 0.42 ton CO₂ per ton of cement production (in 2016).

The process-related, direct coal-related, and indirect electricity-related CO₂ emissions of cement industries at both the national and individual province levels are presented in Table S8, Table S9, and Table S10, respectively. The total cement-related CO₂ emissions are summarized in Table S11.

3.2 Regional differences in cement production

Despite the overall cement-related emissions having peaked in China, considering the regional differences in China, not all provinces have peaked their cement-related emissions yet. Certain provinces are still in the rapidly increasing stage. We classify the 31 provinces (excluding Taiwan, Hong Kong, and Macao due to a lack of data) into four groups at different peak stages, as shown in Figure 4.

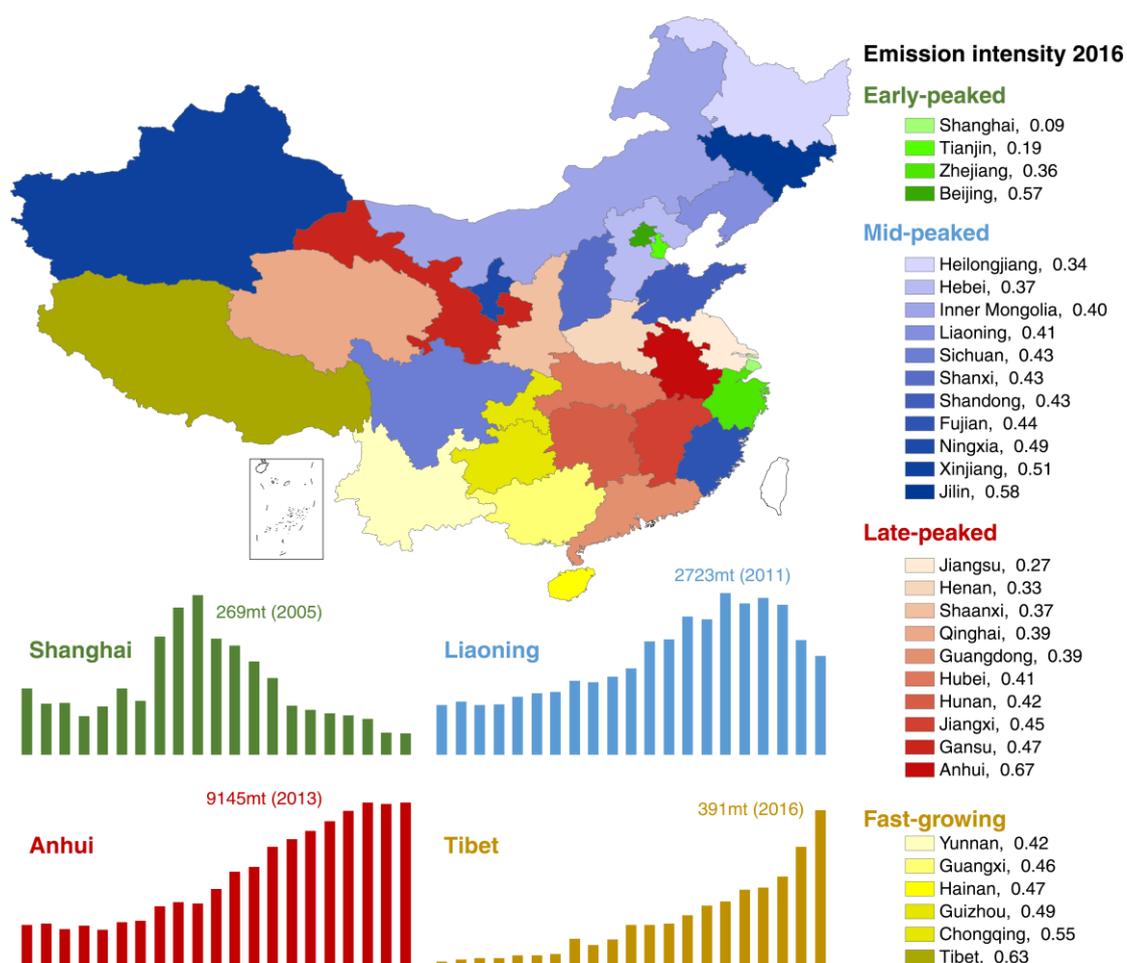


Figure 4 Provincial CO₂ emissions from the cement industry

Note: the number following the province name presents the emission intensity of the province in 2016. The early-peaked, mid-peaked, late-peaked, and fast-growing provinces are shown in green, blue, red, and yellow, respectively.

The early-peaked group includes the four most developed provinces in China: Beijing, Shanghai, Tianjin, and Zhejiang. These four provinces peaked their cement-related emissions around 2006. The early-peaked provinces have the lowest emission intensity (0.35 ton CO₂ per ton cement production) among the four province groups. The mid-peaked group includes 11 provinces, most of them located in northern and northeast China. These provinces peaked their cement-related emissions around 2012. The average emission intensity of these 11 mid-peaked provinces is 0.43 ton CO₂ per ton cement production. Another 10 provinces belong to the late-peaked group, which peaked their cement-related emissions around 2014. The fast-growing provinces are still continuously increasing their cement-related emissions. Yunnan, Guangxi, Hainan, Guizhou, Chongqing, and Tibet belong to this group. The fast-growing group, therefore, has the highest average emission intensity of 0.47 ton CO₂ per ton cement production.

3.3 Production capacity shifts among provinces

The provinces' different technical levels could affect their emission peak stages and emission intensities. The early-peaked provinces have advanced technologies, which consume less energy during the cement production. However, the discrepancies can be largely explained by the clinker trade among provinces, which can be shown from the clinker-to-cement ratios of the provinces.

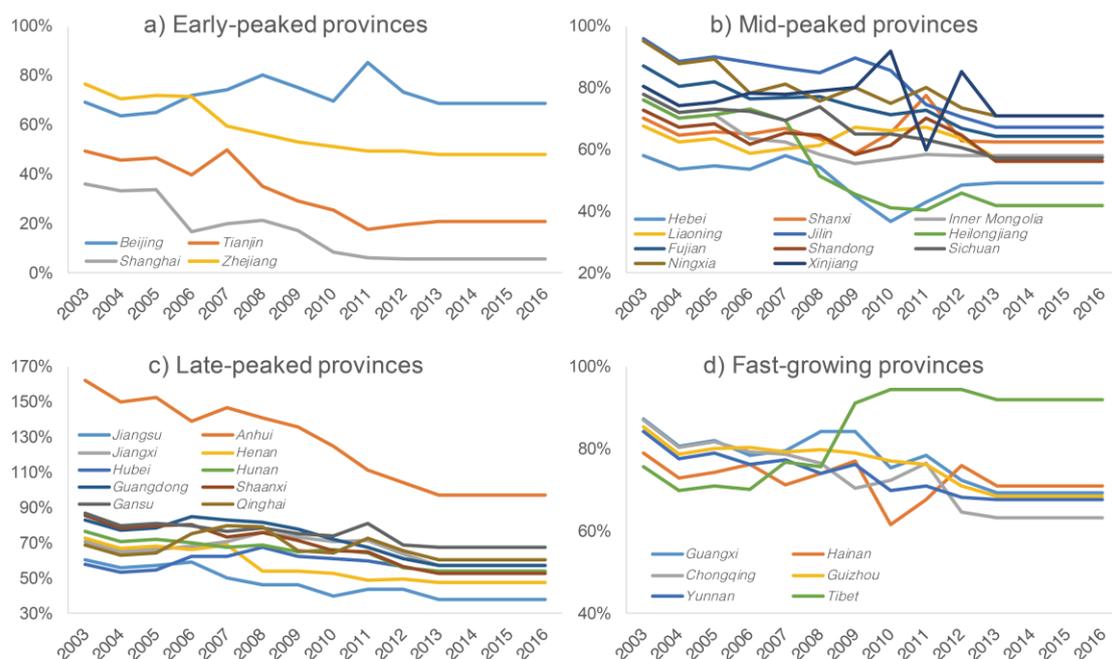


Figure 5 Clinker-to-cement ratio changes in provinces

We present the provinces' clinker-to-cement ratios in Figure 5. The overall national ratio decreased uniformly from 72.4% in 2002 to 53.7% in 2016 with an average value

of 65.0%. A higher ratio indicates a larger clinker production and a smaller cement production, whereas a smaller ratio indicates a smaller clinker production but a larger cement production.

Figure 5-a shows that the early-peaked provinces' clinker-to-cement ratios decreased markedly since 2006, especially Shanghai, Tianjin, and Zhejiang. The decline of the clinker-to-cement ratios implies that these provinces reduced their clinker production and imported clinker from other provinces to produce cement. As most of the CO₂ is emitted during the clinker production process ([Worrell et al. 2001](#)), a clinker-outsourcing policy effectively reduced the provinces' overall CO₂ emissions. Taking Shanghai as an example, its clinker-to-cement ratio decreased considerably from 33.9% (in 2005) to 16.6% (in 2006) and further to 8.5% (in 2010). Shanghai massively reduced its clinker production two times, in 2006 and 2010. Its clinker production reduced by 1.7 Mt (or 46.9%) and 0.8 Mt (or 57.5%), respectively, in the two years. However, the cement production of Shanghai remained stable at the same time (10.5 Mt in 2005, 11.3 Mt in 2006, and 6.7 Mt in 2010), which illustrates that Shanghai reduced its clinker production and imported the clinker from other regions. As a result, the emission intensity of Shanghai is the lowest among all the provinces, with 0.09 ton CO₂ per ton cement production.

Similarly, Figure 5-b shows that most of the mid-peaked provinces' clinker-to-cement ratios decreased from 2007 to 2010, such as Heilongjiang and Jilin. As for the late-peaked provinces (shown in Figure 5-c), there is no remarkable sudden drop in the clinker-to-cement ratio. Despite the ratio of Anhui decreasing continuously since 2003, this decrease is mainly caused by the increase in Anhui's cement production rather than the decrease in its clinker production. Anhui's clinker production kept increasing until 2014, which caused Anhui's cement-related emissions to peak at 9,145 Mt in 2014. Anhui is the largest clinker production base in China. In 2016, the clinker production of Anhui was 121 Mt, accounting for 9.3% of the national production. However, Anhui's cement production accounted for only 5.6% (or 136 Mt) of the national total production, illustrating that Anhui exports large amounts of clinker to other regions. The average clinker-to-cement ratio of Anhui was as high as 134.5% over the past 20 years, which is more than twice the national average level of 61.7%.

Figure 5-d presents the clinker-to-cement ratios of the six fast-growing provinces. We find that most of the provinces had a relatively stable ratio during the past 20 years. It is worth noting that the clinker-to-cement ratio of Tibet increased suddenly from 75.7% (in 2008) to 91.0% (in 2009), mainly due to the increase of Tibet's clinker production. Tibet enlarged its cement production capacity since 2000 and formed the integrated company "Huaxin Cement (Tibet)" in 2009 ([Liu 2017](#); [Shan et al. 2017](#)).

To summarize, certain developed provinces have closed or outsourced their clinker production to other less-developed regions in the past ten years. Such outsourcing

may be effective in reducing the developed provinces' emissions in the short term, but it may not be beneficial to the country's overall emissions reduction ([Shan et al.](#)). The developed provinces usually have more advanced technologies than those in less-developed regions, i.e., low emission intensities. Moving the production capacities from regions with advanced technologies to less-developed regions will, therefore, increase the country's overall emissions. Thus, greater attention should be paid to these key cement production provinces, such as Tibet, which will continue developing its cement production in the future ([Tibet autonomous region government 2011](#)), and Anhui, which is the largest cement production base in China.

3.4 Changes in the drivers of the cement-related CO₂ emissions in China

Figure 2 shows that the total cement-related CO₂ emissions started to grow rapidly since 2002 after China joining the WTO and then peaked in 2014. Understanding the changes in the drivers of the cement-related CO₂ emissions since 2002, especially before and after the peak point (2014) has great policy implications for emissions control in the cement industry. By employing the LMDI method, this study decomposes the changes in China' cement-related CO₂ emissions from 2002 to 2016 into four factors: the construction industry's structure, emission intensity, efficiency, and economic growth. The first factor, "construction industry's structure", is measured by three indicators: the emission proportion induced by cement produced for new residential buildings, for new infrastructural buildings, and for a new proportion of export and others. The results are shown in Table S7 and Figure 6.

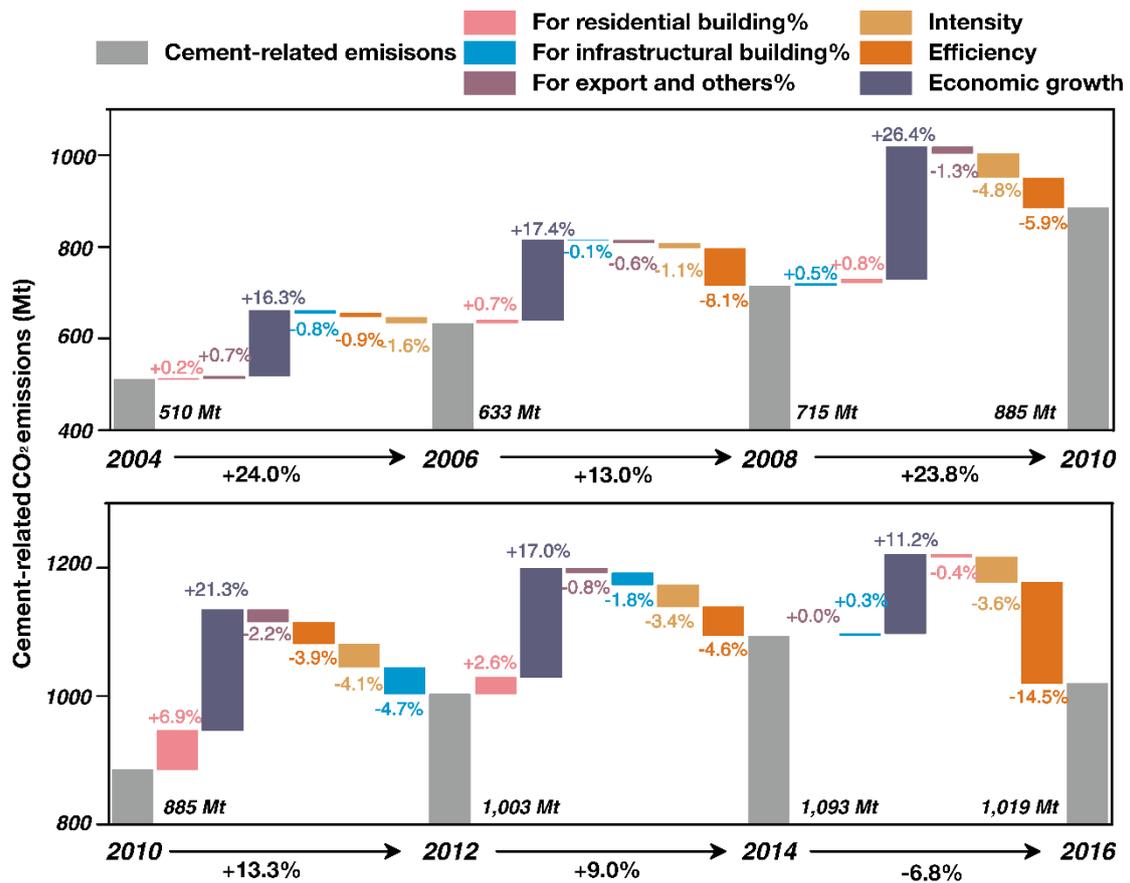


Figure 6 Driving forces of the changes in cement-related CO₂ emissions

Note: the residential buildings in the figure include both residential and commercial buildings; the infrastructural buildings in the figure include infrastructural, manufacturing, and SECHG buildings.

The results show that economic growth (fixed capital formation) was the major source of the cement-related emissions growth for a long time, especially during the period 2008 to 2010. The factor contributed 26.4% of the emissions growth during the period if other factors had remained constant. This growth was mainly stimulated by the “Economic Stimulus Plans” in China. The Chinese government invested four trillion Chinese yuan (approximately 586 billion US dollars) in response to the global financial crisis in 2007. The money was used to expand domestic demand. Local governments in China built several manufacturing plants and infrastructure at the time, such as power plants, cement plants, undergrounds, and high-speed railways. After 2010, the contribution of economic growth decreased slightly to 21.3% (2010 to 2012), 17.0% (2012 to 2014), and 11.2% (2014 to 2016) due to the gradually weakened stimulation of the “Economic Stimulus Plans”, but economic growth was still the primary power of the cement-related emission increase.

Emission intensity and efficiency were two major factors offsetting the growth of cement-related CO₂ emissions. Efficiency offset 14.5% of the emission growth from 2014 to 2016. The efficiency decreased by 14.3% (from 1.19 to 1.02 tons cement

production per 10 thousand yuan fixed capital formation). This change implies a technical improvement in cement production, as the plants produced more cement with less economic inputs. As for the intensity factor, the emission intensity of cement production decreased slightly during the past two decades from 0.54 (in 1996) to 0.42 ton CO₂ per ton cement production (in 2016), as discussed above. As a result, the emission intensity consistently offset 3.5% to 4.5% of the emissions' growth since 2008.

The changes in the construction industry's structure had significant influences on the related emissions changes since 2010. The proportion of newly constructed residential buildings first increased the cement-related emissions by 6.9% and 2.6% during the periods 2010 to 2012 and 2012 to 2014; then, it offset the emission growth by 0.4% during 2014 to 2016. This pattern may be affected by the changes in housing prices. According to the China Real Estate Index System (CREIS), China's housing prices increased by 19.0% from 2010 to 2014, then decreased by 1.1% in 2015 ([China Index Academy 2018](#)). The CREIS housing prices were calculated as the median housing price of 100+ Chinese cities. Considering the delayed action in the construction industry, the construction plan is normally made based on the previous year's housing price. Therefore, the negative contribution of the proportion of newly invested residential buildings in cement-related emissions may be influenced by the housing price decreasing in 2015.

In contrast, the proportion of newly invested infrastructural buildings has acted as a negative contributor to the cement-related emissions since 2010. This factor offset the emissions by 4.7% and 1.8% from 2010 to 2012 and 2012 to 2014, respectively. Stimulated by the "Economic Stimulus Plans", China has faced the problem of overcapacity since 2010 ([Yang and Yu 2011](#); [Yongding 2009](#)). The country then reduced its investments in infrastructure construction.

Cement exports had little influence on the emission changes, except for the period 2010 to 2012. The decrease in cement exports in 2012 was mainly caused by the shrinking of the USA/EU markets, which were affected by the global financial crisis ([Hefei Cement Research & Design Institute 2012](#)).

Comparing the contributions of each factor between 2012 to 2014 and 2014 to 2016, this study finds that the improvement in efficiency and the reduction in residential building construction were the two major reasons causing the cement-related CO₂ emissions' decrease since 2014.

4 Conclusions and policy implications

The cement industry is the primary source of process-related CO₂ emissions in China and worldwide. This industry contributed 11% of the total emissions in China. As the cement industry is regarded as one of the key energy-intensive manufacturing sectors,

greater attention should be paid to its sustainable production and emission control. Understanding the emission characteristics of China's cement industry and the drivers of the emission changes is an essential foundation for related policy making.

Our study first calculates the CO₂ emissions from the cement industries in China. The emissions include process-related emissions, direct emissions from fossil fuel combustion, and indirect emissions from purchased electricity. This study then calculates the cement-related emissions of 31 provinces in China and cluster the provinces into four groups based on different peak stages. Finally, the study calculates the drivers of the changes in cement-related CO₂ emissions with the LMDI decomposition analysis.

The emission accounts of China's cement industry finds that: 1) the total cement-related CO₂ emissions in China peaked in 2014 at 1,093 Mt; 2) the emissions growth was coupled with the trend in China's GDP growth, which implied that the emissions were highly driven by the country's economic gains; 3) the process-related emissions were the primary source of the cement-related emissions in China, accounting for 63.1% in 2016, and the emission mix of the process-related, direct, and indirect emissions has changed slightly over the past 20 years; and 4) the emissions induced by different new-building types also remained stable over the time, implying a relatively stable structure in China's construction industry. Residential buildings are the major contributor to the overall emissions, followed by infrastructure and manufacturing plants.

Then, our regional analysis of China's cement-related CO₂ emissions have significant implications to manage the cement industry and production capacities of every province; and optimize the whole country's cement production and utilization. Four developed provinces belong to the early-peaked group with the lowest emission intensities, whose cement-related emissions peaked around 2006, and 11 provinces are classified as the mid-peaked group, which peaked their emissions around 2012. Another 10 provinces that peaked their emissions around 2014 are grouped as the late-peaked provinces. The remaining six provinces are still increasing their cement-related emissions due to their increasing production capacities. The analysis of provincial clinker-to-cement ratio finds that the above discrepancies in provincial peak stages can be explained by the capacity outsourcing among provinces. The developed provinces have closed or outsourced their clinker production capacities to other less-developed regions. Despite the similar outsourcing can be found in other industries ([Shan et al. 2018b](#)), this is certainly not a sustainable development pathway. Such outsourcing may effectively reduce the developed provinces' emissions in the short term, but it may not be beneficial to the country's overall emissions reduction. Moving the production capacities from regions with advanced technologies to less-developed regions will increase the country's overall emissions. Stimulated by the "Economic Stimulus Plans" and other development strategies, China is still in the stage of

expanding infrastructure construction, especially in the currently backward cities. The central and local governments should co-ordinate the management of cement production in various provinces and cities, avoid overcapacity in the region, and large-scale unnecessary cement production outsourcing and shift among provinces in China. Also, backward areas should learn from developed regions to improve their cement production efficiency and reduce unit output emissions.

The decomposition analysis of the cement-related CO₂ emissions illustrates the driving forces hidden behind the emission changes. Economic growth was the major source of the growth in cement-related emissions for a long time, especially in the period 2008-2010. The emissions intensity and efficiency were two major factors offsetting the growth of cement-related CO₂ emissions. Since 2014, the efficiency played a more importation role in reducing the emissions, which lead to the decoupling of economic growth and cement-related CO₂ emissions (Wu et al. 2018). As more and more studies have found that China is entering a phase of decoupling economic growth from carbon emissions, efficiency gains can further reduce the emissions in the future. For example, the cement plants may consider using a cleaner energy mix to reduce the emission intensity or use low-cost energies (non-recycled plastics and paper as alternative fuels) to improve the efficiency (Huh et al. 2017; Bourtsalas et al. 2018). These low-cost energies should be used in a clean way. Cleaner production techniques should also be developed and applied to the cement plants in China, such as the “calcium looping CO₂ capture” (Schakel et al. 2018).

Apart from the economic driver, the changes in the structure of the construction industry also had significant influences on the related emissions changes since 2010. The proportion of new residential buildings became a negative contributor to emissions growth since 2014, mainly influenced by the housing price fluctuation in China. However, the change in house prices is highly sensitive. The governments should plan the construction industry and new-building construction to eliminate the erratic effects of housing prices on cement production. In this way, the overcapacity and waste of cement production can be avoided.

In the future, we will conduct a more detailed investigation of each province' cement industry to analyze the impact of the cement-related CO₂ emissions. Also, further study could use life-cycle assessment and carbon footprint analysis to provide a more detailed evaluation of the emission performance of cement production and consumption. The LCA and carbon footprint analysis can allocate the cement-related environmental performance to the end use in the construction industry (Fořt and Černý 2018). Then, the emissions from the cement industry can be controlled from both the production and demand perspectives.

Supplemental Figures and Tables

Index Decomposition Analysis (IDA) – LMDI

Figure

Figure S1 CO₂ emissions from China's national communications on climate change

Tables

Table S1 Comparisons of cement production of NBS and CCA

Table S2 Cement production of China and its provinces

Table S3 Clinker production of China and its provinces

Table S4 Clinker-to-cement ratios of China and its provinces

Table S5 Coal consumption from the cement industry of China and its provinces

Table S6 Electricity consumption from the cement industry of China and its provinces

Table S7 Socioeconomic indexes for IDA

Table S8 Process-related CO₂ emissions from the cement industry of China and its provinces

Table S9 Coal-related CO₂ emissions from the cement industry of China and its provinces

Table S10 Electricity-related CO₂ emissions from the cement industry of China and its provinces

Table S11 Total CO₂ emissions from the cement industry of China and its provinces

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The authors have no conflict of interest to declare.

All the data and results can be download freely from China Emission Accounts and Datasets (CEADs) at <http://www.ceads.net>.

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