Plant-level real-time monitoring data reveal substantial abatement potential of air pollution and CO₂ in China’s cement sector

Graphical abstract

Highlights

- We build an emissions dataset for China’s cement plants using real monitoring data
- Air pollutants dropped by >30% under the 2015 emissions standards during 2014–2018
- CO₂ increased by 5% in the absence of CO₂ regulation during 2014–2018
- Pollutants and CO₂ will decline largely if realizing clean air and climate targets

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In brief

China deployed strict regulations in 2015 to abate air pollution generated from cement production, but the effectiveness of these regulations at the plant level has not been assessed. We examine the effectiveness of the regulations by developing an hourly based plant-level 2014–2018 dataset of air pollutants (PM, SO₂, NOₓ) and CO₂. We find that air pollutant emissions have decreased, but CO₂ emissions have not. Further analysis shows that plant operation and technology improvements will likely lead to further emission reductions in line with China’s 2020 ultralow emission standards and carbon neutrality targets.

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Plant-level real-time monitoring data reveal substantial abatement potential of air pollution and CO₂ in China’s cement sector

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SUMMARY

China is the world’s greatest cement producer, generating significant air pollution and CO₂ emissions. To combat these impacts, China introduced stricter air pollution standards for the cement industry in 2015, yet no plant-level analysis exists to determine their effectiveness. To analyze the impacts of emission regulations, we coupled 2014–2018 smokestack-level real-time observations with plant-specific information and constructed an hourly based dataset of air pollutants (particulate matter [PM], sulfur dioxide [SO₂], nitrogen oxide [NOₓ]) and CO₂ emissions. Our analysis shows that regulations introduced in 2015 led to significant reductions in air pollution emissions by 2018, a lack of CO₂-specific policies led to a 5% increase in CO₂ emissions. However, analysis shows that China’s 2060 carbon-neutral goal, together with new ultralow standards introduced in 2020, are likely to lead to further improvements over the coming years.

INTRODUCTION

The global cement industry is the third largest source of industrial air pollution, including particulate matter (PM), sulfur dioxide (SO₂), and nitrogen oxide (NOₓ).1 and it is responsible for 8% of global CO₂ emissions.2 As the world’s largest cement producer, China produces the bulk (54.3%–59.3% for 2010–2019) of the world’s cement.3 At the national level, the Chinese
cement industry represented 16.4%–30.0%, 4.0%–7.1%, and 6.0%–14.7% of PM, SO\(_2\), and NO\(_x\) emissions, respectively, between 2010 and 2015 and accounted for 10.5% of CO\(_2\) emissions in 2015.\(^9,10\)

Because many regions were suffering from severe haze pollution, since 2013, China has imposed progressively more stringent policies to control emissions of air pollutants (particularly PM, SO\(_2\), and NO\(_x\))\(^11,14\), among which the most important is the emissions standards\(^13\) policy that defines the maximum allowable hourly concentrations of pollutants in emitted flue gas (Note S1).\(^15\) In the case of cement industry emissions, the Chinese government passed and issued new emissions standards on plant-smokestack concentrations in December 2013,\(^16\) which reduced the previous (2004) standards by as much as 40% and 50% for PM and NO\(_x\), respectively,\(^16,17\) and began to be enforced in July 2015. Moreover, a range of even tougher local standards were designed and implemented in the provinces of Guangdong, Guizhou, Shandong, Hebei, Chongqing, Fujian, and Beijing (ranked here by cement production) between 2012 and 2016, reducing the standards there to values as low as 50%, 10%, and 50% of the new national limits for PM, SO\(_2\), and NO\(_x\) respectively (Tables S1–S3). However, in 2020, China began promulgating an even more stringent policy in the provinces of Hebei, Henan, Anhui, Jiangsu, Hainan, and Sichuan (Table S3), namely, “ultralow” emissions (ULE) standards.\(^18\) Indeed, such ULE standards go well beyond both the 2015 standards (by 66.7%, 75.0%–85.0%, and 50.0%–87.5% for PM, SO\(_2\), and NO\(_x\), respectively) and the prevailing standards in other developed countries (e.g., as much as 50.0%, 92.5%, and 93.8% lower, respectively, than current European Union [EU] standards\(^19\); Tables S1–S4).

To monitor compliance with PM, SO\(_2\), and NO\(_x\) emissions standards, in 2007, China began deploying a national continuous emissions monitoring system (CEMS) to directly monitor smokestack-level, real-time PM, SO\(_2\), and NO\(_x\) concentrations (the policy targets). By 2018, this CEMS network covered 870 cement plants, together accounting for 74.9% of Chinese cement plants and 87.6% of national clinker production between 2014 and 2018 (Figures 1, S1, and S2; Table S5). Although a few studies have used these high-spatiotemporal-resolution CEMS data to analyze PM, SO\(_2\), and NO\(_x\) emissions from power-generating plants\(^20\) and iron-making and steelmaking plants\(^21\) the cement industry data have not yet been exploited, despite the industry’s considerable emissions. Without CEMS measurements, existing studies resorted to using average emissions factors in estimating cement-related emissions and were thus subject to the following three limitations.\(^9,22–24\) First, such average emissions factors are estimated based on limited numbers of typical facilities and technologies and are specified using many assumptions and sensitive parameters (regarding operations, technologies, fuels, raw materials, and so on), which, in turn, cause high uncertainties in emissions estimation.\(^25\) Fortunately, introducing the real CEMS monitoring data can provide a direct approach for estimating emissions factors and thus avoid such uncertainties associated with average emissions factors.\(^9,22–24\) Second, the average emissions factors used in previous research were usually invariable, which contradicts the reality that emissions factors vary greatly with fuel composition, operations, technologies, and so on.\(^20\) In comparison, the emissions factors estimated based on the facility-level, hourly CEMS monitoring data can reflect the heterogeneities across facilities and dynamics over periods. Third, although the latest available average emissions factors were computed as of 2010,\(^9,22–24\) introducing updated CEMS data (particularly after 2015) can support exploring the effect of the new 2015 standards and the subsequent technological renovations and operational changes.

Although cement production also generates a significant amount of CO\(_2\) emissions, China has not implemented CO\(_2\) regulations in cement plants in the past. On September 22, 2020, China made an ambitious pledge to have CO\(_2\) emissions peak before 2030 and achieve carbon neutrality by 2060.\(^26\) Key to realizing these goals, a number of rules and regulations are being considered to help achieve the carbon-neutrality goal,\(^27,28\) many of which aim to target cement plants, a major CO\(_2\) source.\(^27\) Ensuring the full implementation of such mitigation policies requires strict oversight, and in May 2021, the China Ministry of Ecology and Environment (MEE) announced that CO\(_2\) emissions should be included in the environmental impact assessment soon,\(^29\) which would expand the CEMS network to include CO\(_2\), as the United States does.\(^30\) However, existing knowledge on how the 2015 air pollution standards have affected the performance of air quality, as well as CO\(_2\) emissions in China’s cement plants, remains limited. In addition, whether the 2020 ULE standards and the 2060 carbon-neutrality-associated CO\(_2\) reduction targets could generate co-benefits in China’s cement plants is far from clear.

Here we evaluate the impacts of 2015 pollution standards on air pollutants and CO\(_2\) emissions in China’s cement plants and consider the potential co-benefits of 2020 ULE standards and 2060 carbon neutrality by constructing a new dataset that comprises air pollutants and CO\(_2\) emissions, which we name China Emissions Accounts for Cement plants (CEAC). The dataset couples hourly CEMS-derived measurements of PM, SO\(_2\), and NO\(_x\) smokestack concentrations (for 75% of China’s cement plants between 2014 and 2018) with facility-specific data on production, energy consumption, raw material inputs, operations, technologies, and other individual features. Our CEAC dataset is a unique and accurate database constructed using real-time monitoring (CEMS) data, while existing inventories\(^5,28–30\) report to using average emissions factors in emissions estimation. Using the CEAC dataset, we first evaluate the impacts of 2015 air pollution standards by conducting an ex post analysis of the trends in emissions and emissions intensities for PM, SO\(_2\), NO\(_x\), and CO\(_2\) for the period 2014–2018. We find that the air pollutants, i.e., PM, SO\(_2\), and NO\(_x\), declined by 50.3%, 43.6%, and 34.2%, respectively. About 9.4% of cement plants have already met the 2020 ULE standards by the end of 2018. However, in the absence of CO\(_2\) regulation, these cement plants generated 5% more CO\(_2\) emissions during 2014–2018. We then attempt to test the potential co-benefits of the 2020 ULE standards (Table S3) and the CO\(_2\) reduction targets according to China’s carbon-neutrality goals\(^31\) by specifying mitigation measures and technologies. The results show that these cement plants could have made 68.8%, 66.1%, and 82.2% reduction of PM, SO\(_2\), and NO\(_x\), respectively, and could also have reduced CO\(_2\) by 62.0%. We also validate our results by comparing them with previous estimates\(^5,22–24,32\) and systematically analyzing the uncertainties. These results provide evidence of the potential...
co-benefits by simultaneously implementing air pollution control and climate targets in China’s cement industry.

RESULTS

Response to strengthened pollution standards
The CEMS monitoring data reveal a pronounced decline in the PM, SO\textsubscript{2}, and NO\textsubscript{X} concentrations emitted from Chinese cement plants after 2013 (Figures 1B–1D; Table S6). Between 2014 and 2018, the daily PM, SO\textsubscript{2}, and NO\textsubscript{X} concentrations steadily decreased by 1.9%, 1.7%, and 1.0% per month, respectively. Even before the implementation deadline of the new standards in July 2015, PM and NO\textsubscript{X} concentrations had been declining at rates of 3.0% and 1.8% per month, respectively (97.9% and 150.5% greater declining rates, respectively, than afterward), while SO\textsubscript{2} concentrations’ declining rates (1.6% per month) were otherwise 8.2% smaller before the deadline than after. Moreover, the SO\textsubscript{2} concentrations had a wider distribution, with coefficient of variation (CV; defined by standard deviation [SD] divided by mean) being 154.9% (versus 95.6% and 32.0% for PM and NO\textsubscript{X}, respectively) between 2014 and 2018. Such larger reductions and more convergent observations for PM and NO\textsubscript{X} reflect the fact that more plants were out of compliance with the impending reduced PM and NO\textsubscript{X} standards when these standards were announced in late December 2013 (37.8% and 50.6% of plants were out of compliance, respectively, in January 2014) than the non-targeted (or unchanged) SO\textsubscript{2} standards (to which only 3.7% of plants did not comply). Many plants, therefore, had to rapidly and substantially reduce their PM and NO\textsubscript{X} emissions to meet these new standards before they entered into force in July 2015. In July 2015, PM, SO\textsubscript{2}, and NO\textsubscript{X} concentrations dropped sharply (by 13.8%, 14.4%, and 10.0%, respectively), but these extraordinarily high rates of decrease were short-lived and returned to a moderate and steady level thereafter (at average decrease rates of 1.5%, 1.6%, and 1.8%, respectively).
Table 1. Effect of individual and regional features on smokestack concentrations

| Dependent variables | Logged smokestack concentrations in 2018 (mg m⁻³) |
|---------------------|-----------------------------------------------|
|                     | PM | SO₂ | NOₓ |
| Previous levels     |    |     |     |
| Logged mean annual concentrations 2014–2017 (mg m⁻³) | 0.344*** (0.035) | 0.779*** (0.026) | 0.678*** (0.034) |
| Plant characteristics|    |     |     |
| Removal efficiency of control equipment (%) | –0.013*** (0.002) | –0.009*** (0.001) |
| Ash content in coal (%) | 0.013*** (0.002) |     |     |
| Sulfur content in coal (%) |     | 0.141*** (0.046) |     |
| Volatile content in coal (%) |     |     | –0.001 (0.001) |
| Super-large scale (≥7,000 tons of daily output; 1 = yes) | –0.002 (0.066) | 0.110 (0.092) | 0.051 (0.029) |
| Provincial attributes |    |     |     |
| Logged output of nonmetallic mineral products (N trillion) | –0.068*** (0.013) | 0.007 (0.025) | –0.074*** (0.008) |
| Stricter local standards enforced (1 = yes) | –0.128*** (0.036) | –0.112* (0.064) | –0.120*** (0.024) |
| Constant            | 2.092*** (0.231) | 0.146 (0.100) | 2.277*** (0.251) |
| N                   | 683 | 674 | 676 |
| R²                  | 0.341 | 0.583 | 0.591 |
| F statistic         | 58.221*** | 186.855*** | 160.840*** |

Standard errors are shown in parentheses; *p < 0.1, ***p < 0.01.

1.7%, and 0.7% per month, respectively). Interestingly, regular temporary increases in PM concentrations are observed at the end of winter and the beginning of spring (Figure 1A), which might be the result of the startup of many facilities when increased production of cemented concrete was in high demand (Table S7).

Because pollutant concentrations had been declining for many months prior to July 2015, the overall compliance of Chinese cement plants did not change extensively when these new standards came into force; the share of plants in compliance with the new (2015) standards increased only by 3.0% (Figure S3). The previous levels of compliance with prevailing historical pollution levels in 2014–2017 (reflecting individual heterogeneities among facilities; Table 1), the enacting of abatement measures, plant characteristics such as production scale, facility age, and firm organization showed few remarkable improvements among all regions between 2014 and 2018 (26.3%). This pattern holds across all production scales. In 2014, only 67.5% of small facilities (producing <2,000 tons of clinker per day) complied with the impending standards (compared with 77.8% for large facilities producing ≥4,000 tons of clinker per day); however, compliance among these small facilities improved the most in 2014–2018 (by 46.6% compared with improvement of 27.1% among large facilities; Figure S5). Similarly, the production process of kiln tails had a much lower compliance rate (75.1%) than kiln heads in 2014 (83.3%), but smokestack pollutant concentrations decreased much more for the tails between 2014 and 2018 (by 50.6% compared with 43.9% for kiln heads; Figure S6). By the end of 2018, compliance rates reached similarly high levels across regions, scales, and processes (all >99%; Figures S4–S6).

Our analyses reveal that several other plant characteristics and provincial attributes also influence smokestack concentrations of Chinese cement plants. Although plants’ smokestack concentrations in 2018 were strongly related to each plant’s historical pollution levels in 2014–2017 (reflecting individual heterogeneities among facilities; Table 1), the enacting of abatement measures in place also reduced pollutant concentrations. Most importantly, smokestack PM and SO₂ concentrations were substantially reduced at plants with updated pollution-control equipment, which was installed on 99.7% and 95.5% of production lines in 2018, respectively (compared with 77.8% for large facilities producing ≥4,000 tons of clinker per day).

Another key measure for reducing smokestack concentrations is improving fuel quality. For example, PM and SO₂ concentrations were lower at plants that used coal with lower ash and sulfur contents, respectively, in 2018. With the help of these abatement measures, plant characteristics such as production scale, facility age, and firm organization showed few remarkable improvements among all regions between 2014 and 2018 (26.3%). This pattern holds across all production scales. In 2014, only 67.5% of small facilities (producing <2,000 tons of clinker per day) complied with the impending standards (compared with 77.8% for large facilities producing ≥4,000 tons of clinker per day); however, compliance among these small facilities improved the most in 2014–2018 (by 46.6% compared with improvement of 27.1% among large facilities; Figure S5). Similarly, the production process of kiln tails had a much lower compliance rate (75.1%) than kiln heads in 2014 (83.3%), but smokestack pollutant concentrations decreased much more for the tails between 2014 and 2018 (by 50.6% compared with 43.9% for kiln heads; Figure S6). By the end of 2018, compliance rates reached similarly high levels across regions, scales, and processes (all >99%; Figures S4–S6).
influences on smokestack pollutant concentrations (see t tests in Table S7). Moreover, compliance tended to be higher in provinces with greater overall outputs of clinker and cement, which commonly corresponds to a more highly developed cement industry. For example, in the eastern region of China, where output of nonmetal mineral products was greatest (¥2.40 trillion in 2015), 100.0% and 97.3% of production lines were equipped with PM and NOX control technologies, respectively, in 2018, and thus the smokestack concentrations of these pollutants were well controlled at low levels (Figure S4). Moreover, our results show that plants in provinces with local standards (generally much stricter than the national standards) had lower smokestack concentrations—20.0%, 0.7%, and 33.4% lower than the other provinces for PM, SO2, and NOX, respectively, in 2018. Concomitant with the observed reductions in smokestack concentrations, the emissions intensities of PM, SO2, and NOX (i.e., grams of pollution emitted per kilogram of clinker) in cement plants also steadily and substantially declined between 2014 and 2018, by monthly decreasing rates of 1.7%, 1.3%, and 1.0%, respectively (dotted curves in Figures 2A–2C). As with smokestack concentrations, these reductions in emissions intensities were particularly striking for the regions, scales, and processes that previously had the greatest pollution: the average emissions intensities across air pollutants dropped by 51.2% in the northwest region, by 49.2% among small-scale facilities, and by 47.3% for kiln tails, all larger than the overall decreasing rate of 45.5%. These disproportionate reductions also served to narrow the disparity among facilities: monthly standard deviations in PM, SO2, and NOX emissions intensities decreased by 37.2%, 50.3%, and 41.0%, respectively, from 2014 to 2018. In contrast, because policies regulating CO2 emissions from cement plants are not widespread, plants’ CO2 emissions intensities were virtually unchanged from 2014 to 2018 (decreasing by an average of <0.01% to 0.78 kg CO2 per kilogram of clinker; Figure 2D).

Future mitigation of air pollutants

Although PM, SO2, and NOX cement plant emissions have reduced since the introduction of air pollution standards in both 2013 and 2015, emissions remain problematically high. It is hoped that the introduction of ULE in 2020 will significantly curtail remaining emissions, but this remains untested. Here we predict the impact ULE standards will have on emissions and the most optimal mitigation measures and technologies. Assuming that all Chinese cement facilities meet the (ULE) standards implemented in Hebei Province on May 1, 2020 (currently the most stringent standards worldwide) and keep production at the 2018 levels or are retired for small or outdated facilities
As part of the country’s targeted energy structure transition, the Chinese government is encouraging a shift to fuels that are cleaner than coal. However, almost all (94.3%) Chinese cement plants relied on only coal in 2018. Therefore, shifting to cleaner fuels represents a great opportunity for future mitigation. Indeed, we estimate that introducing and increasing cleaner fuels donated 99.4%, 99.8%, and 99.7% of potential reductions in PM, SO2, and NOX, respectively, under the ULE standards policy (green bars in Figures 3A–3C). For example, natural gas was employed in only 1.3% of plants in 2018 (covering 1.2% of production lines; Table S9) and in none of the production lines that did not meet ULE standards (versus 2.2%, 1.3%, and 2.4% of the production lines that complied with the ULE PM, SO2, and NOX standards, respectively). Therefore, introducing cleaner fuels will be a productive means for these ULE-noncompliant plants to achieve compliance and reduce their air pollutants, providing the potential to reduce PM, SO2, and NOX emissions by 41.9%, 37.1%, and 66.6%, respectively (associated with 98.7%, 98.9%, and 99.2% of potential reductions, respectively; dark green bars in Figures 3A–3C).

There is also substantial potential to improve energy efficiency to further reduce PM, SO2, and NOX emissions, associated with 87.9%, 92.2%, and 89.1% of abatement potentials, respectively, under the ULE scenario (orange bars in Figures 3A–3C). Although the overall energy efficiency exhibited no significant change between 2016 and 2018 (p = 0.19; Table S7), it has been proven that future improvements in energy efficiency can be achieved through a series of economically feasible measures, such as technological upgrading (particularly for pre-calciner kilns, multi-channel combustion technologies, and heat recovery systems). In 2018, the plants that met ULE standards had higher energy efficiencies than ULE noncompliers (averaging 0.12 versus 0.14 kg coal per kilogram of clinker; p < 0.01; Table S7), and the majority (84.2%) of facilities have lower energy efficiencies than the mean of ULE compliers. This finding suggests that enhancing the energy efficiencies of ULE noncompliers to the mean level of ULE compliers could reduce PM, SO2, and NOX emissions by an additional 37.3%, 34.5%, and 59.9%, respectively.

Last, the Chinese government is strongly encouraging and will in some cases require the phase-out of small or outdated cement plants under a range of clean air policies and action plans. Between 2015 and 2018, 17.2% of production lines (accounting for 8.1% of clinker production) were retired, which contributed 18.6%, 18.3%, and 27.4% of the total reductions in PM, SO2, and NOX, respectively, over the same period. These closed facilities were mostly small scale (77.0% of the retired facilities produced <2,000 tons of clinker per day, representing 13.2% of Chinese facilities but only 2.6% of overall production in 2015), mostly lacked pollution-control technologies (e.g., just 29.0% of the retired facilities were equipped with NOX control equipment, compared with 72.3% for unretired facilities), and were much older (7.6% of the retired facilities were >30 years old, compared with 0.9% for the unretired facilities). Shutting down these facilities thus reduced air pollution much more than clinker production (181.7% more), while avoiding mounting costs for...
Figure 3. Potential emissions reductions from Chinese cement plants

(A–C) Potential air pollution emissions reductions if ULE-noncompliant plants implemented the operations and technologies of plants that were ULE compliant in 2018: (A) PM, (B) SO₂, and (C) NOₓ.

(D) Estimated reductions in CO₂ emissions if all plants implemented emissions intensity improvements in line with the carbon-neutral (CN) levels defined by the European Cement Association (2020). Notably, a facility can apply multiple abatement measures, such that the estimated reductions might overlap across measures and the sum of the associated proportions might be more than 100% (see “estimation of future emissions reductions” in experimental procedures).

(E–P) Estimated reductions in (E, I, and M) PM, (F, J, and N) SO₂, (G, K, and O) NOₓ, and (H, L, and P) CO₂ emissions from facilities grouped by (E–H) region, (I–L) scale, and (M–P) process. The black bars show the total emissions in 2018 and in the scenario that all facilities meet the ULE or CN levels and production remains at 2018 levels, and the bright-colored bars represent the emissions reductions from the associated facility groups.
facility maintenance and technological renovations. Meeting ULE standards industry-wide in a cost-effective way will entail further retirements of small and outdated facilities; phasing out all facilities that produce <2,000 tons of clinker per day and are >30 years old (30.6% of production lines and 10.0% of production as of 2018) will reduce PM, SO₂, and NOₓ emissions by 11.6%, 8.3%, and 9.4%, respectively (i.e., 27.3%, 22.3%, and 14.1% of total potential reductions, respectively; purple bars in Figures 3A–3C).

Because the greatest potential reductions correspond to the most-polluting plants in operation, the southwestern region of China (accounting for 21.1%, 21.1%, and 25.1% of cement facilities, clinker production, and air pollutants, respectively, in 2018) can contribute the largest potential reductions in PM, SO₂, and NOₓ (27.3%, 34.5%, and 23.2%, respectively; purple bars in Figures 3E–3G). In comparison, the plants in the eastern region, even accounting for the most cement facilities, clinker production, and air pollutants (24.7%, 30.9%, and 31.1%, respectively), are larger than southwestern plants (producing 811.2 more tons of clinker per day for a facility) and have better control technologies and fuels; thus, their potential future pollution reductions are not as large as expected (orange bars in Figures 3E–3G). For example, in 2018, PM, SO₂, and NOₓ pollution-control technologies were installed at 0.3%, 46.9%, and 0.5% fewer southwestern plants than eastern plants, respectively, and were less advanced with 0.1%, 12.8%, and 4.9% lower removal efficiencies, respectively (p < 0.01; Table S7). Fuels used in southwestern plants were also of lower quality, with 24.7% higher ash, 104.7% higher sulfur, and 21.8% lower volatile contents than eastern plants (p < 0.01). In addition, natural gas, a cleaner fuel, was introduced at 70.7% fewer southwestern facilities than in the eastern region. As a result of these systematic differences, the emissions intensities of southwestern plants in 2018 averaged 0.06, 0.07, and 0.64 g of PM, SO₂, and NOₓ, respectively, per kilogram of clinker (compared with 0.05, 0.06, and 0.61 g per kilogram of clinker in the eastern region), and the southwestern region had the largest proportion of noncompliant facilities (45.9% compared with 9.9% in the eastern region). In contrast, potential pollution reductions identified among facilities of different scales correspond quite closely to the shares of recent emissions: large-scale facilities, which produced 46.8% of clinker and emitted 44.8%, 49.0%, and 47.2% of overall PM, SO₂, and NOₓ, respectively, in 2018 also account for the largest shares of potential reductions under the ULE scenario (35.1%, 43.8%, and 44.8%, respectively; blue bars in Figures 3I–3K). The potential to update NOₓ controls is striking, particularly for kiln tails (Figures 3C and 3O), because not only NOₓ removal efficiencies (averaging 64.0%) were significantly lower than PM and SO₂ controls (98.7% and 77.4%, respectively; p < 0.01; Table S7) but also a considerable part of NOₓ emissions are from thermal NOₓ formation. This suggests that such an effort will reduce NOₓ emissions far more than updating PM (300.4% more) and SO₂ control equipment (824.7%).

The potential of CO₂ mitigation

Given that roughly two-thirds of CO₂ emissions from cement production are related to the calcination process, the goal of eliminating CO₂ emissions from the industry is challenging and may entail substantial changes to production lines. According to recent analyses, promising CO₂ abatement measures include installing and updating carbon capture and storage (CCS) technologies, using decarbonated raw materials, using carbon-neutral fuels (e.g., biomass), and improving thermal efficiency. Very few Chinese plants used any of these measures in 2018: almost no production lines had deployed CCS technologies, 80.5% of plants used limestone as raw material, only 0.5% of plants used biomass, and overall thermal efficiency across the fleet changed little in 2016–2018 (e.g., coal use per unit of clinker production decreased by 0.1% over this period). If small and outdated plants are closed to achieve ULE standards and the four CO₂ abatement measures introduced above are employed to achieve carbon-neutral levels, we estimate that CO₂ emissions intensities will decrease by 30.9% (to an average of 0.54 kg per kilogram of clinker), and that cement-related CO₂ emissions in China will decline by 37.8% (to 0.72 Gt at the 2018 level of production; see “estimation of future emissions reductions” in experimental procedures). Of these five abatement strategies, nearly half (48.0%) of potential reductions come from CCS (blue bar in Figure 3D), and these reductions will be concentrated in the central and southern regions (which produced 27.4% of cement-related CO₂ emissions in 2018 and will represent 26.7% of potential CO₂ reduction; Figure 3H) and especially in the clinker production process at large-scale facilities (Figures 3L and 3P).

In addition, we perform an ex ante assessment of potential mitigation assuming that all cement facilities achieve both the ULE and carbon-neutral levels by 2060 (the policy deadline for China’s carbon neutrality), finding a large co-benefit of these recently promulgated clean air and climate policies (Figure 4; see “estimation of future emissions reductions” in experimental procedures). In particular, the cement-related PM, SO₂, NOₓ, and CO₂ emissions are estimated to further decline by 68.8%, 66.1%, 82.2%, and 62.0%, respectively, from 2018 to 2060 (Figure 4, black bars). Along this carbon-neutral mitigation pathway, although some technologies serve either air pollution reductions (e.g., pollution controls; Figure 4, blue bars) or CO₂ reductions (e.g., CCS; Figure 4, aquamarine bars), the abatement measures of fuel switching (especially from coal to natural gas or biomass; Figure 4, green bars) improved energy efficiencies (Figure 4, orange bars), and phasing out inefficient facilities (Figure 4, purple bars) demonstrates a large co-benefit, jointly accounting for 47.7%, 42.2%, 42.0%, and 28.8% of the projected PM, SO₂, NOₓ, and CO₂ abatement totals, respectively. Interestingly, because the majority of air pollutants, but only 33.4% of CO₂, are derived from energy combustion, improved energy efficiencies lead to proportionally greater reductions in the former (by 12.3%–17.5%) than in the latter (by 7.1%). The projected large reduction in overall cement production, which is mainly attributable to the likely large reductions in highway and rural infrastructure construction, will contribute to 39.0%, 44.1%, 29.6%, and 43.6% of the potential mitigation in PM, SO₂, NOₓ, and CO₂, respectively.

**DISCUSSION**

We have developed a Chinese cement plant emissions dataset by coupling smokestack-level, real-time monitoring data with facility-specific information. Compared with existing air pollutant
inventories for the Chinese cement industry. Our dataset represents a major advance in controlling uncertainties (with 95% confidence interval [CI] of [−1.22%, 1.10%] versus [−35%, −40%] for previous inventories) and improving resolution (on the facility and hour basis), by introducing real, individual, continuous monitoring data from a national monitoring network (namely, CEMS). Using this dataset, we conduct, at the facility level, an ex post analysis of the effects of increasingly ambitious emissions reductions if China’s cement facilities achieve both ultralow emissions and carbon-neutral standards under the five shared socioeconomic pathways (SSPs; see “estimation of future emissions reductions” in experimental procedures): (A, E, I, M, and Q) PM, (B, F, J, N, and R) SO₂, (C, G, K, O, and S) NOₓ, and (D, H, L, P, and T) CO₂. The gray bars show the total emissions in 2018 and 2060, and the bars in bright colors represent the emissions reductions attributable to reduction in production or the associated abatement measures. The 2σ represents the uncertainty ranges of estimation, defined as 2 SDs.

Figure 4. Potential future emissions reductions from 2018 to 2060

(A–T) Future emissions reductions if China’s cement facilities achieve both ultralow emissions and carbon-neutral standards under the five shared socioeconomic pathways (SSPs; see “estimation of future emissions reductions” in experimental procedures): (A, E, I, M, and Q) PM, (B, F, J, N, and R) SO₂, (C, G, K, O, and S) NOₓ, and (D, H, L, P, and T) CO₂. The gray bars show the total emissions in 2018 and 2060, and the bars in bright colors represent the emissions reductions attributable to reduction in production or the associated abatement measures. The 2σ represents the uncertainty ranges of estimation, defined as 2 SDs.
mitigation policies and an ex ante analysis of co-benefits between the recently promulgated clean air (ULE standards) and climate policies (carbon neutrality), and we identify abatement measures and technologies that would enable simultaneous reduction of air pollutants by 68.8%–82.2% and CO₂ emissions by 62.0% by 2060.

Our analyses of CEMS measurements substantiate the effectiveness of stricter PM, SO₂, and NOₓ standards in reducing pollution produced by Chinese cement plants, which resulted in systematic declines in the targeted air pollutants from 2014 to 2018. The declining trends started even prior to and increased sharply at the implementation of the new 2015 standards, reflecting a rapid, early response of Chinese cement plants. The mitigation effect was particularly striking among the most-polluting regions (northwest China), scales (small facilities), and processes (kiln tails) as of 2014 and in the provinces with stricter local standards to avoid heavy penalties after the implementation deadline. In turn, such findings point to operational feasibility and substantial benefits of enforcing tough, nationwide mitigating policies to control CO₂ emissions, as well as the importance of involving CO₂ in the CEMS network for ensuring direct, continuous, overall policy oversight as the United States does. Such policy oversight will be critical for fully implementing any much more stringent mitigation policies (such as the recently promulgated ULE standards and carbon neutrality). We observe a few plants at which compliance has weakened over time, suggesting that the associated incentives and penalties need to be reliably enforced and may also need to be evaluated and adjusted to ensure persistent emissions reductions over time.

Encouragingly, we estimate a large co-benefit of the ULE standards and carbon-neutrality policies on future reductions in air pollutants and CO₂ emissions. Regarding the abatement measures, our results reveal that end-of-pipe pollution controls and CCS represent great opportunities to reduce air pollutants and CO₂ emissions, respectively. However, the co-benefits of these two options are limited: CCS technologies will do little to reduce co-emitted air pollutants, or may even exacerbate the problem because of their energy penalty, and vice versa. Furthermore, the installation, maintenance, and upgrading of state-of-the-art pollution controls and CCS systems are among the costliest options, such that adopting both of them might not be economical. In contrast, our results point to substantial co-benefits from fuel switching (especially from coal to natural gas or biomass), improved energy efficiencies (particularly through technological upgrading), and phasing out inefficient facilities, all of which will simultaneously reduce both air pollutants and CO₂ emissions; thus, Chinese policymakers may need to develop detailed regulations or specifications to encourage cement plants to capture such co-benefits. The substantial decline in air pollutants estimated 2014–2018, whereas the concurrent increase in CO₂ emissions reflects a policy priority for air pollution mitigation in recent years. Because China has now largely addressed haze pollution and cement plants might achieve the ULE level soon (probably by 2025), a focus shift from clean-air-oriented policies to climate-change-oriented policies is, therefore, strongly recommended. In addition, air pollution mitigation associated with air quality improvements and human health benefits locally might be relatively politically feasible in the short term, and CO₂ emissions reductions that result in global benefits needs continuous, multinational efforts in the long term. A system of policy instruments can help prioritize the most cost-effective reductions in both air pollutants and CO₂. This system probably includes a variety of economic instruments, such as pollution permits exchanges and environmental taxes, to reduce air pollutants, as well as national emissions trading scheme (ETS) market and carbon taxes for CO₂, and administrative instruments, such as emissions standards and backward production capacity reductions. In turn, the facility-level, dynamic and nationwide estimates of air pollutants and CO₂ emissions from Chinese cement plants included in our CEAC database can support the development of such policies. For example, our detailed maps point to large mitigation opportunities from southwestern, central, and southern regions, small and large-scale facilities, and the kiln tail and clinker production process, all of which deserve policy priority in the future.

Our CEAC database supports further assessments of the air quality improvements, human health benefits and climate change impacts, associated with the emissions changes at Chinese cement plants. Our analysis of the co-benefits between clean air and climate policies for Chinese cement plants also offers insights to other countries suffering from both air pollution and climate problems thereby seeking large opportunities for reducing cement-related emissions, such as India and Brazil.

**EXPERIMENTAL PROCEDURES**

**Resource availability**

**Lead contact**

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Zhifu Mi (z.mi@ucl.ac.uk).

**Materials availability**

The availability of data and code generated through this analysis is outlined in the data and code availability statement.

**Data and code availability**

The CEAC database that supports the findings of this study is available at: https://doi.org/10.5281/zenodo.6867564.

**Construction of the CEAC database**

We compiled and developed a new database for Chinese cement plants (named the CEAC database) by particularly introducing the smokestack-level, real-time, systematic data on pollutant concentrations monitored by the CEMS network in China to calculate facility-based, time-varying, nationwide emissions intensities (or emissions factors) and absolute emissions of cement-related air pollutants. The CEAC database considers all cement plants operating in mainland China from 2014 to 2018, adding up to 1,103–1,192 plants and 1,471–1,885 production lines (Table S5). We focused on air pollutants of PM, SO₂, and NOₓ (which are the targets of the current emissions standards policy) and CO₂ emissions (for which tough mitigation policies are on the horizon in view of the ambitious promise of carbon neutrality by 2060).

We constructed the CEAC database by coupling two detailed national databases, facility-specific information and smokestack-level CEMS data, both of which were exclusively provided by the MEE. Facility-level information involves activity level (i.e., annual production, inputs, and fuel consumption), fuel quality and raw material quality, kiln type, scale, age, firm organization, geographical location, pollution-control technologies, and so on. For CEMS data, China mandated the installation of CEMS at the smokestacks of kiln heads and kiln tails, directly measuring the pollutant concentrations in flue gas (g m⁻³), converting them into standard values at a standard oxygen level of 10%, and recording the hourly averages. Overall, the CEMS network encompasses a total of 2,819 cement plant smokestacks, accounting for 45.3%–77.2% of national cement plants and 68.5%–87.6% of total clinker production between 2014 and 2018 (Table S5). For facilities without CEMS,
we assumed that their smokestack pollutant concentrations exhibited similar distributions to the facilities involved in CEMS, of the same production process and in the same province.\textsuperscript{21,59} Using CEMS-monitored smokestack-level PM, SO\textsubscript{2}, and NO\textsubscript{X} concentrations (the targets of the emissions standards policy), we explored the individual compliance of Chinese cement-generating facilities. We quantified compliance based on two typical criteria: compliance rate and compliance ratio.\textsuperscript{21,60} Compliance rate was defined herein as the proportion of observations that were in compliance with the associated standards, ranging from 0\% (representing an utter noncomplier at any time) to 100\% (representing a full complier over the whole sampling period).\textsuperscript{21,60,62} Compliance ratio measures the exceedance of the associated standard for a given pollution concentration (see Equation 1):\textsuperscript{21}

\[
R_{c,p} = \frac{S_{c,p} - C_{c,p}}{S_{c,p}}.	ag{1}
\]

where the indexes \(c, f, p, \) and \(h\) indicate the species of emissions, generating facility, production process, and hour, respectively; \(S\) represents the emissions standard (g m\textsuperscript{3}), specified by the related regulations;\textsuperscript{16,17} \(C\) is the pollution concentration measured by CEMS (g m\textsuperscript{3}); and \(R\) is the estimated compliance ratio ranging on (\(-\infty, 1\)), monotonically increasing as compliance improves and being positive (or negative) for compliance (or noncompliance).

**Estimation of emissions factors and emissions**

We calculated the air pollutants and CO\textsubscript{2} emissions from Chinese cement plants on a facility and monthly basis (see Equation 2)\textsuperscript{21,17,20,21,59}

\[
E_{f,p,m} = EF_{f,p,m} \times A_{f,p,m}.	ag{2}
\]

where the subscript \(m\) indicates the month; \(EF\) denotes the emissions factor (or emissions intensity), which is defined as the volume of emissions per unit of clinker production (g kg\textsuperscript{-1}) or fuel consumption (g kg\textsuperscript{-1} for solid or liquid fuels and g m\textsuperscript{3} for gas fuels); \(A\) represents the activity level, namely, the volume of clinker production (kg) or fuel consumption (kilogram for solid or liquid fuels and cubic meters for gas fuels), which was collected as yearly facilitate-level data (provided by the MEE) and allocated on a monthly scale according to monthly provincial clinker production (available at: http://www.cementchina.net);\textsuperscript{20,21,17} and \(E\) indicates the estimated emissions (g).

**Emissions factors of air pollutants**

The introduction of CEMS data allows a direct estimation for facility-level, hourly emissions factors, thus avoiding many assumptions and the associated sensitive parameters used in previous studies,\textsuperscript{21,20,21,59} as shown in Equation 3:

\[
EF_{f,p,m} = \frac{C_{f,p} \times V_{f,p}}{A_{f,p}}.	ag{3}
\]

where \(V\) indicates the theoretical flue-gas rate, calculated as the volume of flue gas per unit of clinker production (m\textsuperscript{3} kg\textsuperscript{-1}); and \(EF\) is the emissions factor, represented by the volume of air pollutants per unit of clinker production (g kg\textsuperscript{-1}); in which the effect of pollution-control systems (if employed) is considered as potential mitigation in China’s cement-related air pollutants and CO\textsubscript{2} emissions. In the policy scenario, we assumed that all Chinese cement facilities in the entire industry adopt appropriate abatement measures to improve their poor operations and technologies to meet the ULE standards implemented in Hebei Province on May 1, 2020 (currently the most stringent standards worldwide) and to achieve carbon-neutral emissions intensities,\textsuperscript{21} hold production at the 2018 level\textsuperscript{21} or are retired if small (producing <2,000 tons of clinker per day) or outdated (aged >30 years),\textsuperscript{21,12,15} as for the estimation results shown in Figure 3.

In the context of China’s carbon neutrality, we also conducted a projection for the year 2060 (the policy deadline for reaching carbon neutrality),\textsuperscript{20} assuming that all plants will follow a uniform development rate in cement production or will retire small or outdated plants, and the total cement production was assumed to meet the expected total cement consumption.\textsuperscript{51,65,66} In particular, we projected future emissions by following a method similar to that for 2014–2018 (based on Equations 2 and 3), with the data for all model inputs (as well as the associated explanations, data sources, projection methods, underlying assumptions, and supporting references) provided in Table S11. The cement demand includes the cement used in the construction of buildings, highways, railways, rural infrastructures, and other uses,\textsuperscript{31} which was estimated by adding up the cement products demanded multiplied by the associated cement use intensities,\textsuperscript{51,67,68} as shown in Equation 5:

\[
P_{i} = \sum_{y=1}^{y_{y}} CP_{i,y} \times CI_{i,y} + Others_{y},\tag{5}
\]

where the subscripts \(i\) and \(y\) represent the cement product and year, respectively; \(P\) means the annual cement production in China; \(CP\) indicates the demand for cement products, i.e., the cement used in the construction of buildings, highways, railways, and rural infrastructures; \(O\) represents the cement intensity, which is defined as the amount of cement required per cement product; and \(C_{i}\) denotes the cement demands of urban public transportation, electricity power construction, etc. For buildings, highways, and railways, both the newly constructed amounts and the discarded amounts were considered;\textsuperscript{51} we projected the newly constructed amounts based on the expected levels of related official planning and current levels of developed countries;\textsuperscript{16,17,20} and estimated the discarded amounts according to the lifetimes of buildings and railways (assumed to reach the designed ages)\textsuperscript{25} and the performance of highways (assumed to reach the associated standards).\textsuperscript{31} For rural infrastructures, the cement demand was estimated based on the
The authors declare no competing interests.

AUTHOR CONTRIBUTIONS
L.T., X.B., Z.M., and S.J.D. led the project. X.B. processed and analyzed the SSPs (bars in bright colors), as well as 2 SDs of ±36.4 and 95% CIs of (-32.9%, 41.4%).

Limitations
Our CEAC dataset suffers from certain uncertainties and limitations. For instance, the Chinese CEMS network has not yet expanded to include all Chinese cement plants yet, with coverage gaps of 25.1% in plants and 12.4% in production; in future work, we will add field measurements to obtain a complete database. Nevertheless, the CEMS-monitored measurements of PM, SO2, and NOx pollution concentrations greatly improve the spatiotemporal resolution of our estimates relative to those obtained in prior studies, and our analyses indicate that the uncertainty ranges of the monthly emissions are quite small (all within ±1.17%; Figures 2A–2C). In contrast, in the absence of CEMS data, the CO2 estimation using average emissions factors is subject to much larger uncertainties (±7.83%; Figure 2D), but still small compared with existing studies (±7%–14%). Fortunately, in view of the carbon-neutrality promise and the concomitant upcoming tough mitigation policies, CO2 measurements are likely to be included in the CEMS network soon; future versions of our CEAC dataset will incorporate these detailed, real-time, nationwide CO2 monitoring data, thus improving the accuracy of our emissions estimates. Although Chinese policymakers have gone to great lengths to ensure the reliability of CEMS data, further verifications against independent satellite and ground-level monitoring data would be worthwhile and could provide insights into whether and to what extent the changes in cement-related emissions be controlled at least at the 2014–2018 levels, assuming few associated future changes, because some measure-related information is lacking at the facility level before 2016; nevertheless, this will be involved in the future research if these data become available, which can provide useful information for policy-makers and businesses. Further CO2 emissions reduction is possible, especially from improving CCS technologies, which needs a careful investigation when the required technical parameters are available.

SUPPLEMENTAL INFORMATION
Supplemental information can be found online at https://doi.org/10.1016/j.onear.2022.07.003.

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AUTHOR CONTRIBUTIONS
L.T., X.B., Z.M., and S.J.D. led the project. X.B. processed and analyzed the data of Continuous Emission Monitoring Systems. G.D. and J.R. compiled and analyzed the facility-specific information for Chinese cement plants. J.R. and S.W. conducted the experimental work. L.T. and S.J.D. wrote the paper. All authors contributed to developing and writing the manuscript.

DECLARATION OF INTERESTS
The authors declare no competing interests.

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Supplemental information

Plant-level real-time monitoring data reveal substantial abatement potential of air pollution and CO₂ in China's cement sector

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Supplemental Information

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Supplemental Notes

Note S1. Punishment and incentive policies for emissions standards

According to existing related regulations, the emissions standards are mandatory policies. In particular, noncompliance with emissions standards, in terms of a percentage of overshoot, would face financial punishments, such as penalties of RMB 0.10-1.00 million, doubled sewage charges, production restriction or ban and plant suspension or shutdown.1,2

In contrast, compliance and even overcompliance can gain financial incentives: for example, a 50% discount on sewage charges, if emissions concentrations are controlled 50% lower than the associated standards before 2018;2 a 25% (or even 50%) discount on environmental taxes, if emissions concentrations are 30% (or even 50%) lower than the standards since 2018;3 the benefits from selling, transferring and mortgaging surplus pollution permits, if total emissions are lower than the total pollution permits allowed.4

Note S2. Determinants of emissions changes

After the introduction of the new 2015 emissions standards at the end of 2013, the decreased PM, SO₂ and NOₓ emissions intensities led to systematic reductions in the air pollutants from Chinese cement plants, while the CO₂ emissions climbed as with the increased production (Figure 2). Between 2014 and 2018, the total PM, SO₂ and NOₓ emissions show a downward trend, decreasing from 0.15, 0.14 and 1.35 Mt in 2014 to 0.08, 0.08 and 0.89 Mt in 2018 by 50.3%, 43.6% and 34.2%, respectively (Figure S7). Of such total decreases, the reductions in PM, SO₂ and NOₓ emissions intensities accounted for 109.2%, 119.0% and 112.4%, respectively (that is, a 5.0% growth in clinker production 2014-2018 would have promoted the emissions by 4.5%, 7.3% and 4.2%, respectively, were it not for the abatement in emissions intensities). From 2014 to 2015, with the combination of a rapid response to the new standards and a 5.8% decline in production, the PM, SO₂ and NOₓ emissions decreased much greater (by 26.7%, 24.9% and 24.6% per year, respectively) than 2015-2018 (by 12.2%, 9.1% and 4.5% per year, respectively); even in this case, the leading driver of emissions abatement still remained the reduced emissions intensities (accounting for 79.0%, 79.5% and 77.5%, respectively). Between 2015 and 2018, the clinker production continuously grew over the four years (totally by 11.5%), contributing to the increases in PM, SO₂ and NOₓ emissions by 11.5%, 16.5% and 11.4%, respectively; however, such increases were completely offset by the decrease in emissions intensities, thus the three air pollutants continued to fall by 32.2%, 24.9% and 12.8%, respectively. In sharp contrast, the CO₂ emissions, due to little improvement in emissions intensity, generally followed a similar changing trend to the production and increased by 5.0% from 2014 to 2018 (more especially, decreasing by 5.8% from 1.10 to 1.04 Gt 2014-2015 and increasing by 11.5% to 1.16 Gt 2015-2018).

Our dataset points to the largest reductions in air pollutants and the largest increases in CO₂ emissions 2014-2018 from what dominated the cement market and the growth in production, respectively. Air pollutants reduced the greatest in the eastern region (accounting for 28.9%, 28.9% and 37.7% of total PM, SO₂ and NOₓ abatement, respectively), on the large production lines (48.7%, 42.9% and 48.3% for PM, SO₂ and NOₓ, respectively) and for kiln tails (69.2% for PM and almost all for SO₂ and NOₓ; Figure S8). The contributions to emissions reductions generally correspond to market shares; these three region, scale and process-specific top
contributors dominated Chinese cement industry between 2014 and 2018, accounting for the
largest shares of plants (25.6%, 27.6% and 100.0%, respectively), clinker production (31.1%,
49.0% and 100.0%) and air pollutants (31.3%, 48.6% and 85.7%; Figures S9 and S10). Such
three emissions hotspots, in turn, were often targeted in smokestack concentration reductions
and improved into high levels of compliance (87.9%, 87.1% and 83.8% of plants, respectively,
in compliance with the new 2015 standards in 2018, compared with the overall level of 83.5%).
In view of their already good compliance, continuously encouraging these three emissions
hotspots to greatly contribute to future emissions reductions, therefore, needs introducing
stricter policy: since 2020, China has promulgated a series of ambitious ULE standards (as
much as 87.5% lower than the national standards and 90.0% lower than in other countries) or
even enforced them in some provinces. In sharp comparison, given that almost all changes in
CO\textsubscript{2} emissions were attributable to the changes in production (Figure 2D), the southwestern
region and the middle-scale production lines (those producing 2,000-4,000 tons of clinker per
day), which represented the largest shares of the increase in clinker production 2014-2018
(60.0% and 104.8%, respectively), contributed to the largest shares of the increase in CO\textsubscript{2}
emissions over the same period (65.1% and 106.9%, respectively); and clinker production
process made a 101.0% larger contribution share to CO\textsubscript{2} increase than fossil fuel combustion,
followed by a 713.6% larger growth in production than in energy consumption.

**Note S3. Uncertainties in CEMS observation**

Generally, the CEMS consists of a sampling system (for filtering and sampling flue gases), an
analysis system (for monitoring, evaluating and adjusting the parameters of the targeted flue
gases, particularly emissions concentrations) and a data processing system (for collecting,
processing and reporting the observations).\textsuperscript{5-7} The three systems should be properly
maintained and operated, or high uncertainties might occur from the instrument detections and
operation of CEMS, including: observation biases from the instrument detections and operation
of CEMS sampling and analysis systems, in terms of zero drift, span drift and indication errors;\textsuperscript{7}
and data losses and misplacement from the operation of CEMS analysis and data processing
systems, in terms of null and invalid values.\textsuperscript{7} According to official regulations, the uncertainties
in CEMS observations jointly are expected to be controlled within the uncertainty ranges of
±15%, ±5% and ±5% for PM, SO\textsubscript{2} and NO\textsubscript{X} concentrations, respectively (HJ/T 75-2007).\textsuperscript{6}

We conduct an uncertainty analysis examining how these uncertainties effect our estimates.
In particular, we assume uniform distributions for CEMS observations on the corresponding
acceptable uncertainty ranges (i.e., ±15%, ±5% and ±5% for PM, SO\textsubscript{2} and NO\textsubscript{X} concentrations,
respectively; HJ/T 75-2007)\textsuperscript{6} on the hourly, source and pollutant basis. Random pollution
concentrations are generated using the Monte Carlo technique and put into Eq. (3) to re-
estimate emissions factors and then Eq. (2) for emissions, and a total of 10,000 simulations are
run to estimate the uncertainty ranges of our estimates. The results show that, even with the
uncertainties in CEMS observations, our estimation is still stable, with 2 standard deviations of
±0.93% and 95% confidence interval of (-0.90%, 0.92%).
Figure S1. Geographic distribution of Chinese cement plants in 2014

The cement plants operating in mainland China for 2014 (totalling 1,192 plants), of which 45.3% were covered by the Chinese CEMS network (accounting for 68.5% of clinker production). The dots indicate individual plants, with the size standing for clinker production (in $10^4$ tons) and intensities for compliance rates (defined as the proportion of observations in compliance with the associated standards, %); and the background represents the proportion of compliers in the given province (%).
Figure S2. Geographic distribution of Chinese cement plants in 2015

The cement plants operating in mainland China for 2015 (totalling 1,192 plants), of which 59.9% were covered by the Chinese CEMS network (accounting for 79.0% of clinker production). The dots indicate individual plants, with the size standing for clinker production (in $10^4$ tons) and intensities for compliance rates (defined as the proportion of observations in compliance with the associated standards, %); and the background represents the proportion of compliers in the given province (%).
Figure S3. Temporal distribution of standard compliance, 2014-2018

(A-F) Daily (A-C) and monthly distributions (D-F) of smokestack-level compliance ratios (defined as the exceedance of the associated standard for a smokestack concentration, in %; left y axis) for PM (A and D), SO\textsubscript{2} (B and E) and NO\textsubscript{x} (C and F). The color gradation (in the left column) shows the percentiles of daily compliance ratios, the boxplots (right column) indicate the monthly quartiles, the black dashed vertical lines mark 1 July 2015 when the new emissions standards were implemented, the colored full curves (left column) and dotted curves (right column) indicate the mean compliance ratios (in green) and compliance rates (defined as the proportion of observations in compliance with the associated standards, %; in yellow; right y axis), and the red dashed lines (left column) denote the linear regression on the mean before or after the new standards were implemented.
Figure S4. Temporal distribution of smokestack concentrations by region, 2014-2018

(A-R) Daily and monthly (in the insets) distributions of smokestack concentrations (in mg m$^{-3}$) at the cement plants in the northern (A-C), northeastern (D-F), eastern (G-I), central and southern (J-L), southwestern (M-O) and northwestern regions (P-R) for PM (A, D, G, J, M and P), SO$_2$ (B, E, H, K, N and Q) and NO$_x$ (C, F, I, L, O and R). The color gradation indicates the percentiles of daily smokestack concentrations, the black dashed vertical lines mark 1 July 2015 when the new emissions standards were implemented, the back full curves represent daily mean smokestack concentrations, and the red dashed lines denote the linear regression
on the mean before or after the new standards were implemented. In the insets, the boxplots show the quartiles of monthly compliance ratios (defined as the exceedance of the associated standard for a smokestack concentration, %; left y axis), the blue dotted curves represent monthly mean compliance ratios (%; left y axis), and the red dotted curves denote monthly mean compliance rates (defined as the proportion of observations in compliance with the associated standards, %; right y axis).
Figure S5. Temporal distribution of smokestack concentrations by scale, 2014-2018

(A-L). Daily and monthly (in the insets) distributions of smokestack concentrations (mg m⁻³) at the cement production lines that produce <2,000 (A-C), 2,000-4,000 (D-F), 4,000-7,000 (G-I) and ≥7,000 tons of clinker per day (J-L) for PM (A, D, G and J), SO₂ (B, E, H and K) and NOₓ (C, F, I and L). The color gradation indicates the percentiles of daily smokestack concentrations, the black dashed vertical lines mark 1 July 2015 when the new emissions standards were implemented, the back full curves represent daily mean smokestack concentrations, and the red dashed lines denote the linear regression on the mean before or after the new standards were implemented. In the insets, the boxplots show the quartiles of monthly compliance ratios (defined as the exceedance of the associated standard for a smokestack concentration, %; left y axis), the blue dotted curves represent monthly mean compliance ratios (%; left y axis), and the red dotted curves denote monthly mean compliance rates (defined as the proportion of observations in compliance with the associated standards, %; right y axis).
Figure S6. Temporal distribution of smokestack concentrations by process, 2014-2018

(A-D) Daily and monthly (in the insets) distributions of smokestack concentrations (mg m$^{-3}$) at kiln heads (A) and kiln tails (B-D) for PM (A and B), SO$_2$ (C) and NO$_x$ (D). The color gradation indicates the percentiles of daily smokestack concentrations, the black dashed vertical lines mark 1 July 2015 when the new emissions standards were implemented, the back full curves represent daily mean smokestack concentrations, and the red dashed lines denote the linear regression on the mean before or after the new standards were implemented. In the insets, the boxplots show the quartiles of monthly compliance ratios (defined as the exceedance of the associated standard for a smokestack concentration, %; left y axis), the blue dotted curves represent monthly mean compliance ratios (%; left y axis), and the red dotted curves denote monthly mean compliance rates (defined as the proportion of observations in compliance with the associated standards, %; right y axis).
Figure S7. Emissions changes by emissions intensity and production, 2014-2018
(A-C) Annual emissions (blue bars; Mt) and emissions changes attributable to the changes in emissions intensities (green bars) and production (red bars) for PM (A), SO$_2$ (B) and NO$_x$ (C). The emissions changes driven by emissions intensities are calculated by assuming that production maintained the same levels as the base year, and the emissions changes driven by production are estimated by assuming that emissions intensities maintained unchanged.
Figure S8. Emissions changes from Chinese cement facility groups, 2014-2018

(A-L) The changes in PM (A, E and I), SO₂ (B, F and J), NOₓ (C, G and K) and CO₂ emissions (D, H and L) from the cement plants grouped by region (A-D), scale (E-H) and process (I-L).

The black bars show the annual emissions (in Mt), and the bright-colored bars indicate the emissions changes from the associated facility groups across years.
Figure S9. Emissions from Chinese cement facility groups in 2014

(A-L) The mean per-production emissions (in kg t⁻¹; left y axis) across the cement facilities grouped by region (A-D), scale (E-H) and process (I-L) for PM (A, E and I), SO₂ (B, F and J), NOₓ (C, G and K) and CO₂ (D, H and L), with the colors of bars denoting the facility groups, the widths proportional to the total production, the areas proportional to the total emissions, and the shaded areas proportional to the emissions from compliers (dark) and noncompliers (light) with the 2004 standards. The full curves indicate the distributions of facility-level compliance ratios (defined as the exceedance of the associated standard for a smokestack concentration, %; right y axis) in the given groups, and the dashed lines represent the mean compliance ratios across all facilities.
Figure S10. Emissions from Chinese cement facility groups in 2018

(A-I) The mean per-production emissions (in kg t\(^{-1}\); left y axis) across the cement facilities grouped by region (A-D), scale (E-H) and process (I-L) for PM (A, E and I), SO\(_2\) (B, F and J), NO\(_x\) (C, G and K) and CO\(_2\) (D, H and L), with the colors of bars denoting the facility groups, the widths proportional to the total production, the areas proportional to the total emissions, and the shaded areas proportional to the emissions from compliers (dark) and noncompliers (light) with the 2015 standards. The full curves indicate the distributions of facility-level compliance ratios (defined as the exceedance of the associated standard for a smokestack concentration, %; right y axis) in the given groups, and the dashed lines represent the mean compliance ratios across all facilities.
## Supplemental Tables

**Table S1.** Summary of emissions standards in China and the EU.

| Standards                     | Region                  | Target (mg m$^{-3}$) |
|-------------------------------|-------------------------|----------------------|
|                               |                         | PM       | SO$_2$ | NO$_x$ |
| 2004 emissions standards      | China                   | 50       | 200    | 400    |
| 2015 emission standards       | China                   | 30       | 200    | 400    |
| Ultralow emissions standards  | Hebei, China            | 10       | 30     | 100    |
|                              | Other provinces, China  | 10       | 35-100 | 50-200 |
| European emissions standards  | European Union          | 10-20    | 50-400 | 200-800 |
| Number        | Region             | Release date | Implementation date | Expiration date | Process | Targets       | Frequency | Mandatory |
|--------------|--------------------|--------------|---------------------|----------------|---------|---------------|-----------|-----------|
| GB 4915-2004 | Nationwide         | 2004/12/29   | 2005/1/1            |                | Kiln tail Kiln head | 2009/12/31 100 100 400 800 | 1h        | √         |
|              |                    |              |                     | 2015/6/30       | Kiln tail Kiln head | 50 50 200 800 |           |           |
| GB 4915-2013 | Nationwide         | 2013/12/27   | 2014/3/1            |                | Kiln tail Kiln head | 2015/6/30 30 30 200 400 | 1h        | √         |
| DB 50/418-2012 | Chongqing    | 2012/10/29   | 2012/12/1           | 2016/1/31       | Kiln tail Kiln head | 2016/10/31 15 15 100 150 250 250 | 1h        | √         |
|              | Affected areas²   |              |                     |                | Kiln tail Kiln head | 2016/12/1 30 30 200 200 350 350 | 1h        |           |
|              | Others             |              |                     |                | Kiln tail Kiln head | 2016/12/1 50 50 200 550 |           |           |
| DB 50/656-2016 | Chongqing    | 2016/1/22    | 2016/2/1            |                | Kiln tail Kiln head | 2016/10/31 15 15 100 150 250 250 | 1h        | √         |
|              | Main urban areas³ |              |                     |                | Kiln tail Kiln head | 2016/12/1 30 30 200 200 350 350 | 1h        |           |
|              | Others             |              |                     |                | Kiln tail Kiln head | 2016/12/1 50 50 200 550 |           |           |
| DB 44/818-2010 | Guangdong  | 2010/10/22   | 2010/11/1           | 2013/12/31     | Kiln tail Kiln head | 2013/12/31 50 50 200 800 | 1h        | √         |
| DB 35/1311-2013 | Fujian         | 2013/1/21    | 2013/4/1            | 2013/12/31     | Kiln tail Kiln head | 2013/12/31 30 30 100 200 400 800 | 1h        | √         |
| DB 52/893-2014 | Guizhou      | 2014/6/12    | 2014/6/20           | 2014/12/31     | Kiln tail Kiln head | 2014/6/30 50 50 200 400 300 800 | 1h        | √         |
| DB 37/2373-2013 | Shandong  | 2013/5/24    | 2013/9/1            | 2014/12/31     | Kiln tail Kiln head | 2014/12/31 30 30 100 200 400 800 | 1h        | √         |
| DB 13/2167-2015 | Hebei       | 2015/2/15    | 2015/3/1            |                | Kiln tail Kiln head | 2015/6/30 30 30 100 400 | 1h        | √         |
| DB 11/1054-2013 | Beijing     | 2013/12/26   | 2014/1/1            |                | Kiln tail Kiln head | 2015/12/31 30 30 320 | 1h        | √         |

Note: New: Represents new plants; Existing: Represents existing plants.

* Represents the main urban areas here include the districts of Banan, Beibei, Dadukou, Jiangbei, Jiulongpo, Nan'an, Shapingba, Yubei, Yuzhong and North New in Chongqing.

* Represents the affected areas include the 26 towns in the districts of Jiangjin, Hechuan and Bishan.

* Represents the main urban areas here include the districts of Yuzhong, Dadukou, Jiangbei, Nan'yan, Shapingba, Jiulongpo, Beibei, Yubei and Banan.

* Represents the emissions standards for existing plants came into force since 1 Jan 2016.

* Represents the emissions standards for new plants came into force since 1 Sep 2013.
### Table S3. ULE emissions standards.

| Number       | Region                      | Release date  | Process        | Targets                      | Frequency | Mandatory |
|--------------|-----------------------------|---------------|----------------|------------------------------|-----------|-----------|
| DB 13/2167-2020 | Hebei                       | 2020/3/13     | Kiln tail      | PM (mg m⁻³): 10, SO₂ (mg m⁻³): 30, NOₓ (mg m⁻³): 100 | 1h        | ✓         |
|              |                             |               | Kiln head      |                              |           |           |
| DB 34/3576-2020 | Anhui                       | 2020/3/23     | Kiln tail      | PM (mg m⁻³): 10, SO₂ (mg m⁻³): 50, NOₓ (mg m⁻³): 100 | 1h        | ✓         |
|              |                             |               | Kiln head      |                              |           |           |
| DB 41/1953-2020 | Henan                       | 2020/5/13     | Kiln tail      | PM (mg m⁻³): 10, SO₂ (mg m⁻³): 35, NOₓ (mg m⁻³): 100 | 1h        | ✓         |
|              |                             |               | Kiln head      |                              |           |           |
| DB 46/524-2021 | Hainan                      | 2021/1/26     | Kiln tail      | PM (mg m⁻³): 10, SO₂ (mg m⁻³): 100, NOₓ (mg m⁻³): 200 | 1h        | ✓         |
|              |                             |               | Kiln head      |                              |           |           |
| DB 32/4149-2021 | Jiangsu                     | 2021/12/9     | Kiln tail      | PM (mg m⁻³): 10, SO₂ (mg m⁻³): 35, NOₓ (mg m⁻³): 100 | 1h        | ✓         |
|              |                             |               | Kiln head      |                              |           |           |

**Note:**

- Represents the emissions standards on the first stage of policy implementation.
- Represents the emissions standards on the second stage of policy implementation.
- Represents the main urban areas here include Panzhihua, Tibetan Qiang Autonomous Prefecture of Ngawa, Tibetan Autonomous Prefecture of Garzê and Liangshan Yi Autonomous Prefecture.

### Table S4. EU emissions standards.

| Policy                                      | Agency                                                                 | Release date | Emission source                          | Kiln type        | Pollutants   | Target                      |
|---------------------------------------------|------------------------------------------------------------------------|--------------|------------------------------------------|------------------|--------------|-----------------------------|
| Best available techniques (BAT)             | European Commission                                                   | 2013/4/9     | Kiln firing                              | -                | PM           | Lower limit (mg m⁻³): 10    |
| reference document for the production of cement, lime and magnesium oxide |                          |              | Cooling and milling                      | -                | SO₂          | Upper limit (mg m⁻³): 20    |
|                                             |                          |              | kiln firing and/or preheating/precalcining processes | Preheater kilns  | NOₓ          |                |
|                                             |                          |              |                                          |                  |              | 200             |
|                                             |                          |              |                                          |                  |              | 450             |
|                                             |                          |              |                                          |                  |              | 500⁺            |

**Note:**

- Represents the emissions standards if the initial NOₓ level after primary techniques is >1 000 mg/Nm³.
### Table S5. Facility information, emissions intensities, emissions and CEMS coverage of Chinese cement plants in CEAC.

| Year | Region | Facility information | Emissions intensity | Emissions | CEMS coverage |
|------|--------|----------------------|---------------------|-----------|--------------|
|      |        | Number of facilities | PM (g/Kg) | SO2 (g/Kg) | NOx (Kg/Kg) | PM (Kt/yr) | SO2 (Kt/yr) | NOx (Kt/yr) | Proportion of clinker production (%) | Number of facilities | Proportion of clinker production (%) |
| 2014 | Central and South | 347 | 0.040 | 0.076 | 0.746 | 29 | 28 | 252 | 77.00 | 219 | 86.19 |
|      | East | 407 | 0.038 | 0.078 | 0.781 | 44 | 33 | 252 | 72.90 | 243 | 75.28 |
|      | North | 168 | 0.037 | 0.080 | - | 11 | 6 | 117 | 70.28 | 100 | 80.09 |
|      | Northeast | 78 | 0.051 | 0.097 | 0.70 | 20 | 14 | 47 | 63.00 | 122 | 78.09 |
|      | Northwest | 205 | 0.051 | 0.097 | 0.64 | 29 | 14 | 43 | 70.40 | 114 | 77.93 |
|      | Southwest | 363 | 0.042 | 0.097 | 0.67 | 21 | 10 | 29 | 48.66 | 288 | 78.09 |
|      | Small | 604 | 0.043 | 0.107 | 0.74 | 29 | 10 | 37 | 39.31 | 326 | 78.06 |
|      | Medium | 504 | 0.042 | 0.097 | 0.67 | 29 | 10 | 37 | 56.44 | 384 | 88.18 |
|      | Large | 420 | 0.040 | 0.107 | 0.74 | 29 | 10 | 37 | 78.84 | 843 | 88.48 |
|      | Super-large | 1,568 | 0.039 | 0.094 | 0.74 | 48 | 16 | 53 | 88.18 | 1,042 | 1,042 |
| 2015 | Central and South | 347 | 0.034 | 0.076 | 0.746 | 29 | 28 | 252 | 86.19 | 256 | 1042 |
|      | East | 407 | 0.034 | 0.078 | 0.781 | 44 | 33 | 252 | 75.28 | 252 | 1042 |
|      | North | 168 | 0.030 | 0.080 | - | 11 | 6 | 117 | 70.09 | 117 | 1042 |
|      | Northeast | 78 | 0.031 | 0.097 | 0.70 | 20 | 14 | 47 | 62.99 | 47 | 1042 |
|      | Northwest | 205 | 0.048 | 0.097 | 0.64 | 29 | 14 | 43 | 61.99 | 43 | 1042 |
|      | Southwest | 363 | 0.034 | 0.107 | 0.74 | 29 | 10 | 37 | 51.99 | 37 | 1042 |
|      | Small | 604 | 0.035 | 0.097 | 0.74 | 29 | 10 | 37 | 51.99 | 37 | 1042 |
| May | Medium | 504 | 0.035 | 0.107 | 0.74 | 29 | 10 | 37 | 51.99 | 37 | 1042 |
| 2016 | Large | 420 | 0.035 | 0.094 | 0.74 | 48 | 16 | 53 | 51.99 | 37 | 1042 |
|      | Super-large | 1,568 | 0.033 | 0.094 | 0.74 | 48 | 16 | 53 | 51.99 | 37 | 1042 |

**Total clinker production (Mt):**
- 2014: 2014.47 + 447.17 + 105.59 + 66.02 + 138.21 + 270.38 + 176.49 + 428.44 + 694.29 + 114.62 + 1,413.84
- 2015: 384.16 + 421.35 + 99.50 + 62.21 + 130.23 + 254.77 + 185.52 + 431.18 + 645.85 + 69.67 + 1,332.23
- 2016: 377.39 + 416.05 + 111.98 + 65.24 + 124.93 + 267.97 + 161.13 + 431.18 + 645.85 + 69.67 + 1,332.23
| Year | Facility information | Number of facilities | Total clinker production (Mt) | Per facility clinker production (Mt) | Emissions intensity | PM (g/Kg) | SO₂ (g/Kg) | NOₓ (g/Kg) | CO₂ (Kg/Kg) | Emissions | PM (Kt/yr) | SO₂ (Kt/yr) | NOₓ (Kt/yr) | CO₂ (Mt/yr) |
|------|----------------------|----------------------|-----------------------------|-----------------------------------|---------------------|-----------|------------|------------|-------------|------------------|-----------|------------|------------|------------|
|      |                      |                      |                             |                                   |                     | Kiln head | Kiln tail  | Kiln tail  | Kiln tail   | Kiln head         | Kiln head | Kiln tail  | Kiln tail  | Kiln tail   | Kiln tail   | Kiln tail |
| 2017 |                      |                      |                             |                                   |                     | 0.025     | 0.032      | 0.061      | 0.638       | 0.0781             | 0.020     | 0.027      | 0.052      | 0.582       | 0.776         | 0.776     |
|      |                      |                      |                             |                                   |                     | 0.031     | 0.031      | 0.065      | 0.673       | 0.781              | 0.022     | 0.026      | 0.057      | 0.609       | 0.778         | 0.778     |
|      |                      |                      |                             |                                   |                     | 0.019     | 0.028      | 0.034      | 0.552       | 0.780              | 0.019     | 0.024      | 0.020      | 0.471       | 0.781         | 0.781     |
|      |                      |                      |                             |                                   |                     | 0.043     | 0.033      | 0.059      | 0.713       | 0.780              | 0.037     | 0.033      | 0.054      | 0.662       | 0.780         | 0.780     |
|      |                      |                      |                             |                                   |                     | 0.033     | 0.036      | 0.046      | 0.605       | 0.780              | 0.028     | 0.032      | 0.072      | 0.611       | 0.783         | 0.783     |
|      |                      |                      |                             |                                   |                     | 0.025     | 0.033      | 0.084      | 0.698       | 0.780              | 0.027     | 0.034      | 0.045      | 0.636       | 0.783         | 0.783     |
|      |                      |                      |                             |                                   |                     | 0.028     | 0.036      | 0.061      | 0.620       | 0.780              | 0.027     | 0.034      | 0.050      | 0.655       | 0.783         | 0.783     |
|      |                      |                      |                             |                                   |                     | 0.028     | 0.035      | 0.061      | 0.645       | 0.780              | 0.028     | 0.034      | 0.056      | 0.665       | 0.783         | 0.783     |
|      |                      |                      |                             |                                   |                     | 0.028     | 0.033      | 0.058      | 0.654       | 0.780              | 0.028     | 0.032      | 0.058      | 0.654       | 0.783         | 0.783     |
| 2018 |                      |                      |                             |                                   |                     | 0.0781    | 0.781      | 0.780      | 0.780       | 0.781              | 0.0781    | 0.781      | 0.780      | 0.780       | 0.781         | 0.781     |
|      |                      |                      |                             |                                   |                     | 0.781     | 0.780      | 0.780      | 0.780       | 0.781              | 0.781     | 0.780      | 0.780      | 0.780       | 0.781         | 0.781     |

Note: 221 Small: <2,000 tons of clinker per day; Medium: 2,000-4,000 tons of clinker per day; Large: 4,000-7,000 tons of clinker per day; Super-large: >=7,000 tons of clinker per day.
### Table S6. Linear regression for smokestack concentrations, compliance rates and compliance ratios.

| Variable | PM | Coeff. | t-stat. | p-value | Std. Coeff. | Coeff. | t-stat. | p-value | Std. Coeff. | Coeff. | t-stat. | p-value | Std. Coeff. |
|----------|----|--------|---------|---------|-------------|--------|---------|---------|-------------|--------|---------|---------|-------------|
| Daily data | | -0.01*** | -99.02*** | 0.00 | 0.00 | -0.02*** | -75.90*** | 0.00 | 0.00 | -0.09*** | -91.49*** | 0.00 | 0.00 |
| From 2014 to 2018 | | | | | | | | | | | | | |
| N | 1,824 | 1,824 | 1,824 | | | | | | | | | | |
| F-stat. | 9,805.58*** | 5,761.54*** | 8,369.80*** | | | | | | | | | | |
| R² | 0.84 | 0.76 | 0.82 | | | | | | | | | | |
| Monthly data | | -0.01*** | -20.11*** | 0.00 | 0.00 | -0.02*** | -16.49*** | 0.00 | 0.00 | -0.09*** | -16.78*** | 0.00 | 0.01 |
| N | 58 | 58 | 58 | | | | | | | | | | |
| F-stat. | 404.24*** | 271.79*** | 281.59*** | | | | | | | | | | |
| R² | 0.87 | 0.82 | 0.83 | | | | | | | | | | |
| From Jan 2014 to Jun 2015 | | -0.02*** | -43.10*** | 0.00 | 0.00 | -0.01*** | -5.97*** | 0.00 | 0.00 | -0.21*** | -83.77*** | 0.00 | 0.00 |
| Daily data | | | | | | | | | | | | | |
| N | 544 | 544 | 544 | | | | | | | | | | |
| F-stat. | 1,857.77*** | 35.65*** | 7,017.50*** | | | | | | | | | | |
| R² | 0.77 | 0.06 | 0.93 | | | | | | | | | | |
| Monthly data | | -0.02*** | -12.06*** | 0.00 | 0.00 | -0.01*** | -1.19 | 0.25 | 0.01 | -0.21*** | -19.27*** | 0.00 | 0.01 |
| N | 16 | 16 | 16 | | | | | | | | | | |
| F-stat. | 145.49*** | 1.42 | 371.36*** | | | | | | | | | | |
| R² | 0.90 | 0.08 | 0.96 | | | | | | | | | | |
| From Jul 2015 to Dec 2018 | | -0.01*** | -54.53*** | 0.00 | 0.00 | -0.01*** | -49.43*** | 0.00 | 0.00 | -0.04*** | -67.29*** | 0.00 | 0.00 |
| Daily data | | | | | | | | | | | | | |
| N | 1,278 | 1,278 | 1,278 | | | | | | | | | | |
| F-stat. | 2,973.76*** | 2,443.04*** | 4,528.05*** | | | | | | | | | | |
| R² | 0.70 | 0.66 | 0.78 | | | | | | | | | | |
| From Jan 2014 to Jun 2015 | | -0.01*** | -13.62*** | 0.00 | 0.00 | -0.01*** | -12.65*** | 0.00 | 0.00 | -0.04*** | -13.47*** | 0.00 | 0.00 |
| Monthly data | | | | | | | | | | | | | |
| N | 40 | 40 | 40 | | | | | | | | | | |
| F-stat. | 155.591.51 - 0.01 t | 24,768.04 - 0.01 t | 100,127.17 - 0.04 t | | | | | | | | | | |
| From Jul 2015 to Dec 2018 | | | | | | | | | | | | | |
| Daily data | | 6.4e-5*** | 79.74*** | 0.00 | 0.00 | 1.7e-5*** | 44.86*** | 0.00 | 0.00 | 2.6e-5*** | 29.08*** | 0.00 | 0.00 |
| N | 1,824 | 1,824 | 1,824 | | | | | | | | | | |
| F-stat. | 6,359.21*** | 2,012.44*** | 845.54*** | | | | | | | | | | |
| R² | 0.78 | 0.52 | 0.32 | | | | | | | | | | |
| From Jan 2014 to Jun 2015 | | 6.4e-5*** | 18.07*** | 0.00 | 0.00 | 1.7e-5*** | 12.33*** | 0.00 | 0.00 | 2.6e-5*** | 5.93*** | 0.00 | 0.00 |
| Monthly data | | | | | | | | | | | | | |
| N | 58 | 58 | 58 | | | | | | | | | | |
| F-stat. | 326.88*** | 152.01*** | 35.11*** | | | | | | | | | | |
| R² | 0.85 | 0.72 | 0.38 | | | | | | | | | | |

**Y is smokestack concentration (mg m⁻³) From 2014 to 2018**

- Daily data: y = 27,121.40 - 0.01 t
- Monthly data: y = 27,174.14 - 0.01 t

**Y is compliance rate (%) From 2014 to 2018**

- Daily data: y = 27,174.14 - 0.01 t
- Monthly data: y = 27,174.14 - 0.01 t

Regression equations:

- Daily data: y = 27,121.40 - 0.01 t
- Monthly data: y = 27,174.14 - 0.01 t

For more information, refer to Table S6.
The regression equation
\[ y = -156.23 + 6.4e^{-5} \ t \]
\[ y = -40.75 + 1.7e^{-5} \ t \]
\[ y = -62.10 + 2.6e^{-5} \ t \]

From Jan 2014 to Jun 2015

Daily data
\[ 1.1e^{-4}*** \quad 21.73*** \quad 0.00 \quad 0.00 \quad 1.2e^{-5}*** \quad 3.62*** \quad 0.00 \quad 0.00 \quad 1.0e^{-4}*** \quad 24.01*** \quad 0.00 \quad 0.00 \]
N 544 544 544
F-stat. 472.39*** 13.10*** 0.02
\( R^2 \) 0.46 0.51

The regression equation
\[ y = -275.17 + 1.1e^{-4} \ t \]
\[ y = -27.31 + 1.2e^{-5} \ t \]
\[ y = -254.88 + 1.0e^{-4} \ t \]

Monthly data
\[ 1.1e^{-4}*** \quad 5.44*** \quad 0.00 \quad 0.00 \quad 1.1e^{-5} \quad 0.92 \quad 0.37 \quad 0.00 \quad 1.0e^{-4}*** \quad 5.41*** \quad 0.00 \quad 0.00 \]
N 16 16 16
F-stat. 1909.80*** 475.22*** 0.36
\( R^2 \) 0.65 0.65

The regression equation
\[ y = -268.63 + 1.1e^{-4} \ t \]
\[ y = -25.07 + 1.1e^{-5} \ t \]
\[ y = -248.62 + 1.0e^{-4} \ t \]

From Jul 2015 to Dec 2018

Daily data
\[ 5.4e^{-5}*** \quad 43.70*** \quad 0.00 \quad 0.00 \quad 9.4e^{-6}*** \quad 21.80*** \quad 0.00 \quad 0.00 \quad 3.8e^{-5}*** \quad 26.74*** \quad 0.00 \quad 0.00 \]
N 1,278 1,278 1,278
F-stat. 1,909.80*** 714.98*** 0.36
\( R^2 \) 0.60 0.60

The regression equation
\[ y = -132.49 + 5.4e^{-5} \ t \]
\[ y = -22.17 + 9.4e^{-6} \ t \]
\[ y = -91.68 + 3.8e^{-5} \ t \]

Monthly data
\[ 5.4e^{-5}*** \quad 9.40*** \quad 0.00 \quad 0.00 \quad 9.3e^{-6}*** \quad 7.79*** \quad 0.00 \quad 0.00 \quad 3.7e^{-5}*** \quad 5.33*** \quad 0.00 \quad 0.00 \]
N 40 40 40
F-stat. 88.35*** 28.46*** 0.42
\( R^2 \) 0.69 0.69

The regression equation
\[ y = -132.22 + 5.4e^{-5} \ t \]
\[ y = -21.83 + 9.3e^{-6} \ t \]
\[ y = -91.03 + 3.7e^{-5} \ t \]

From Jan 2014 to Jun 2015

Daily data
\[ 1.1e^{-4}*** \quad 21.73*** \quad 0.00 \quad 0.00 \quad 1.2e^{-5}*** \quad 3.62*** \quad 0.00 \quad 0.00 \quad 1.0e^{-4}*** \quad 24.01*** \quad 0.00 \quad 0.00 \]
N 544 544 544
F-stat. 472.39*** 13.10*** 0.02
\( R^2 \) 0.46 0.51

The regression equation
\[ y = -275.17 + 1.1e^{-4} \ t \]
\[ y = -27.31 + 1.2e^{-5} \ t \]
\[ y = -254.88 + 1.0e^{-4} \ t \]

Monthly data
\[ 1.1e^{-4}*** \quad 5.44*** \quad 0.00 \quad 0.00 \quad 1.1e^{-5} \quad 0.92 \quad 0.37 \quad 0.00 \quad 1.0e^{-4}*** \quad 5.41*** \quad 0.00 \quad 0.00 \]
N 16 16 16
F-stat. 1909.80*** 714.98*** 0.36
\( R^2 \) 0.65 0.65

The regression equation
\[ y = -268.63 + 1.1e^{-4} \ t \]
\[ y = -25.07 + 1.1e^{-5} \ t \]
\[ y = -248.62 + 1.0e^{-4} \ t \]

From Jul 2015 to Dec 2018

Daily data
\[ 5.4e^{-5}*** \quad 43.70*** \quad 0.00 \quad 0.00 \quad 9.4e^{-6}*** \quad 21.80*** \quad 0.00 \quad 0.00 \quad 3.8e^{-5}*** \quad 26.74*** \quad 0.00 \quad 0.00 \]
N 1,278 1,278 1,278
F-stat. 1,909.80*** 714.98*** 0.36
\( R^2 \) 0.60 0.60

The regression equation
\[ y = -132.49 + 5.4e^{-5} \ t \]
\[ y = -22.17 + 9.4e^{-6} \ t \]
\[ y = -91.68 + 3.8e^{-5} \ t \]

Monthly data
\[ 5.4e^{-5}*** \quad 9.40*** \quad 0.00 \quad 0.00 \quad 9.3e^{-6}*** \quad 7.79*** \quad 0.00 \quad 0.00 \quad 3.7e^{-5}*** \quad 5.33*** \quad 0.00 \quad 0.00 \]
N 40 40 40
F-stat. 88.35*** 28.46*** 0.42
\( R^2 \) 0.69 0.69

The regression equation
\[ y = -132.22 + 5.4e^{-5} \ t \]
\[ y = -21.83 + 9.3e^{-6} \ t \]
\[ y = -91.03 + 3.7e^{-5} \ t \]
|                          | N  | 1.278 | 1.278 | 1.278 |
|--------------------------|----|-------|-------|-------|
| F-stat.                  |    | 3,269.06*** | 2,099.59*** | 7,255.32*** |
| R²                       |    | 0.72   | 0.62  | 0.85  |
| From Jul 2015 to Dec 2018|    |        |       |       |
| The regression equation  | N  | 2.6e-4*** | 5.5e-5*** | 1.3e-4*** |
| Monthly data             |    | 0.00   | 0.00  | 0.00  |
|                          | R² | 184.33*** | 146.34*** | 301.70*** |
|                          |    | 0.82   | 0.79  | 0.88  |
| The regression equation  | N  | -635.08 + 2.6e-4 t | -135.88 + 5.6e-5 t | -310.59 + 1.3e-4 t |
| Monthly data             |    |        |       |       |
|                          | N  | 40     | 40    | 40    |
| F-stat.                  |    | 184.33*** | 146.34*** | 301.70*** |
| R²                       |    | 0.82   | 0.79  | 0.88  |
| The regression equation  | N  | -634.73 + 2.6e-4 t | -135.52 + 5.5e-5 t | -311.37 + 1.3e-4 t |

Note: *** and * denote significance at 1%, 5% and 10%, respectively.
### Table S7. Statistical tests of main findings.

| Targets | Group | Indicator | Descriptive | Test | Result | p-value | 95% CI |
|---------|-------|-----------|-------------|------|--------|---------|--------|
| Startup (for 48 h); Other time | | PM concentrations of targeted regions by production ban in 2016 | Mean ± SD(upper); 23.13 ± 50.87 Mean ± SD(lower); 16.83 ± 19.16 | Paired t-test | t = 2.44, df = 164 (One-tailed) | < 0.01 | [2.32, Inf] |
| Regular temporary increases in PM concentration (mg m⁻³) | | PM concentrations of targeted regions by production ban in 2017 | Mean ± SD(upper); 21.22 ± 49.89 Mean ± SD(lower); 14.28 ± 25.10 | Paired t-test | t = 3.61, df = 356 (One-tailed) | < 0.01 | [4.03, Inf] |
| Feb.-Mar.; Other time | | PM concentrations of targeted regions by production ban in 2018 | Mean ± SD(upper); 19.17 ± 37.82 Mean ± SD(lower); 11.49 ± 23.87 | Paired t-test | t = 3.45, df = 411 (One-tailed) | < 0.01 | [3.34, Inf] |
| | | PM concentrations nationwide in 2016 | Mean ± SD(upper); 19.22 ± 37.14 Mean ± SD(lower); 15.69 ± 12.00 | Paired t-test | t = 2.23, df = 283 (One-tailed) | 0.01 | [1.02, Inf] |
| | | PM concentrations nationwide in 2017 | Mean ± SD(upper); 15.86 ± 27.31 Mean ± SD(lower); 14.12 ± 19.29 | Paired t-test | t = 3.93, df = 651 (One-tailed) | < 0.01 | [1.26, Inf] |
| | | PM concentrations nationwide in 2018 | Mean ± SD(upper); 13.15 ± 14.49 Mean ± SD(lower); 12.65 ± 31.56 | Paired t-test | t = 4.30, df = 770 (One-tailed) | < 0.01 | [1.28, Inf] |
| | | PM concentrations of targeted regions by production ban in 2016 | Mean ± SD(upper); 22.05 ± 51.02 Mean ± SD(lower); 16.32 ± 14.67 | Paired t-test | t = 1.91, df = 144 (One-tailed) | 0.03 | [0.86, Inf] |
| | | PM concentrations of targeted regions by production ban in 2017 | Mean ± SD(upper); 15.58 ± 34.49 Mean ± SD(lower); 14.09 ± 24.80 | Paired t-test | t = 4.13, df = 314 (One-tailed) | < 0.01 | [1.23, Inf] |
| | | PM concentrations of targeted regions by production ban in 2018 | Mean ± SD(upper); 12.47 ± 19.40 Mean ± SD(lower); 11.45 ± 23.85 | Paired t-test | t = 2.77, df = 375 (One-tailed) | < 0.01 | [1.09, Inf] |
| The exceedance of Jun 2015 for monthly proportion of compliers (%), for examining better compliance than in Jun 2015 | From Mar 2016 to Dec 2018; 88.61 | Proportion of compliers for PM | Mean ± SD(upper); 95.70 ± 2.55 | One sample t-test | t = 16.19, df = 33 (One-tailed) | < 0.01 | [96.47, Inf] |
| | From Sep 2015 to Dec 2018; 98.31 | Proportion of compliers for SO₂ | Mean ± SD(upper); 99.04 ± 0.70 | One sample t-test | t = 6.55, df = 39 (One-tailed) | < 0.01 | [98.65, Inf] |
| | From May 2016 to Dec 2018; 95.36 | Proportion of compliers for NOₓ | Mean ± SD(upper); 97.04 ± 1.71 | One sample t-test | t = 5.02, df = 30 (One-tailed) | < 0.01 | [96.47, Inf] |
| | Facilities producing >=7,000 tons of clinker per day; Facilities producing <7,000 tons of clinker per day | PM concentration (mg m⁻³) | Mean ± SD(upper); 11.05 ± 3.20 Mean ± SD(lower); 11.39 ± 6.55 | Unpaired t-test | t = -0.32, df = 916 (Two-tailed) | 0.75 | [-2.38, 1.71] |
| | | SO₂ concentration (mg m⁻³) | Mean ± SD(upper); 23.83 ± 23.41 Mean ± SD(lower); 20.18 ± 20.79 | Unpaired t-test | t = 1.08, df = 890 (Two-tailed) | 0.28 | [-2.99, 10.29] |
| | | NOₓ concentration (mg m⁻³) | Mean ± SD(upper); 258.67 ± 46.24 Mean ± SD(lower); 231.42 ± 67.00 | Unpaired t-test | t = 2.54, df = 890 (Two-tailed) | 0.01 | [6.22, 48.28] |
| Difference in smokestack concentrations between individual features in 2018 | Facilities aged >30 years; Facilities aged <30 years | PM concentration (mg m⁻³) | Mean ± SD(upper); 11.44 ± 2.88 Mean ± SD(lower); 11.54 ± 3.42 | Unpaired t-test | t = -0.24, df = 1,157 (Two-tailed) | 0.81 | [-0.93, 0.73] |
| | | SO₂ concentration (mg m⁻³) | Mean ± SD(upper); 19.40 ± 12.36 Mean ± SD(lower); 20.39 ± 18.74 | Unpaired t-test | t = -0.43, df = 1,157 (Two-tailed) | 0.67 | [-5.51, 3.53] |
| | | NOₓ concentration (mg m⁻³) | Mean ± SD(upper); 219.98 ± 55.25 Mean ± SD(lower); 233.19 ± 61.84 | Unpaired t-test | t = -1.72, df = 1,157 (Two-tailed) | 0.09 | [-26.30, 1.86] |
| | Incorporated firms; Unincorporated firms | PM concentration (mg m⁻³) | Mean ± SD(upper); 11.20 ± 6.97 Mean ± SD(lower); 11.39 ± 4.62 | Unpaired t-test | t = -0.45, df = 874 (Two-tailed) | 0.66 | [-1.08, 0.68] |
| | | SO₂ concentration (mg m⁻³) | Mean ± SD(upper); 19.50 ± 20.29 Mean ± SD(lower); 22.00 ± 22.32 | Unpaired t-test | t = -1.64, df = 850 (Two-tailed) | 0.10 | [-5.48, 0.49] |
| | | NOₓ concentration (mg m⁻³) | Mean ± SD(upper); 231.65 ± 66.81 Mean ± SD(lower); 232.89 ± 65.90 | Unpaired t-test | t = -0.22, df = 850 (Two-tailed) | 0.83 | [-10.50, 8.41] |
### Difference between ULE-compliers and ULE-noncompliers in 2018

| PM and NO\(\times\) removal efficiencies (%) | Mean ± SD | Compliers: 82.61 ± 5.73 | Unpaired \(t\)-test \(t = 6.03,\) df = 1,334 (One-tailed) | \(< 0.01 [1.52, \text{Inf}]\) |
|---------------------------------------------|-----------|--------------------------|-------------------------------------------------|-----------------------------|
| Ash content of fuel (%) | Mean ± SD | Compliers: 19.09 ± 5.44 | Unpaired \(t\)-test \(t = -7.22,\) df = 650 (One-tailed) | \(< 0.01 [-\text{Inf}, -2.48]\) |
| Sulfur content of fuel (%) | Mean ± SD | Compliers: 0.85 ± 0.63 | Unpaired \(t\)-test \(t = -1.94,\) df = 650 (One-tailed) | \(0.03 [-\text{Inf}, -0.02]\) |
| Volatile content of fuel (%) | Mean ± SD | Compliers: 29.02 ± 7.74 | Unpaired \(t\)-test \(t = 3.36,\) df = 650 (One-tailed) | \(< 0.01 [1.55, \text{Inf}]\) |
| Energy efficiency (coal use per kg clinker; \(\text{kg kg}\)\(^{-1}\)) | Mean ± SD | Compliers: 0.15 ± 0.13 | Unpaired \(t\)-test \(t = -2.40,\) df = 661 (One-tailed) | \(< 0.01 [-\text{Inf}, -0.01]\) |

### Relationship between fuel quality and smokestack concentrations

| | | Correlation analysis | | |
|---|---|---|---|---|
| Ash content of fuel (%) | Smokestack concentration of PM (mg m\(^{-3}\)) | Pearson: \(r = 0.29,\) N = 1,448 | \(< 0.01\) |  |
| Sulfur content of fuel (%) | Smokestack concentration of SO\(_2\) (mg m\(^{-3}\)) | Pearson: \(r = 0.14,\) N = 1,448 | \(< 0.01\) |  |
| Volatile content of fuel (%) | Smokestack concentration of NO\(_\times\) (mg m\(^{-3}\)) | Pearson: \(r = -0.14,\) N = 1,448 | \(< 0.01\) |  |

### Difference in energy efficiency between 2016 and 2018

| | | Paired \(t\)-test | | |
|---|---|---|---|---|
| Energy efficiency (coal use per kg clinker; \(\text{kg kg}\)\(^{-1}\)) | 2016: 0.15 ± 0.08 | \(t = -1.31,\) df = 1,310 (Two-tailed) | \(< 0.01 [-0.01, 0.00]\) |  |
| 2018: 0.16 ± 0.12 | | | |  |

### Differences in pollution controls and fuel quality between Southwest and East

| | | Unpaired \(t\)-test | | |
|---|---|---|---|---|
| PM and NO\(\times\) removal efficiencies (%) | Southwest: 80.31 ± 7.11 | \(t = -3.02,\) df = 697 (One-tailed) | \(< 0.01 [-\text{Inf}, -0.71]\) |  |
| East: 81.86 ± 6.46 | | | |  |
| SO\(_2\) removal efficiency (%) | Southwest: 67.70 ± 17.59 | \(t = -3.26,\) df = 187 (One-tailed) | \(< 0.01 [-\text{Inf}, -4.89]\) |  |
| East: 77.61 ± 20.13 | | | |  |
| Ash content of fuel (%) | Southwest: 24.55 ± 5.73 | \(t = 10.61,\) df = 668 (One-tailed) | \(< 0.01 [4.10, \text{Inf}]\) |  |
| East: 19.70 ± 6.04 | | | |  |
| Sulphur content of fuel (%) | Southwest: 1.36 ± 1.05 | \(t = 12.09,\) df = 668 (One-tailed) | \(< 0.01 [0.60, \text{Inf}]\) |  |
| East: 0.66 ± 0.27 | | | |  |
| Volatiles content of fuel (%) | Southwest: 21.47 ± 8.05 | \(t = -9.89,\) df = 668 (One-tailed) | \(< 0.01 [-\text{Inf}, -4.98]\) |  |
| East: 27.45 ± 7.58 | | | |  |

### Difference in pollution removal efficiency between NO\(_\times\) and PM or SO\(_2\)

| | | Unpaired \(t\)-test | | |
|---|---|---|---|---|
| PM | 98.74 ± 3.74 | | |  |
| NO\(_\times\) | 64.01 ± 11.32 | \(t = -111.71,\) df = 2,979 (One-tailed) | \(< 0.01 [-\text{Inf}, -34.22]\) |  |
| SO\(_2\) | 77.37 ± 19.14 | \(t = -17.14,\) df = 1,849 (One-tailed) | \(< 0.01 [-\text{Inf}, -12.09]\) |  |
## Table S8. Proportion of compliers in 2018.

| Standards                  | Unit       | Dec-18  | 2018  |
|----------------------------|------------|---------|-------|
|                            | Plant      | Production | Plant | Production |
| 2015 emissions standards   | %          | 99.0     | 99.5  | 83.5      | 86.2 |
| Ultralow emissions standards| %          | 9.4      | 9.2   | 0.1       | 0.1  |

## Table S9. Measures penetration in 2018

| Plant         | Measure                         | Unit | Production line | Production |
|---------------|---------------------------------|------|-----------------|------------|
| ULE-compliers | PM control equipment            | %    | 100.0           | 100.0      |
|               | SO\textsubscript{2} control equipment | %    | 19.7            | 20.6       |
|               | NO\textsubscript{X} control equipment | %    | 100.0           | 100.0      |
|               | Cleaner fuel (natural gas)      | %    | 2.1             | 2.5        |
|               | PM control equipment            | %    | 100.0           | 100.0      |
| ULE-noncompliers | SO\textsubscript{2} control equipment | %    | 40.4            | 45.6       |
|               | NO\textsubscript{X} control equipment | %    | 99.8            | 99.9       |
|               | Cleaner fuel (natural gas)      | %    | 0.0             | 0.0        |
|               | PM control equipment            | %    | 99.5            | 99.7       |
|               | SO\textsubscript{2} control equipment | %    | 26.9            | 32.5       |
|               | NO\textsubscript{X} control equipment | %    | 92.1            | 98.3       |
|               | Cleaner fuel (natural gas)      | %    | 1.4             | 0.8        |
|               | PM control equipment            | %    | 99.7            | 99.9       |
| Others        | SO\textsubscript{2} control equipment | %    | 25.7            | 29.2       |
|               | NO\textsubscript{X} control equipment | %    | 95.5            | 99.1       |
|               | Cleaner fuel (natural gas)      | %    | 1.2             | 1.0        |
| Overall       | PM control equipment            | %    | 99.7            | 99.9       |
|               | SO\textsubscript{2} control equipment | %    | 25.7            | 29.2       |
|               | NO\textsubscript{X} control equipment | %    | 95.5            | 99.1       |
|               | Cleaner fuel (natural gas)      | %    | 1.2             | 1.0        |

## Table S10. Theoretical flue-gas rates.

| Process     | Unit    | Theoretical value\textsuperscript{a} | Measured mean\textsuperscript{b} | Measured range\textsuperscript{b} (%) |
|-------------|---------|---------------------------------------|-----------------------------------|---------------------------------------|
| Kiln head   | Nm\textsuperscript{3}/t | 1,800                                | 1,572                             | ± 6.69                                |
| Kiln tail   | Nm\textsuperscript{3}/t | 2,500                                | 2,639                             | ± 4.89                                |

Note:

\textsuperscript{a} Represents the values are derived from the Technical Specification for Application and Issuance of Pollutant Permit Cement Industry;\textsuperscript{b} Represents the values are estimated based on the samples of flue-gas volume collected at 919 facilities in the CEMS dataset.
### Table S11. Input data for future outlook.

| Input | Explanation | Data or data source for 2060 (y=2060) | Unit | Assumption or method | Reference |
|-------|-------------|--------------------------------------|------|----------------------|----------|
| Emissions | Emissions of air pollutant or CO$_2$ | $E_{i,y}=E_{i,y-1}A_{i,y}$ | g | The same method as that for 2014-2018 (Eq. (2)) | Bo et al. (2021); Tang et al. (2019) |
| EF | Emissions factor for air pollutants | $EF_{i,y}=C_{i,y}$ | g/kg | The same method as that for 2014-2018 (Eq. (3)) | Bo et al. (2021); Tang et al. (2019) |
| EF$_{CO_2}$ | Emissions factor for CO$_2$ | CEMBUREAU (2020) | g/kg | Assuming that all plants will reach the carbon-neutral levels in 2060 | CEMBUREAU (2020); Liu et al. (2015); Liu et al. (2021) |
| C | Pollution concentrations of air pollutants | $C_{i,y}=\min(C_{i,y}, S_{i,y}, Y_{i,f})$ | g/m$^3$ | Assuming that the plants having not reached the ultralow emissions (ULE) standards in 2018 will achieve the compliance in 2060 | Tang et al. (2019) |
| S$_{ULE}$ | ULE standards | | | ULE standards that have been implemented in Hebei province (currently the most stringent worldwide) | Department of Ecology and Environment of Hebei Province (2020) |
| V | Theoretical flue-gas rate | $1800$ for kiln head, $2500$ for kiln tail | Nm$^3$/t | A comprehensive field measurement | MEE (2017) |
| A | Activity level, represented by cement production | $A_{i,y}=A_{i,y-1}P_{y}A_{i,y}$ | kg | Assuming that plants will follow a uniform development rate in production and retire if small (producing < 2,000 tons of clinker per day) or outdated (> 30 years old) | Bo et al. (2021) |
| P | Cement production | $P_{y}A_{i,y}$ | ton | Assuming that the total production should meet the total demand (Eq. (5)) | Li et al. (2017) |
| Cl$_{i,1}$ | Cement intensities for urban building | 0.33 | ton/m$^2$ | - | Li et al. (2017); Riahi et al. (2017) |
| Cl$_{i,2}$ | Cement intensities for rural building | 0.17 | - | - | Li et al. (2017); Tong et al. (2010) |
| Cl$_{i,3}$ | Cement intensities for highway | 3,700 for ordinary road, 9,000 for expressway | ton/km | Statistical analysis of the data for six projects (covering a total length of 942 kilometers of road) | CCA (2019); Li et al. (2017); Tong et al. (2010) |
| Cl$_{i,4}$ | Cement intensities for railway | 1,600 | ton/km | - | Li et al. (2017) |
| Cl$_{i,5}$ | Cement intensities for rural infrastructure | 0.03 | billion tons/trillion | - | Li et al. (2017); Xu et al. (2020) |
| CP | Demand of cement products for building, highway or railway | $CP_{i,y}=CP_{i,y-1}+POP_{i,y}$ | - | Projection based on the financial expenditure for agriculture and development of primary industry | Li et al. (2017); Xu et al. (2020) |
| PCP | Demand of cement products for rural infrastructure | 6.93 | trillion RMB yuan | - | Li et al. (2017) |
| POP | Population | 1.33 | billion | Following the paths of five shared socioeconomic pathways (SSPs) | Riahi et al. (2017) |
| PCP$_{u}$ | Per capita urban building | 42.70 | m$^2$ | Assuming that it will follow the paths of economic in SSPs and reach the current level of developed countries in 2060 | Li et al. (2017); Riahi et al. (2017) |
| PCP$_{r}$ | Per capita rural building | 54.90 | m$^2$ | Assuming that it will follow the paths of economic in SSPs and reach the current level of developed countries in 2060 | Li et al. (2017); Riahi et al. (2017) |
| PCP$_{h}$ | Per capita highway mileage | 45.04 | km | Assuming that it will follow the paths of economic in SSPs and reach the expected levels of National Highway Network Planning for 2030 and current level of developed countries in 2060 | Li et al. (2017); MOT (2013); Riahi et al. (2017) |
| PCP$_{r}$ | Per capita railway mileage | 2.48 | km | Assuming that it will follow the paths of economic in SSPs and reach the expected levels of Medium and Long Term Railway Network Planning for 2025 and current level of developed countries in 2060 | Li et al. (2017); MOT (2016); Riahi et al. (2017) |
| DR$_{u}$ | Discarded rate of urban building | 2% | - | Assuming that it will reach the designed lifetime of 50 years after 2030 | Yin et al. (2017) |
| DR$_{r}$ | Discarded rate of rural building | 2% | - | Assuming that it will reach the designed lifetime of 50 years after 2030 | Yin et al. (2017) |
| DR$_{h}$ | Discarded rate of highway | 0.22% for expressway, 0.73% for other highway | - | - | Highway Performance Assessment Standards (JTG 5210-2018) | MOT (2018) |
\[ DR_{i,c} \]: Discarded rate of railway
- 6.67% for ballasted base railway - Assuming a lifetime of 15 years
- 2% for non-ballasted base railway - Assuming a lifetime of 50 years

\[ \text{Cement demand of other sectors} \]
\[ 17.4\% \sum CP_{i,y} \times CI_{i,y} \] ton
Assuming that it account for a constant share of total demand

Index:
- \( s \): Species of emissions
- \( f \): Generating facility
- \( p \): Production process
- \( h,m,y \): Time indexes for hour (\( h \)), month (\( m \)) and year (\( y \))
- \( i \): Cement product

Li et al. (2017)\(^5\)
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