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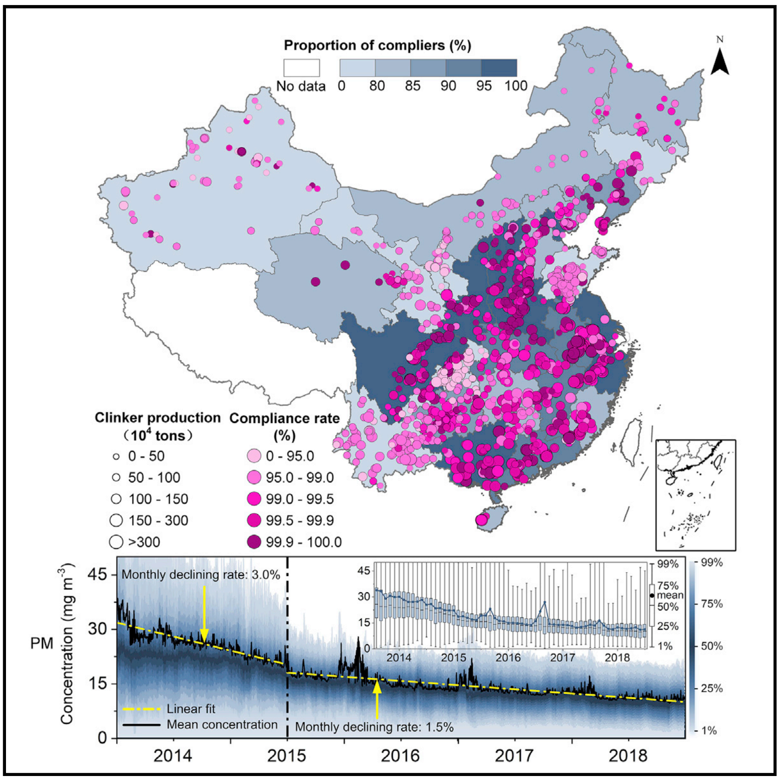
# Plant-level real-time monitoring data reveal substantial abatement potential of air pollution and $CO_2$ in China's cement sector

## 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
- $CO_2$ increased by 5% in the absence of $CO_2$ regulation during 2014–2018
- Pollutants and $CO_2$ will decline largely if realizing clean air and climate targets


## Authors

Ling Tang, Jianhui Ruan, Xin Bo, Zhifu Mi, Shouyang Wang, Guangxia Dong, Steven J. Davis

## Correspondence

boxin@buct.edu.cn (X.B.), z.mi@ucl.ac.uk (Z.M.), sjdavis@uci.edu (S.J.D.)



## 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, $SO_2$, $NO_X$) and $CO_2$. We find that air pollutant emissions have decreased, but $CO_2$ 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 $CO_2$ in China's cement sector

Ling Tang,[1,2] Jianhui Ruan,[1] Xin Bo,[3,*] Zhifu Mi,[4,9,*] Shouyang Wang,[1,5] Guangxia Dong,[6] and Steven J. Davis[7,8,*]

[1]School of Economics and Management, University of Chinese Academy of Sciences, Beijing 100190, China
[2]School of Economics and Management, Beihang University, Beijing 100191, China
[3]Department of Environmental Science and Engineering, Beijing University of Chemical Technology, Beijing 100029, China
[4]The Bartlett School of Sustainable Construction, University College London, London WC1E 7HB, UK
[5]Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100190, China
[6]China National Environmental Monitoring Centre, Beijing 100012, China
[7]Department of Earth System Science, University of California at Irvine, Irvine, CA 92697, USA
[8]Department of Civil and Environmental Engineering, University of California at Irvine, Irvine, CA 92697, USA
[9]Lead contact
*Correspondence: boxin@buct.edu.cn (X.B.), z.mi@ucl.ac.uk (Z.M.), sjdavis@uci.edu (S.J.D.)
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**SCIENCE FOR SOCIETY** Cement is widely used in infrastructures (e.g., buildings and roads) and is key to socioeconomic development. Yet cement production has enormous environmental impacts: it is the third largest industrial source of air pollution and if the cement industry were a country, it would rank as the world's fourth largest greenhouse gas emitter. China, the biggest cement producer in the world, set strict air pollution standards for cement production in 2015. However, whether these standards can improve cement plants' air quality and also benefit $CO_2$ mitigation remains unclear. We move closer to answering this question by collecting hourly based air pollutants (PM, $SO_2$, $NO_X$) observations from each cement plant's smokestack and calculating $CO_2$ emissions based on each plant's energy use and cement production details. Our data show that although the 2015 standards led to significant reductions in air pollution emissions by 2018, a lack of $CO_2$-specific policies led to a 5% increase in $CO_2$ 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.

## SUMMARY

China is the world's greatest cement producer, generating significant air pollution and $CO_2$ 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 [$SO_2$], nitrogen oxide [$NO_X$]) and $CO_2$ emissions. Our analysis shows that regulations introduced in 2015 led to PM, $SO_2$, and $NO_X$ reductions of 50.3%, 43.6%, and 34.2%, respectively, but $CO_2$ increased by 5%. Interestingly, 9.4% of the plants analyzed reached China's 2020 ultralow air pollution standards in 2018. Further analysis shows that if small and old plants are phased out and all remaining plants implement advanced equipment and improve fuels and energy efficiency, PM, $SO_2$, $NO_X$, and $CO_2$ could be further reduced by 68.8%, 66.1%, 82.2%, and 62.0% by 2060. Our results reveal the co-benefits of clean air and climate policies for cement production.

## INTRODUCTION

The global cement industry is the third largest source of industrial air pollution, including particulate matter (PM), sulfur dioxide ($SO_2$), and nitrogen oxide ($NO_X$),[1] and it is responsible for 8% of global $CO_2$ 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,[4–6] $SO_2$,[5–8] and $NO_X$[5–8] 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[6,28–30] resorted 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[9,22–24,32] and systematically analyzing the uncertainties. These results provide evidence of the potential

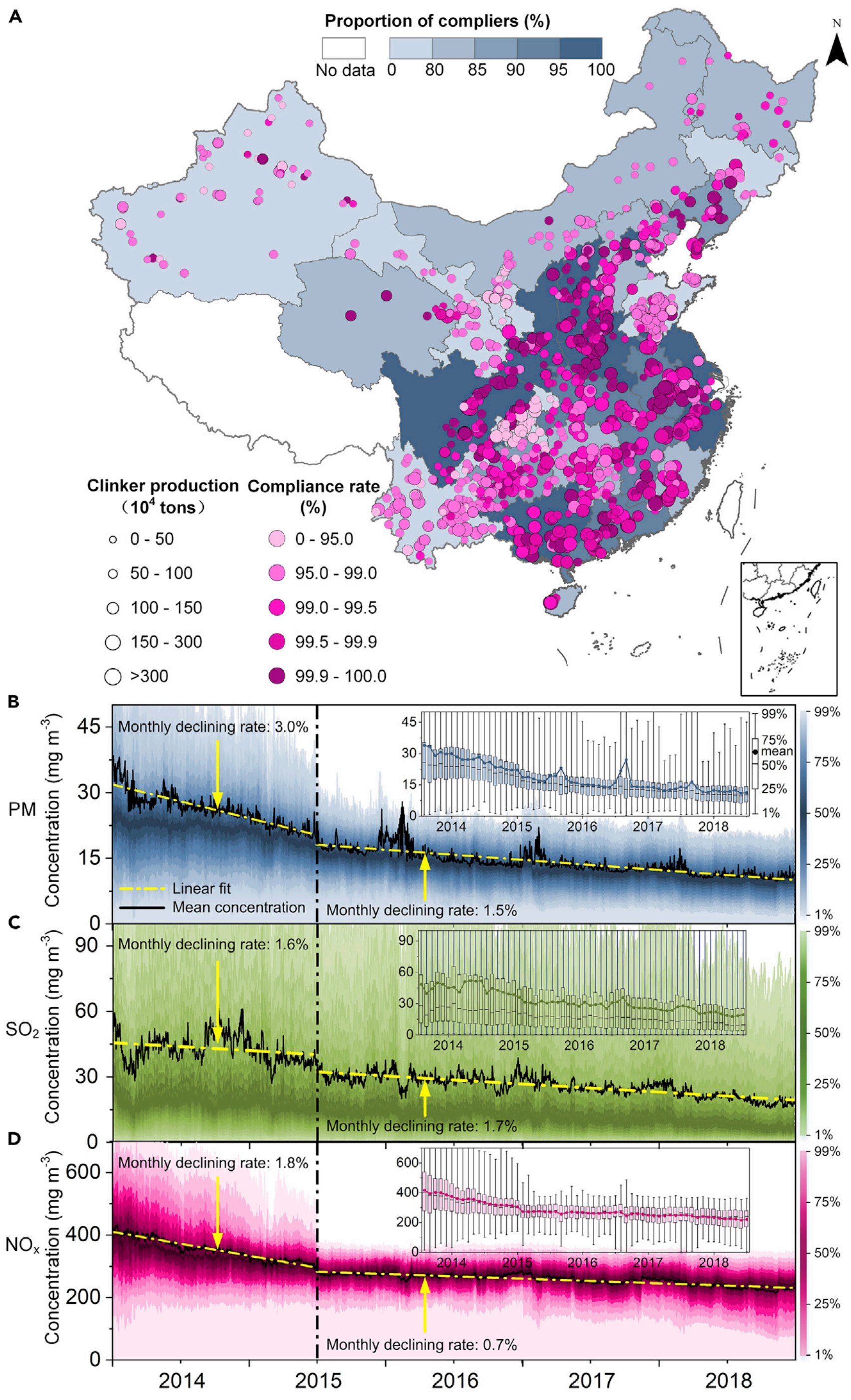


**Figure 1. Geographic and temporal distributions of smokestack concentrations at Chinese cement plants 2014–2018**

(A) The cement plants operating in mainland China for 2018 (totalling 1,162 plants), of which 74.87% were covered by the Chinese CEMS network (accounting for 87.58% 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 prevailing standards, %); the background represents the proportion of compliers in the given province (%).

(B–D) Daily and monthly (in the insets) distributions for (B) PM, (C) $SO_2$, and (D) $NO_X$ smokestack concentrations (mg $m^{-3}$). The color gradation indicates the percentiles of daily smokestack concentrations; the black dashed vertical lines mark July 1, 2015, when the new emission standards were implemented; the black full curves show 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 and dots indicate the quartiles and mean of monthly smokestack concentrations, respectively.

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, $SO_2$, and $NO_X$ concentrations emitted from Chinese cement plants after 2013 (Figures 1B–1D; Table S6). Between 2014 and 2018, the daily PM, $SO_2$, and $NO_X$ 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 $NO_X$ 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 $SO_2$ concentrations' declining rates (1.6% per month) were otherwise 8.2% smaller before the deadline than after. Moreover, the $SO_2$ 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 $NO_X$, respectively) between 2014 and 2018. Such larger reductions and more convergent observations for PM and $NO_X$ reflect the fact that more plants were out of compliance with the impending reduced PM and $NO_X$ 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) $SO_2$ standards (to which only 3.7% of plants did not comply). Many plants, therefore, had to rapidly and substantially reduce their PM and $NO_X$ emissions to meet these new standards before they entered into force in July 2015. In July 2015, PM, $SO_2$, and $NO_X$ 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%,

**Table 1. Effect of individual and regional features on smokestack concentrations**

| | Logged smokestack concentrations in 2018 (mg $m^{-3}$) | | |
|---|---|---|---|
| Dependent variables | PM | $SO_2$ | $NO_X$ |
| 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 (¥ 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 |
| $R^2$ | 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[33] when the production ban for winter or heating season[34,35] is over (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 all targets in July 2015 dropped by only 3.0% (Figure S3). Moreover, the previous levels of compliance with prevailing PM, $SO_2$, and $NO_X$ standards were regained after 9, 3, and 11 months, respectively, and since March 2016, September 2015, and May 2016, respectively, significantly more plants were in compliance with the new (2015) standards than had been the previous (2004) standards in June 2015 (see t tests in Table S7). By the end of 2018, 99.0% of plants were in compliance with all pollutant standards, and mean PM, $SO_2$, and $NO_X$ concentrations were 63.2%, 91.0%, and 43.1% lower than the 2015 standards, respectively, likely as a result of the incentives for overcompliance (e.g., discounts on sewage fees and environmental taxes, as well as profits from surplus pollution permits[36–38]).

Our results also show that the most-polluting plants in 2014 were prioritized for controlling smokestack concentration and mostly brought into compliance by 2018. For example, in 2014, the share of out-of-compliance measurements with the impending 2015 standards was greatest in the northwestern region of China (30.3%), but by 2018, only 0.5% of total measurements there did not comply with the standards (an improvement of 42.7% in compliance; Figure S4). In comparison, the eastern region, where compliance was the greatest in 2014 (78.6%), showed the least improvement 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[39]) complied with the impending standards (compared with 77.8% for large facilities producing ≥4,000 tons of clinker per day[39]); 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 $NO_X$ concentrations were substantially reduced at plants with updated pollution-control equipment,[40] which was installed on 99.7% and 95.5% of production lines, respectively, by 2018. We see that plants whose control technologies achieved higher removal efficiencies indeed had lower smokestack pollutant concentrations. In comparison, $SO_2$ control systems were deployed on only 25.7% of production lines in 2018, mainly because cement raw meal is already quite efficient at fixing sulfur during pulverized coal combustion.[41] Another key measure for reducing smokestack concentrations is improving fuel quality. For example, PM and $SO_2$ 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

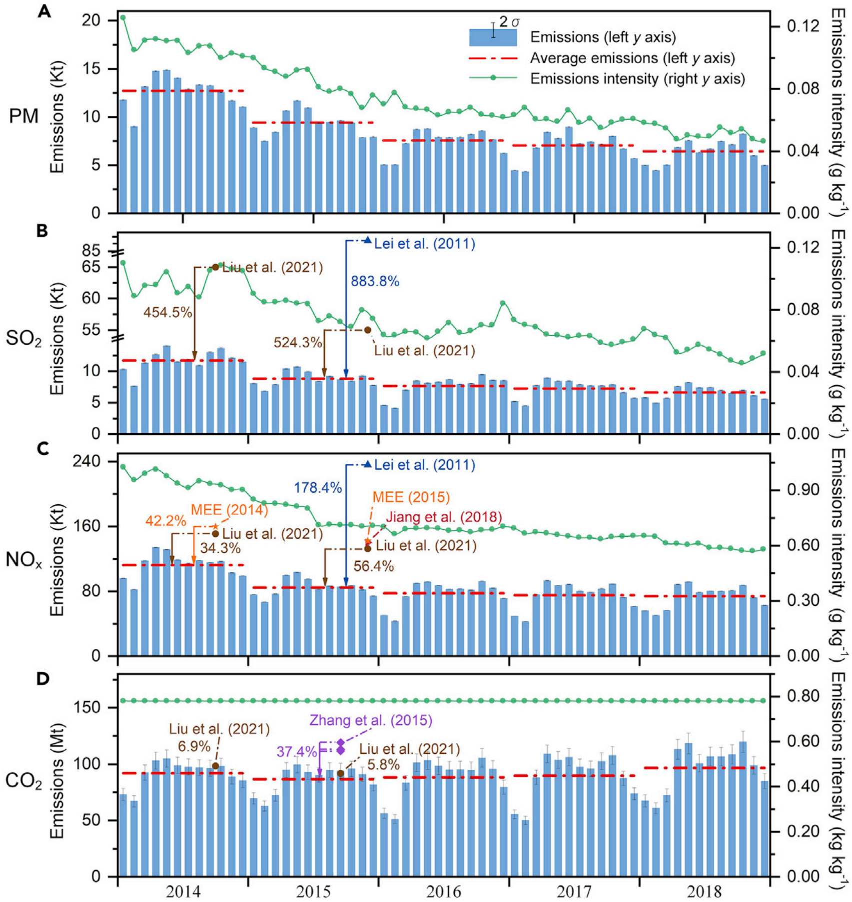

**Figure 2. Emissions and emissions intensities of Chinese cement plants 2014–2018**

(A–D) Monthly emissions (blue bars; in Kt or Mt, left y axis) and emissions intensities (dotted green curves; g kg$^{-1}$ or t kg$^{-1}$, right y axis) for (A) PM, (B) $SO_2$, (C) $NO_X$, and (D) $CO_2$. For comparison, the discrete data points represent the emissions estimates by previous studies (in Kt or Mt, left y axis). The dashed horizontal lines indicate the annual emissions; the $2\sigma$ represents the uncertainty ranges of estimation, defined as 2 standard deviations (SDs); and the percentages are the difference of existing estimates (discrete data points) from our estimates (dashed horizontal lines).

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.[42] 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 $NO_X$ 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, $SO_2$, and $NO_X$, respectively, in 2018.

Concomitant with the observed reductions in smokestack concentrations, the emissions intensities of PM, $SO_2$, and $NO_X$ (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 (45.5%). These disproportionate reductions also served to narrow the disparity among facilities: monthly standard variances in PM, $SO_2$, and $NO_X$ emissions intensities decreased by 37.2%, 50.3%, and 41.0%, respectively, from 2014 to 2018. In contrast, because polices regulating $CO_2$ emissions from cement plants are not widespread, plants' $CO_2$ emissions intensities were virtually unchanged from 2014 to 2018 (decreasing by an average of <0.01% to 0.78 kg $CO_2$ per kilogram of clinker; Figure 2D).

Thus, although Chinese clinker production increased by 5.0% in 2014–2018, the decreased emissions intensities of pollutants nonetheless led to systematic reductions in cement-related air pollution (PM, $SO_2$, and $NO_X$ emissions decreased by 50.3%, 43.6%, and 34.2%, respectively; bars in Figures 2A–2C, S7, and S8), whereas cement-related $CO_2$ emissions rose by 5.0% over the same period (Figures 2D and S8–S10; Note S2). Notably, our CEMS-based analyses suggest that previous studies[9,22–24] that applied average emissions intensities evaluated as of or before 2010 overestimated cement-related air pollution by 34.3%–883.8%. In contrast, our estimated cement-related $CO_2$ emissions largely mirror the clinker production trends, first decreasing by 5.8% (from 1.10 to 1.04 Gt) in 2014–2015 and then increasing by 11.5% (to 1.16 Gt) in 2015–2018; these findings are consistent with prior estimates (differing by 5.8%–37.4%).[9,32]

## Future mitigation of air pollutants

Although PM, $SO_2$, and $NO_X$ 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 (producing <2,000 tons of clinker per day or aged >30 years), we assess further decreases in average PM, $SO_2$, and $NO_X$ emissions intensities by 36.1%, 30.5%, and 63.6%, respectively, and total reductions in PM, $SO_2$, and $NO_X$ by 42.4%, 37.5%, and 67.2%, respectively (Figure 3; see experimental procedures for details). However, although a similar ULE policy implemented for Chinese power plants nationwide led to substantial emissions reductions,[20] attaining the ULE standards throughout the Chinese cement industry may be more challenging: as of 2018, 16.5% of plants did not yet comply with the 2015 standards. However, 9.4% of cement plants had already achieved ULE levels by the end of 2018 (Table S8), supporting the operational feasibility of the ULE standards and pointing to specific abatement measures for other plants to follow. By comparing with the operations and technologies of these ULE-compliant plants (Tables S7 and S9), a ULE-noncompliant plant can identify its leverage points and select the corresponding (commonly multiple) abatement measures for ULE renovations (colored bars in Figures 3A–3C; see "estimation of future emissions reductions" in experimental procedures).

Our analysis shows that improving pollution-control equipment will still be important for future mitigation,[40,43] associated with 32.9%, 78.5%, and 83.9% of potential reductions in PM, $SO_2$, and $NO_X$, respectively, if all facilities meet the ULE standards (blue bars in Figures 3A–3C). These percentages represent the potential emissions reductions from the ULE-noncompliant facilities using the associated measure (improving pollution controls here). PM and $NO_X$ control equipment were already widespread in Chinese cement plants as of 2018 (covering 99.7% and 95.5% of production lines, respectively). However, removal efficiencies of PM and $NO_X$ in the plants that did not meet ULE standards in 2018 were 0.1% and 11.9%, respectively, lower than those in ULE-complying plants ($p < 0.01$; Table S7). Thus, upgrading such poorer pollution-control equipment is estimated to reduce total PM and $NO_X$ emissions by 13.9% and 55.7% or 32.8% and 82.9% of total abatement potentials, respectively (light blue bars in Figures 3A and 3C). In contrast, $SO_2$ control equipment was installed on only 25.7% of production lines in 2018, and a majority (59.6%) of the production lines that did not achieve the ULE levels had not yet introduced $SO_2$ control equipment by 2018. We estimate that installing advanced control technologies at these ULE noncompliers will thus reduce $SO_2$ emissions by 23.4%, associated with 62.5% of total potential reduction (dark blue bars in Figure 3B).

Another considerable opportunity for encouraging future PM, $SO_2$, and $NO_X$ reductions is improving fuel quality,[43] associated with 65.6%, 35.6%, and 67.8% of mitigation potentials, respectively, under the ULE scenario (pink bars in Figures 3A–3C). Generally, plants using better fuels, in terms of lower ash, lower sulfur, and higher volatile contents, tend to have a lower level of smokestack concentrations ($p < 0.01$; Table S7). As a result, further fuel improvements represent a large mitigation opportunity: the fuels used in the plants that reached the ULE standards in 2018 were significantly better (with ash, sulfur, and volatile contents averaging 19.1%, 0.9%, and 29.0%, respectively) than those used in the plants that did not yet meet the ULE levels (22.3%, 1.0%, and 26.0%, respectively; $p < 0.05$; Table S7). This pattern emphasizes improving fuel quality in ULE renovations, which is estimated to further reduce total PM, $SO_2$, and $NO_X$ emissions from Chinese cement plants by 27.9%, 13.3%, and 45.6%, respectively.

As part of the country's targeted energy structure transition, the Chinese government is encouraging a shift to fuels that are cleaner than coal.[13,44] 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, $SO_2$, and $NO_X$, 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, $SO_2$, and $NO_X$ 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, $SO_2$, and $NO_X$ 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[32,45] to further reduce PM, $SO_2$, and $NO_X$ 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).[45,46] 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, $SO_2$, and $NO_X$ 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.[11,12] 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, $SO_2$, and $NO_X$, 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 $NO_X$ 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

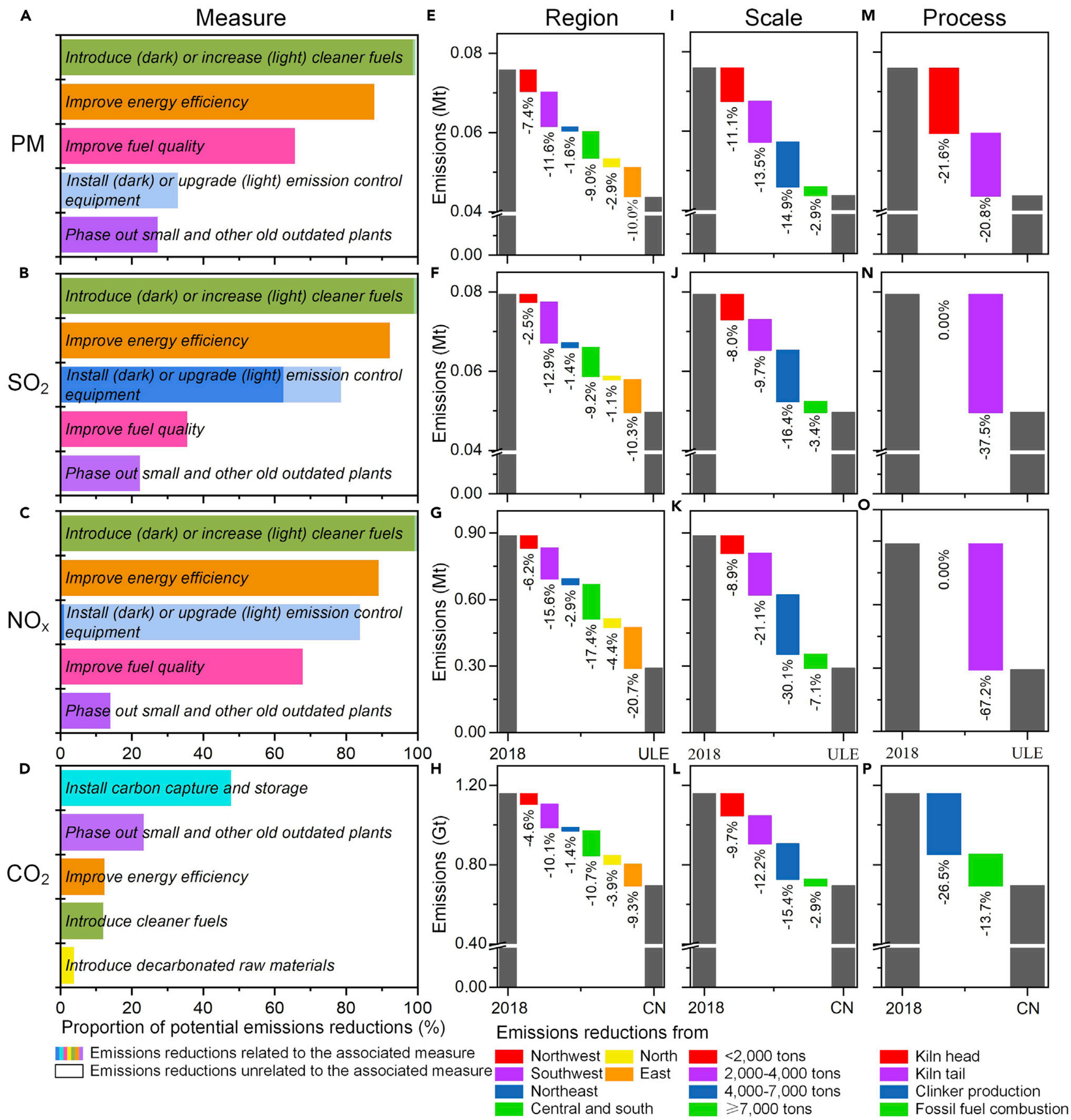


**Figure 3. Potential emissions reductions from Chinese cement plants**

(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) $SO_2$, and (C) $NO_X$.

(D) Estimated reductions in $CO_2$ 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) $SO_2$, (G, K, and O) $NO_X$, and (H, L, and P) $CO_2$ 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.[21] 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, $SO_2$, and $NO_X$ 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, $SO_2$, and $NO_X$ (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, $SO_2$, and $NO_X$ 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, $SO_2$, and $NO_X$, 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, $SO_2$, and $NO_X$, 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 $NO_X$ controls is striking, particularly for kiln tails (Figures 3C and 3O), because not only $NO_X$ removal efficiencies (averaging 64.0%) were significantly lower than PM and $SO_2$ controls (98.7% and 77.4%, respectively; $p < 0.01$; Table S7) but also a considerable part of $NO_X$ emissions are from thermal $NO_x$ formation.[47] This suggests that such an effort will reduce $NO_X$ emissions far more than updating PM (300.4% more) and $SO_2$ control equipment (824.7%).

### The potential of $CO_2$ mitigation

Given that roughly two-thirds of $CO_2$ emissions from cement production are related to the calcination process, the goal of eliminating $CO_2$ emissions from the industry is challenging and may entail substantial changes to production lines.[48,49] According to recent analyses,[31,32,45,48] promising $CO_2$ 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[20,50] and the four $CO_2$ abatement measures introduced above are employed to achieve carbon-neutral levels,[31,48] we estimate that $CO_2$ emissions intensities will decrease by 30.9% (to an average of 0.54 kg per kilogram of clinker), and that cement-related $CO_2$ 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 $CO_2$ emissions in 2018 and will represent 26.7% of potential $CO_2$ 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, $SO_2$, $NO_X$, and $CO_2$ 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 $CO_2$ 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, $SO_2$, $NO_X$, and $CO_2$ abatement totals, respectively. Interestingly, because the majority of air pollutants, but only 33.4% of $CO_2$, are derived from energy combustion,[25] 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,[51] will contribute to 39.0%, 44.1%, 29.6%, and 43.6% of the potential mitigation in PM, $SO_2$, $NO_X$, and $CO_2$, 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

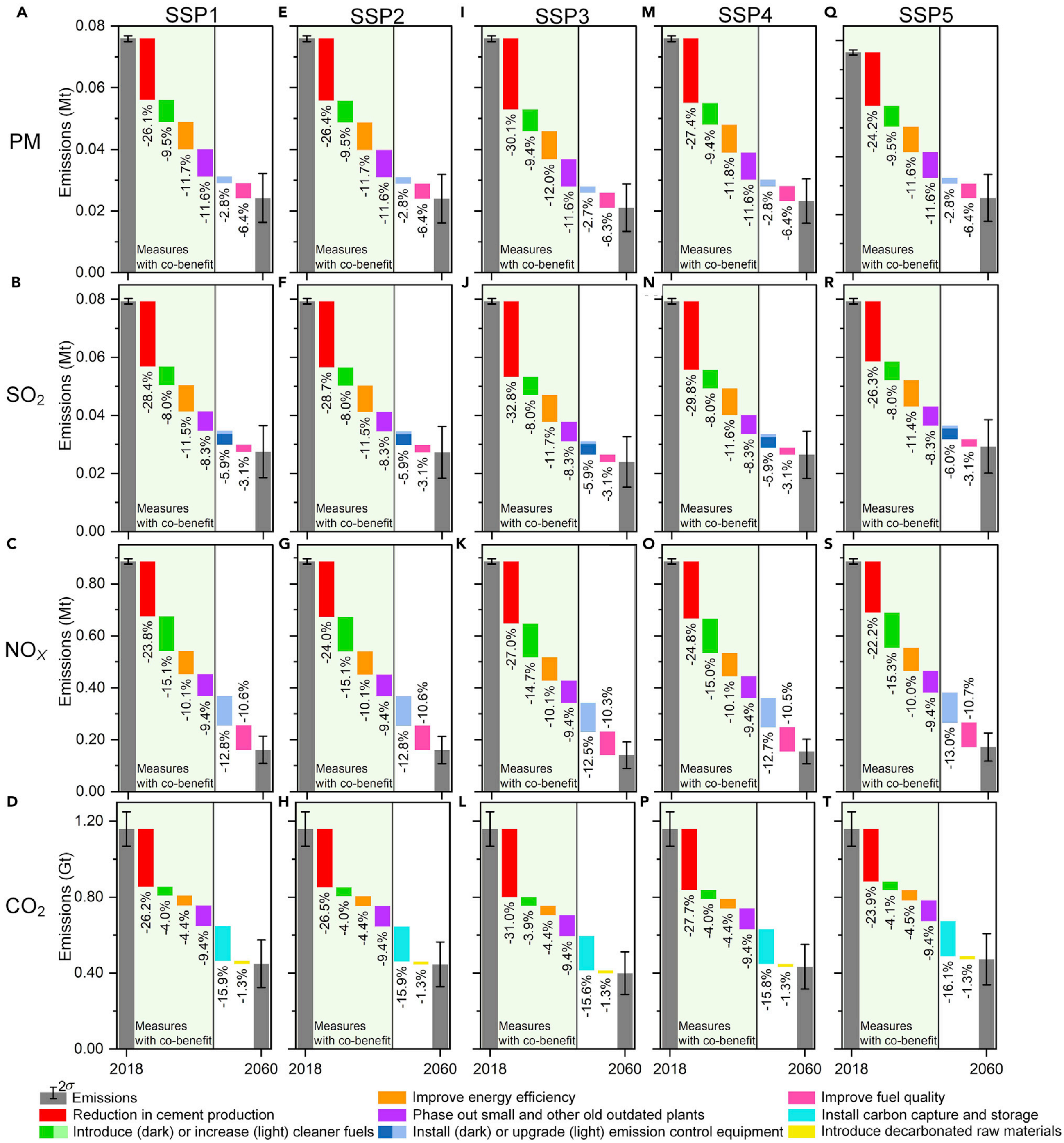


**Figure 4. Potential future emissions reductions from 2018 to 2060**

(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) $SO_2$, (C, G, K, O, and S) $NO_X$, and (D, H, L, P, and T) $CO_2$. 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.

inventories for the Chinese cement industry,[9,22–24] 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 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 $CO_2$ emissions by 62.0% by 2060.

Our analyses of CEMS measurements substantiate the effectiveness of stricter PM, $SO_2$, and $NO_X$ 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 $CO_2$ emissions, as well as the importance of involving $CO_2$ in the CEMS network for ensuring direct, continuous, overall policy oversight as the United States does.[30] 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 $CO_2$ emissions. Regarding the abatement measures, our results reveal that end-of-pipe pollution controls and CCS represent great opportunities to reduce air pollutants and $CO_2$ emissions, respectively. However, the co-benefits of these two options are limited: CCS technologies will do little to reduce co-emitted air pollutants,[52] or may even exacerbate the problem because of their energy penalty,[53] and vice versa.[54] Furthermore, the installation, maintenance, and upgrading of state-of-the-art pollution controls and CCS systems are among the costliest options,[32,45] such that adopting both of them might not be economical. In contrast, our results point to substantial co-benefits from fuel switching[13,44] (especially from coal to natural gas or biomass[54]), improved energy efficiencies[32,45] (particularly through technological upgrading[46]), and phasing out inefficient facilities,[11,12] all of which will simultaneously reduce both air pollutants and $CO_2$ 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 $CO_2$ 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),[55] 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,[53] and $CO_2$ emissions reduction that results 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 $CO_2$. This system probably includes a variety of economic instruments, such as pollution permits exchanges[38] and environmental taxes,[37] to reduce air pollutants, as well as national emissions trading scheme (ETS) market[56] and carbon taxes[57] for $CO_2$, and administrative instruments, such as emissions standards[16,17] and backward production capacity reductions.[27] In turn, the facility-level, dynamic and nationwide estimates of air pollutants and $CO_2$ emissions from Chinese cement plants included in our CEAC database can support the development of such policies. For example, our detailed map points 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,[32] human health benefits,[53] and climate change impacts,[53] associated with the emissions changes at Chinese cement plants. Our analysis of the co-benefits between clean air and climate polices 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.[3,58]

## 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, $SO_2$, and $NO_X$ (which are the targets of the current emissions standards policy) and $CO_2$ 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 datasets, facility-specific information and smokestack-level CEMS data, both of which were exclusively provided by the MEE.[20,21] 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%,[16] 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.[21,59] Using CEMS-monitored smokestack-level PM, $SO_2$, and $NO_X$ 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.[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).[20,21,60] Compliance ratio measures the exceedance of the associated standard for a given pollution concentration (see Equation 1):[21]

$$R_{s,f,p,h} = \frac{S_{s,f,p} - C_{s,f,p,h}}{S_{s,f,p}}, \qquad \text{(Equation 1)}$$

where the indexes $s$, $f$, $p$, and $h$ indicate the species of emissions, generating facility, production process, and hour, respectively; $S$ represents the emissions standard (g $m^{-3}$), specified by the related regulations[16,17]; $C$ is the pollution concentration measured by CEMS (g $m^{-3}$); 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 $CO_2$ emissions from Chinese cement plants on a facility and monthly basis (see Equation 2):[20,21,59]

$$E_{s,f,p,m} = EF_{s,f,p,m} \times A_{f,p,m}, \qquad \text{(Equation 2)}$$

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 $kg^{-1}$) or fuel consumption (g $kg^{-1}$ for solid or liquid fuels and g $m^{-3}$ 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 facility-level data (provided by the MEE) and allocated on a monthly scale according to monthly provincial clinker production (available at: http://www.cementchina.net/);[20,21] 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,[9,22–24] as shown in Equation 3:

$$EF_{s,f,p,h} = C_{s,f,p,h} \times V_{f,p}, \qquad \text{(Equation 3)}$$

where $V$ indicates the theoretical flue-gas rate, calculated as the volume of flue gas per unit of clinker production ($m^3$ $kg^{-1}$); and $EF$ is the emissions factor, represented by the volume of air pollutants per unit of clinker production (g $kg^{-1}$), in which the effect of pollution-control systems (if employed) is considered as CEMS monitors are deployed at smokestacks.

Notably, theoretical flue-gas rates were introduced to avoid substantial underestimation attributable to a large proportion of missing data on flue-gas volume in the CEMS dataset.[20,21,59] Such theoretical rates were computed based on systematic on-site measurements conducted by the MEE (Table S10),[61] and flue-gas volume was calculated by multiplying the theoretical flue-gas rates by the associated clinker production. Nevertheless, we examined the theoretical flue-gas rates based on the available samples of flue-gas volume collected at 919 facilities in the CEMS dataset. We found that the actual flue-gas rates drawn from CEMS-monitored samples generally approached the corresponding theoretical values, with a range of ±6.69% at the 95% confidence level. This result is consistent with the findings of previous research[20,21,59] and, again, support the employment of theoretical flow rates.

The Chinese government has designed and implemented a series of strict policies to ensure the reliability of CEMS data;[20,21,59] however, some null and abnormal observations still exist in the CEMS dataset. Seriously following CEMS-related regulations, we set null values (or zeros) successive for >24 h to the associated monthly mean and null values successive for 1–24 h to the arithmetic mean of the two closest valid values recorded before and after the missing value;[20,21,62] in addition, we treated abnormal values (e.g., those beyond the measurement ranges of the associated CEMS monitors) in the same way as null values.[62]

#### *Emissions factors of $CO_2$*

The $CO_2$ emissions from cement plants are primarily attributable to limestone dissociation and fuel combustion, which can be calculated based on $CO_2$ process and fuel emissions factors, respectively.[48,49] $CO_2$ process emissions factors for different kiln types, represented as the volume of $CO_2$ emissions per unit of clinker production (g $kg^{-1}$), were derived from a nationwide sampling survey in China.[9] $CO_2$ fuel emissions factors were estimated according to the method of the Intergovernmental Panel on Climate Change (IPCC),[63,64] as shown in Equation 4:

$$EF_{CO_2,f} = CA_f \times O_f \times H_f \times 44/12, \qquad \text{(Equation 4)}$$

where $CA$ indicates the carbon content of fuels (kg $GJ^{-1}$); $O$ denotes the carbon oxidation rate of fuels (%); $H$ represents the heating value (KJ $g^{-1}$ for solid or liquid fuels and MJ $m^{-3}$ for gas fuels); 44/12 means the molecular weight ratio of $CO_2$ to carbon; and$EF_{CO_2}$ is the $CO_2$ fuel emissions factor estimated herein, defined as the volume of $CO_2$ emissions per unit of fuel combustion (g $kg^{-1}$ for solid or liquid fuels and g $m^{-3}$ for gas fuels). These inputs used to estimate $CO_2$ fuel emissions factor were specified according to previous literature.[25]

### Estimation of future emissions reductions

Using our facility-level dataset and the same bottom-up method described earlier (Equations 2, 3, and 4), we performed an *ex ante* assessment of the potential mitigation in China's cement-related air pollutants and $CO_2$ 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,[31] or hold production at the 2018 level[21] or are retired if small (producing <2,000 tons of clinker per day) or outdated (aged >30 years),[11,12] 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),[26] 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.[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,[51] which was estimated by adding up the cement products demanded multiplied by the associated cement use intensities,[51,67,68] as shown in Equation 5:

$$P_y = \sum_{i=1} CP_{i,y} \times CI_{i,y} + Others_y, \qquad \text{(Equation 5)}$$

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; $CI$ represents the cement intensity, which is defined as the amount of cement required per cement product; and *Others* 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[51]: we projected the newly constructed amounts based on the population[69] and demand for per capita ownership (which is assumed to reach the expected levels of related official planning and current levels of developed countries)[51,70,71] and estimated the discarded amounts according to the lifetimes of buildings and railways (assumed to reach the designed ages)[72] and the performance of highways (assumed to reach the associated standards).[73] For rural infrastructures, the cement demand was estimated based on the financial expenditure for agriculture[51] and development of primary industry.[74] For other sectors, the cement demand was assumed to account for a constant share of the total demand.[51] The projection results are shown in Figure 4.

### Uncertainty analysis

We conducted systematic uncertainty analyses to verify the reliability of our estimates for air pollutants and $CO_2$ emissions separately in the Monte Carlo framework.[15,20,21] Our results show that uncertainty ranges are far smaller for air pollutants estimated based on CEMS data (with 2 SDs of ±1.17 and 95% CI of [−1.22%, 1.10%]) than $CO_2$ emissions based on average emissions factors (±7.83% and [−7.77%, 7.67%]).

In the estimation for air pollutants, uncertainties might arise from the volatilities in high-frequency CEMS data, from the use of theoretical flue-gas rates, and from the estimation of monthly facility-based activity levels. To examine the volatility in CEMS data, we fit probability distributions for pollutant concentrations on a pollutant, smokestack, and monthly basis, using the associated hourly CEMS observations; for a facility without CEMS, we used the bootstrap method to randomly draw samples from the observations for the facilities involved in CEMS, of the same production process, in the same region, and over the same period. For the use of theoretical flue-gas rates regardless of the heterogeneities across individual facilities, we evaluated the likely ranges based on CEMS-monitored samples (Table S10) and assumed a uniform distribution around the associated theoretical value within the corresponding likely range for each individual flue-gas rate. To capture the uncertainty stemming from the allocation of yearly facility-specific activity levels to monthly scale, we assumed a normal distribution with a 5% CV for monthly clinker production at each facility.[9] We employed the Monte Carlo approach to generate random values for pollutant concentrations, flue-gas rates, and activity levels following their respective distributions and ran a total of 10,000 simulations to estimate the uncertainty ranges.[9,21] The associated results illustrated in Figures 2A–2C confirm that our CEMS-based estimates are quite stable, with 2 SDs of ±1.17 and 95% CI of (−1.22%, 1.10%).

For $CO_2$ emissions estimates, the use of uniform, invariable average emissions factors (without considering heterogeneities across facilities and periods), as well as the conversion of yearly activity levels into monthly scale, may lead to high uncertainties. In the uncertainty analysis, we assumed normal distributions with 2 SD values of ±1% for $CO_2$ process emissions factors and ±3%, ±2%, and ±1% for $CO_2$ fuel emissions factors from the combustion of coal, gas, and oil, respectively, according to the sufficient field research.[25] Similar to the uncertainty analysis conducted for air pollutants, we assumed a normal distribution with a 5% CV for activity levels (clinker production or fuel consumption) on a facility and monthly basis.[9] Figure 2D shows that the estimation for $CO_2$ emissions based on average emissions factors represents a relatively high level of uncertainty compared with CEMS-based estimation for air pollutants, with 2 SDs of ±7.83 and 95% CI of (−7.77%, 7.67%).

In addition, we performed an uncertainty analysis to assess the uncertainties in future projection. Because our *ex ante* assessment of mitigation potential followed the same bottom-up method as the *ex post* estimation for 2014–2018, the uncertainties in future projections similarly arise from the observation or estimation of the model inputs in Equations 2, 3, and 4: the uncertainties from CEMS observations, use of theoretical flue-gas rates and $CO_2$ emissions factors, and projection of activity levels. The first two types of uncertainty could be controlled at least at the 2014–2018 levels, assuming few associated future technical improvements; in contrast, the long-term projection for activity levels (represented by cement production) otherwise suffers from high uncertainties, which not only largely depend on the socioeconomic development but are also sensitive to a series of technical parameters in the estimation (Table S11). Thus, we considered the socioeconomic uncertainties in the projected economic growth and population values and then cement production value, by using the five shared socioeconomic pathways (SSPs);[69] we assumed normal distributions for the technical parameters of cement intensities and lifetime of cement products with CVs of 30%[75] and 20%,[51] respectively; we assumed uniform distributions for CEMS observations on the acceptable uncertainty ranges (Note S3); and we captured the uncertainties arising from the use of theoretical flue-gas rates and $CO_2$ emissions factor in a similar way to the uncertainty analysis for *ex post* estimates. Figure 4 illustrates the associated results and reveals that our projections are relatively stable, with projected measure-specific contributions to future mitigation generally similar across the five 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, $SO_2$, and $NO_X$ 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 $CO_2$ estimation using average emissions factors is subject to much larger uncertainties (±7.83%; Figure 2D), but still small compared with existing studies (±7%–14%).[9,25] Fortunately, in view of the carbon-neutrality promise and the concomitant upcoming tough mitigation policies, $CO_2$ measurements are likely to be included in the CEMS network soon; future versions of our CEAC dataset will incorporate these detailed, real-time, nationwide $CO_2$ 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,[20,21,62] further verifications against independent satellite and ground-level monitoring data[21] would be worthwhile and could provide insights into whether and to what extent the changes in cement-related emissions alter air quality at larger scales. We identified the effects of different measures on emissions mitigation in 2018 (Table 1) and in the future (Figure 3). However, such an analysis cannot be fully supported for the 2014–2018 changes, because some measure-related information is lacking at the facility level before 2018; nevertheless, this will be involved in the future research if these data become available, which can provide useful information for policymakers and businesses.[40] Further $CO_2$ emissions reduction is possible, especially from improving CCS technologies,[76] 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.oneear.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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