Effect of strengthened standards on Chinese ironmaking and steelmaking emissions

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China has produced roughly half of the world's steel in recent years, but the country's iron and steel industry is a major source of air pollutants, especially particulate matter, SO_2 and NO_X emissions. To reduce such emissions, China imposed new emission standards in 2015 and promoted ultralow emission standards in 2019. Here, we use measurements from China's continuous emissions monitoring systems (covering 69-91% of national iron and steel production) to develop hourly, facility-level emissions estimates for China's iron and steel industry. In turn, we use this data to evaluate the emission reductions related to China's increasingly stringent policies. We find steady declines in emission concentrations at iron- and steelmaking plants since the 2015 standards were implemented. From 2014 to 2018, particulate matter and SO_2 emissions fell by 47% and 42%, respectively, and NO_X increased by 3%, even as the production increased by 14%. Moreover, we estimate that if all facilities achieve the ultralow emission standards, particulate matter, SO_2 and NO_X emissions will drop by a further 50%, 37% and 58%, respectively. Our results thus reveal the substantial benefits of the Chinese government's interventions to curb emissions from iron and steel production and emphasize the promise of ongoing ultralow emission renovations. ***[200 words]***

China's iron and steel industry dominates the global market, producing 45-53% of crude steel worldwide between 2010 and 2019[1-5], and the country's crude steel production has grown faster than global production over the same period (at an average annual rate of 5% compared with 3% globally)[1]. As an energy-intensive industry, such production represents similarly large amounts of fossil fuel consumption; between 2010 and 2018, iron and steel production accounted for 7-9% of coal use in China[3,4,6,7]. In turn, the industry has greatly contributed to China's haze pollution[3-6,8-10], accounting for 7-25%, 7-12% and 1-6% of the country's anthropogenic emissions of particulate matter (PM, including all PM size categories)[8,9], sulfur dioxide (SO_2) [8-10] and nitrogen oxide (NO_X)[8-10], respectively, between 2010 and 2015.

In an effort to reduce emissions from iron- and steelmaking, China introduced emission standards for the major stationary sources (generating facilities, units, boilers and machines) in 2012[11-15], which are defined as the allowed upper limits of the emission concentrations in flue gas (in mg m^{-3}; Supplementary Table 1)[2]. In 2015, China strengthened these standards by lowering the limits as much as 60%, 67% and 40% for PM, SO_2 and NO_X, respectively[11-15]. In addition, stricter local standards were designed for Shandong[16] and Hebei provinces[17], reducing the limits in those provinces up to 50% and 40% lower than the national standards, respectively. In April 2019, China announced a set of even stricter ultralow emissions (ULE) standards[18] that reduce the 2015 standards by yet another 50-80%, 40-83% and 25-83% for PM, SO_2 and NO_X, respectively, and largely go well beyond the standards of other developed regions (for example, at most 75%, 94% and 77% less than EU standards for PM, SO_2 and NO_X, respectively[19], and

85% less than US standards for PM[20,21]).

In support of the country's industrial emission standards, since 2007 China has developed a continuous emissions monitoring system (CEMS) for high-emitting facilities (covering 63-72% of the Chinese iron- and steelmaking plants and 69-91% of iron and steel production in different processes between 2014 and 2018; Supplementary Table 2, Fig. 1 and Supplementary Figs. 1 and 2) to measure facility-level, real-time smokestack concentrations (the target of emission standards). The CEMS data has now been used by several studies to estimate the emissions from electricity-generating units[22-24], but, despite the large share of air pollution related to the industry, the data from iron- and steelmaking facilities has not been systematically assessed. Here we present a new dataset based on industry CEMS measurements, the China Emissions Accounts for Iron- and Steelmaking facilities (CEAIS; available at http://www.ieimodel.org/), and use it to analyse trends in hourly PM, SO_2 and NO_X concentrations at the smokestacks of 1,885 iron- and steelmaking plant processes across China between 2014 and 2018. In turn, we perform an ex post analysis of reductions in air pollution related to China's tightening emission standards as well as an ex ante assessment of future abatement if the more ambitious ULE standards are fully implemented. We also compare our CEMS-based estimates with the existing emission inventories[3,5] and conduct extensive uncertainty analyses as well as an independent atmospheric verification. Further details of our data sources and approach are in the Methods.

Response to strengthened standards

Monitoring (CEMS) data reveal a steady decline in the smokestack concentrations of pollutants at Chinese iron- and steelmaking plants after the 2015 standards were implemented (R^2 = 0.96, 0.87 and 0.44 for PM, SO_2 and NO_X, respectively, and $P < 0.01$ for all; Supplementary Table 3), with mean monthly reductions between 2015 and 2018 of 2% for PM and SO_2 and 1% for NO_X, respectively (black curves in Fig. 1). Even in 2014 (before emission standards were strengthened), PM and SO_2 concentrations declined by 20% and 27%, respectively, although NO_X concentrations increased by 13% in that year. The divergent trends of these pollutants reflect the fact that many more plants were out of compliance with the impending PM and SO_2 limits at the start of 2014 (85.5% and 57.1% of plants, respectively, in January 2014) than for the new NO_X standard (only 4.6% of plants); thus, these plants needed to reduce their PM and SO_2 concentrations more rapidly (beginning in 2014) to achieve compliance and at a greater rate relative to NO_X (by 926% and 774% per month, respectively, from 2014 to 2018; Supplementary Table 4). In the first month after the new standards became effective on 1 January 2015, PM and SO_2 concentrations declined by 7.7% and 4.0%, respectively, a steep change in the reductions (compared with 2.0% and 2.8% per month in 2014). For NO_X there was an inflection point in January 2015, when the trend of concentrations reversed from increasing to decreasing.

The tightening of emission standards led to a decline in both the share of plants in compliance (from 69.9% to 17.5%) and the extent of compliance in January 2015 (from 70.0% to 46.0%; Supplementary Fig. 3). However, this decline was relatively short-lived: previous levels of compliance were regained, after 9 months of substantial concentration reductions for PM and SO_2 and 18 months for NO_X (surpassing 2014 values by 19%, 30% and 115% per month for PM, SO_2 and NO_X, respectively). Specifically, by September 2015, September 2015 and June 2016, the shares of complying observations (measured by compliance rate[22,23]) with the 2015 standards for PM, SO_2 and NO_X, respectively, surpassed those with the previous 2012 standards in 2014 (albeit narrowly, by 0.28%, 1.13% and 0.03%, respectively). Afterwards, monthly compliance rates were no longer significantly below the 2014 levels (see *t*-tests in Supplementary Table 5). Between 2015 and 2018, the share of plants in compliance with the new standards continued to increase (Supplementary Fig. 4), such that 92.1% of plants met all three targets in December 2018. Indeed, mean PM, SO_2 and NO_X smokestack concentrations were 74%, 70% and 61%, respectively, lower than the standards in 2018, reflecting the additional incentives for over-compliance (such as tax reductions and benefits from surplus pollution permits[25-27]).

Multiple lines of evidence suggest that the most-polluting facilities as of 2015 were often targeted and largely brought into compliance by 2018. For example, few electric arc furnaces complied with the new standards in 2015, but their smokestack concentrations were reduced by an average of 73% between 2015 and 2018, increasing the compliance rate of such facilities by 144% (Supplementary Fig. 5). In comparison, 95.7% of basic oxygen furnaces were in full compliance in 2015 but showed the least improvement among all processes in their compliance rate from 2015 to 2018 (by 5%). This pattern holds regionally: the central and southern region, which featured the smallest proportion of compliers in 2015 (20.3%, versus the highest proportion of 45.1% in the northeastern region), nonetheless reduced smokestack concentrations relatively quickly (by an average of 1.1% per month between 2015 and 2018 compared with the lowest rate of 0.9%) and finally achieved relatively high compliance rate in 2018 (95.7% versus 94.2% in the northeastern region). By the end of 2018, compliance rates across processes and regions thus reached similar, high levels, ranging from 81.3% for electric arc furnaces to 100.0% for basic oxygen furnaces, and from 83.9% in the northwestern region to 98.5% in the northern region.

In comparison, high levels of compliance were sometimes followed by increases in smokestack pollutant concentrations. For example, after achieving NO_X compliance ratios (reflecting the extent of compliance) beyond the highest threshold (50%) in February 2017 to earn the largest discount on sewage charges[25] ($P < 0.01$, 95% confidence interval (CI) = $[57.8, \infty]$; Supplementary Table 5), plants' concentrations continuously increased from February to

June ($P < 0.01$, 95% CI = [0.7-5.0, ∞]; Fig. 1d). Despite such increases, plants largely remained in compliance (as reflected by no significant decrease in compliance rates; $P = 0.27$-0.88, 95% CI = [-∞, 0.1-0.3]) and still gained the largest incentives for over-compliance (with compliance ratios significantly above the 50% threshold; $P < 0.01$, 95% CI = [51.2-57.8, ∞]). This unexpected result suggests that emission standards and incentive policies should be carefully designed and adjusted according to ever-changing compliance to encourage continuous emission reductions.

Effect of strengthened standards

Reductions in smokestack pollutant concentrations corresponded to similar reductions in the emission intensities of Chinese iron- and steelmaking between 2015 and 2018. In 2014, emission intensities for PM and SO_2 decreased by an average of 1% per month (to an average of 0.7 and 0.6 g per kg of raw steel at the end of 2014, respectively), while the average NO_X emission intensities increased by 2% per month that year (to an average of 1.0 g per kg of steel; Fig. 2a-c). Between 2015 and 2018, emission intensities for all three pollutants decreased: by 2% per month for PM and SO_2 and 1% per month for NO_X (to an average of 0.3, 0.3 and 0.7 g per kg of raw steel at the end of 2018, respectively). As with smokestack concentrations, decreases in emission intensities 2014-2018 were particularly dramatic among what had been the most-polluting processes and regions: emission intensities of electric arc furnaces dropped by an average of 82% (compared with 53% across all processes) and emission intensities in the central and southern region fell by 49% (compared with 47% nationwide). These disproportionate reductions decreased the heterogeneity among facilities: we estimate the standard variances of source-level monthly emission intensities between 2015 and 2018 were 52% and 63% less than in 2014 for PM and SO_2, respectively.

In turn, we find that reduced emission intensities are the primary driver of decreases in emissions from Chinese iron- and steelmaking. Of total reductions of 47% and 42% in PM and SO_2 emissions between 2014 and 2018, the reductions in emission intensities accounted for 130.5% and 152.0%, respectively (that is, emissions would have increased by 14% and 22%, respectively, due to a 14% increase in production were it not for the decreases in the emission intensities of the industry; Fig. 2d,e). Similarly, although total NOx emissions increased by 3% between 2014 and 2018, the increase would have been considerably larger (12%) were it not for the decreases in emission intensities (Fig. 2f). Between 2014 and 2015, PM, SO_2 and NO_X emissions decreased by 40%, 33% and 8%, of which reduced emission intensities accounted for 93.9%, 88.9% and 76.6% but the decline in production (by 3% on average across products) contributed to only 6.1%, 11.1% and 23.4%, respectively. From 2015 to 2018, the large growth in production (by 17%) contributed to upward increases in PM, SO_2 and NO_X emissions by 28%, 38% and 16%, respectively, which were largely offset by decreases in emission intensities, such that annual PM and SO_2 emissions continuously declined (by 12% and 13%, respectively), and the NO_X emissions increased only slightly (by 13%). In sharp contrast to our CEMS-based results, previous studies that applied average emission factors that were developed up to 2013 estimated drastically higher emissions (by up to 1,078%) from Chinese iron- and steelmaking plants[3,5].

Thus, as with smokestack concentrations, we find substantial decreases in pollutant emissions from iron- and steelmaking related to the standards implemented in 2015. Considering the ULE standards which were promulgated in April 2019 but have not yet entered into force, we project potential further reductions in average PM, SO_2 and NO_X emission intensities by 14%, 11% and 31%, respectively (to an average of 0.2, 0.2 and 0.3 g per kg of raw steel; dashed lines in Fig. 2a-c) and concomitant decreases in total emissions by 50%, 37% and 58%, respectively (patterned bars in Fig. 2d-f). Potential reductions are especially large for NO_X emissions, for which the ULE standards are particularly strict (reducing the NO_X limits by up to 83.3%, as compared with 80.0% and 82.5% for PM and SO_2, respectively) and there is still substantial progress to be made (with NO_X smokestack concentrations on average 78% higher than the ULE standards at the end of 2018, as compared with -20% and 11% for PM and SO_2, respectively). Moreover, our analysis points to the largest potential emission reductions in the future from what accounts for the bulk of current emissions: from the sintering process (accounting for 55.5%, 81.2% and 95.8% of projected reductions in PM, SO_2 and NO_X emissions, respectively; red bards in Fig. 3a-c); in the northern and eastern regions (60.1%, 39.4% and 62.8%; yellow and orange bars in Fig. 3d-f); among large-scale plants (that is, those producing >2 million tonnes of crude steel per year; 70.9%, 66.1% and 71.4%; green, purple and yellow bars in Fig. 3g-i); and among non-compliers with the 2015 standards as of 2018 (39.8%, 47.1% and 31.8%, associated with only 13.9% of facilities; all light-shaded bars in Fig. 3; Supplementary Note 1). However, although a similar ULE policy was successfully implemented in Chinese power plants with good results[22], achieving ULE standards throughout the iron- and steelmaking industry may be quite challenging given that 7.9% of plants did not meet the 2015 standards at the end of 2018. Yet a large portion (19.1%) of plants had attained ULE levels for all pollutants by the end of 2018, suggesting the operational feasibility and technical viability of the ULE standards (and perhaps demonstrating a path for other plants to follow).

Measures to meet strengthened standards

To meet emission standards, individual Chinese iron- and steelmaking plants have implemented a range of different, and often multiple, abatement measures (Supplementary Table 6). Between 2015 and 2018, the most important of such measures was improvements in emissions control equipment such as scrubbers, hoods and furnace enclosures (Supplementary Table 7), which accounted for 35.3%, 56.0% and 27.4% of the decreases in PM, SO_2 and NO_X

emissions, respectively, during that period (red bars in Fig. 4a-c). In 2015, PM and SO_2 control equipment was already prevalent in Chinese iron- and steelmaking plants (installed at 85.7% and 68.1% of plants and covering 88.5% and 87.7% of production on average across products, respectively) and was used for most of the plants' operating time (99.2% and 96.0% of the operating time, on average, respectively; Supplementary Note 2). Nevertheless, many such PM and SO_2 control systems were extensively updated 2015-2018 (in 44.2% and 51.1% of plants covering 44.0% and 69.4% of production, respectively), enhancing their average removal efficiencies from 93.9% and 61.5% to 98.2% and 89.8%, respectively. In contrast, NO_X control equipment was rare in 2015 (installed in only 0.3% of plants and covering 0.2% of production, and even then used only 70.0% of operating time) but was installed in 17.6% of plants (covering 34.7% of production) between 2015 and 2018, with an average removal efficiency where installed of 74.0%. With these efforts, 98.1%, 93.7% and 17.9% of plants (covering 99.0%, 97.8% and 30.7% of production) had deployed PM, SO_2 and NO_X control technologies, respectively, by the end of 2018.

Our analysis shows that emissions control technologies will also be important to further reductions under the ULE standards (associated with 22.8%, 32.3% and 78.5% of projected reductions in PM, SO_2 and NO_X, respectively, if all facilities meet the ULE standards; red bars in Figs. 4d-f). Specifically, 32.4% and 30.0% of the facilities that did not yet meet with the ULE standards had inferior PM and SO_2 control equipment, respectively (with average removal efficiencies of 92.6% and 78.5%, respectively) to the facilities that met the ULE standards in 2018 (97.1% and 87.8%). Meanwhile, a large majority (78.5%) of facilities not meeting ULE standards had not deployed NO_X control equipment as of 2018.

Another key opportunity for emission reductions is improving the quality of fuels and raw materials. Such improvements accounted for 44.7%, 53.1% and 28.8% of emission reductions between 2015 and 2018 (green and orange bars in Fig. 4a-c). Specifically, many plants shifted to better fuels with lower ash, lower sulphur and higher volatile contents (68.3%, 52.9% and 28.2% of plants covering 66.5%, 48.8% and 38.1% of production on average across products, respectively). These changes led to improvements in the average ash, sulphur and volative contents in fuels used by such plants from 15.3%, 0.7% and 12.3% to 11.2%, 0.5% and 19.0%, respectively. Similarly, more than half of plants (56.0%, covering 62.0% of production) also shifted to better raw materials, reducing their average percentage of sulphur in feedstocks from 0.2% to 0.1%. Again, further improvements in fuels and raw materials are possible: in 70.9% and 25.2% of the facilities that did not yet meet the ULE standards in 2018, the quality of fuels and raw materials, respectively, was poorer than the mean level of the facilities that met the ULE standards. As a result, improvements in fuels and raw materials account for 49.9%, 73.6% and 56.8% of projected reductions in PM, SO_2 and NO_X, respectively, if all facilities meet the ULE standards (green and orange bars in Figs. 4d-f).

Promoting entirely different clean fuels as part of structural adjustments in the Chinese energy sector[28] has also been an improvement means of reducing emissions, associated with 33.6%, 35.2% and 28.9% of reductions in PM, SO_2 and NO_X emissions, respectively, between 2015 and 2018 (blue bars in Figs. 4a-c). For example, the share of China's iron and steel plants using natural gas increased from 8.2% in 2015 to 11.5% in 2018 and many (25.0%) of such plants continuously enhanced the amount used over that period, which increased their average volume of natural gas used per unit of crude steel produced from 14.1 to 18.2 m^3t^{-1} between 2015 and 2018. We expect such fuel switching to be even more important in the future, accounting for 98.7%, 98.2% and 99.2% of the projected reductions in PM, SO_2 and NO_X, respectively, if all facilities meet ULE standards (blue bars in Fig. 4d-f), largely because almost none of the facilities not in compliance with ULE standards as of 2018 achieved the average amount of natural gas used per unit of crude steel produced by ULE-complying facilities.

Finally, the phasing out of small or outdated plants to eliminate the most inefficient facilities and technologies[29,30] has been and will continue to be an important means of reducing emissions. Between 2015 and 2018, 36.6% of iron- and steelmaking plants were shut down, accounting for 25.6%, 20.9% and 82.4% of the reductions in PM, SO_2 and NO_X, respectively, over that period (purple bars in Figs. 4a-c). Most of these closed plants were small -scale (87.1% produced <1 million tonnes of crude steel per year) or old (13.3% had been operating >40 years). Although the small plants that closed represented 31.9% of all plants, they produced only 6.8% of iron and steel production in 2015 and mostly lacked control technologies (21.3% had SO_2 controls and none had SO_2 and NO_X controls), such that their retirement led to much larger reductions in emissions than production capacity[30]. Of the large plants (that is, those producing >10 million tonnes of crude steel per year) that closed, all were older than 40 years, and half were older than 80 years; by virtue of their age, these plants also accounted for disproportionately large emissions relative to their production[31]. Meeting ULE standards will probably entail further retirements of smaller (that is, those producing <1 million tonnes of crude steel per year) and older plants (that is, those operating >80 years); we estimate that phasing out such plants will contribute 21.4%, 24.5% and 20.8% of reductions in PM, SO_2 and NO_X emissions, respectively (purple bars in Fig. 4d-f).

Discussion

Our analyses of Chinese iron- and steelmaking emissions show that the adoption of new emission standards in 2015 led to a large mitigation effect, particularly among high-emitting facilities (which were subject to heavy penalties for noncompliance after the standards entered into force), but the effect was relatively weak, even negative in some cases, among low-polluting facilities, reflecting the lack of incentives for those facilities to further improve (see, for example, the increase in NO_X smokestack concentrations during 2017 in Fig. 1d). This finding suggests that effective standards, penalties and incentives may need to be regularly adjusted as the levels and extents of compliance evolve over time. Indeed, given high levels of compliance as of 2018, future emission reductions may depend upon the enforcement of stricter policies such as the announced ULE standards[18], especially for NO_X emissions. Moreover, our results show that compliance with standards tends to be higher in provinces with higher levels of economic development (commonly corresponding to larger technological potential) and in key regions targeted by clean air action plans (where government oversight is greater; Supplementary Note 1)[32,33]. This suggests that future mitigation efforts might productively focus on less developed and non-key regions (for example, the southwest and northwest)[2]. Alongside the emission standard policy, there also existed a series of other additional policies targeting iron- and steelmaking emissions (Supplementary Table 1), and we examine their effect in facilitating standard compliance and reducing smokestack concentrations (Supplementary Note 3). Moreover, administrative instruments such as the new ULE standards are not the only possible policy approach; economic instruments such as an emissions trading scheme, which has been shown to be effective in controlling carbon emissions[34], might complement such standards and incentivize overcompliance by allowing plant owners to sell surplus emissions permits[27]. At the same time, our results show that sintering processes, northern and eastern parts of the country and large-scale plants represent important targets for further large emission reductions, and highlight the potential of fuel switching (for example, from coal to natural gas) and improving NO_X control equipment[18,35]. By comparing their processes and technologies with plants that have already met ULE standards, individual facilities can identify leverage points and adopt the corresponding abatement measures.

Our CEAIS dataset is subject to limitations and uncertainties. For example, some iron- and steelmaking plants have not yet been covered by the Chinese CEMS network, accounting for 8.8-31.5% of national production of different iron and steel products between 2014 and 2018; further improvement entails comprehensive field measurements and the collection of these samples. We conduct a series of uncertainty analyses on instrumental errors of CEMS measurements (Supplementary Note 4) and other uncertain factors (detailed in the Methods), and the results show that our estimates are relatively stable (with 2 s.d. all within ±4.0% for emission intensities and ±1.6% for total emissions; Fig. 2). Furthermore, we perform an independent verification against satellite data and ground-level monitoring data, examining the potential atmospheric impact of the large emission reductions drawn from the CEMS measurements (Supplementary Note 5). Nevertheless, this provides a starting point for interesting atmospheric research that seeks to verify the results drawn from the CEMS data using a variety of other independent datasets and translate these results to actual atmospheric impacts (particularly on a large scale and at a high spatiotemporal resolution) and, consequently, discernable improvements in air quality[2] and human health[28].

Despite remaining limitations, our CEMS-based estimates represent a major advance in estimating trends in emissions from iron- and steelmaking in China by greatly reducing uncertainty and enhancing spatiotemporal resolution[22,36]. We demonstrate the use of this data by evaluating in detail the reductions in pollutant emissions after implementation of China's 2015 emission standards and the potential future reductions if all facilities ultimately meet the latest ULE standards. Future work may extend our analysis to include other environmental[2,37] and health benefits[28] associated with the operational and technological changes in Chinese iron- and steelmaking facilities in recent years. The CEAIS database may also include measurements of greenhouse gases (particularly CO_2) in the future, which would support analyses of climate-change-related policies and synergies and trade-offs with clean air policies[38]. By 2018, the Chinese CEMS network covered a total of 17,494 stationary emission sources in 5,336 operating plants across different industries, and the CEAIS dataset can be extended into a multisector dataset to support a full-scale analysis of clean air policies and plan actions targeting Chinese industrial emissions [32,33]. In the meantime, though, our results offer important insights to policymakers in China and elsewhere (such as India[39] and Brazil[40]) seeking targeted opportunities for reducing emissions from the iron and steel industry.

Methods

Construction of the CEAIS database. The CEAIS database is a new database for iron- and steelmaking facilities that uses CEMS data (the actual systematic, source-level and real-time emission measurements) to estimate nationwide, detailed and dynamic emission factors (that is, emission intensities) and total emissions (available at http://www.ieimodel.org/). The CEAIS dataset encompasses all iron- and steelmaking plants in mainland China (Supplementary Table 2), totalling 574-605 plants and 1,659-1,885 plant processes between 2014 and 2018. We focus on the three main air pollutants that form haze pollution and are targeted in the emission standards policies: PM, SO_2 and NO_X.

We compile and develop the CEAIS dataset by combining two detailed national databases for Chinese iron- and steelmaking plants provided by China Ministry of Ecology and Environment (MEE): one with facility- or unit-based information regarding the activity level (production, inputs and energy consumption; yearly), facility type, emission sources involved, production process associated, emissions control technology, age, fuel quality, raw material quality, geographic location, and so on and another with source-level measurements of the smokestack PM, SO_2 and NO_X concentrations (hourly), which are monitored and recorded by China's CEMS network. The introduction of source-level, hourly CEMS data substantially enhances the spatiotemporal resolution[22,36], while the combination of CEMS data and facility information facilitates the exploration of specific determinants and measures that have been or will be important for meeting the increasingly tight emission standards in China[22,23].

Tang et al.[22], Karplus et al.[23] and Gouw et al.[24] introduced CEMS data in studies on power-generating emissions, however, CEMS data have not yet been applied to other sector emissions nationwide. Without CEMS data, existing research estimated iron- and steelmaking emissions based on average emission factors[3-6], which suffer from the following three main limitations. First, average emission factors are not real monitoring results for individual facilities but proxies for broad technology classes at a relatively aggregated level. In emissions estimation, the average emission factors are specified based on many assumptions and indirect parameters (regarding operational status and technologies)[3-6], which are subject to high degrees of uncertainty[41]. Second, the emission factors used in existing inventories were uniform and invariable and failed to reflect heterogeneous and dynamic features across facilities and periods, respectively. Third, the emission factors for Chinese iron- and steelmaking plants available were evaluated up to 2013[3-6], however, the severely strengthened emission standards in 2015 brought systematic technologic and operational changes to Chinese iron- and steelmaking facilities[2,3,10]. Therefore, introducing CEMS data (direct, detailed, real-time and up-to-date actual measurements) can effectively address the above limitations attributable to the use of indirect, uniform, invariable and out-of-date average emission factors.

We are granted exclusive access to systematic data from China's national CEMS network for iron- and steelmaking facilities (http://www.envsc.cn/). China mandates installing CEMS in the facilities, units, boiler furnaces or machines along the iron and steel production processes of sintering, pelletizing, coking, ironmaking, steelmaking via a basic oxygen furnace and steelmaking via an electric arc furnace[42]. In total, the CEMS data cover 62.9-71.6% of Chinese iron- and steelmaking plants, representing 87.7-88.3% of national crude steel production between 2014 and 2018 (Supplementary Table 2). The CEMS network directly measures in real time the smokestack concentrations of PM, SO_2 and NO_X in flue gas (g m^{-3}) emitted from different sources in operating facilities and records these measurements as hourly averages. For a facility without CEMS, we assume that its pollution concentrations follow similar distributions to its counterparts (the facilities of the same type and process, located in the same region and covered by the CEMS network).

To guarantee the quality and reliability of CEMS data, Chinese government has made a great effort (detailed in Supplementary Note 4)[22,36], including: developing specifications and technical guidelines for the correct operation, maintenance and examination of the CEMS network[43,44]; conducting random inspections to avoid data manipulation[45]; comparing data amongst plants to detect outliers[46]; mandating plants to conduct regular calibration, maintenance and verification on CEMS instruments[47,48]; and introducing third parties to make technical check and acceptance on the CEMS network[47]. Yet null, zero and abnormal observations still exist in CEMS data, mainly due to technical errors[22,36,47], and we treat these observations seriously according to official documents and regulations. The Specifications for Continuous Emissions Monitoring of Flue Gas Emitted from Stationary Sources (HJ/T 75-2007)[47] assumes that successive nulls or zeros for >24 hours fluctuate around their historical levels immediately before the time (for this study, we set them to the monthly averages[22,36]) and suggests setting nulls or zeros for 1-24 hour(s) to the arithmetic mean of the two adjacent valid points before and after the time[47]. We review each observation via data visualization to identify abnormal values (particularly those out of CEMS measurement ranges) and process them in a similar way to nulls according to regulation HJ/T75-2007[22,36,47]. Furthermore, we conduct an uncertainty analysis on the instrumental errors of CEMS measurements and find the associated uncertainties acceptable (with 2 standard deviations (s.d.) within ±0.7% for emission intensities and ±0.2% for total emissions; see Supplementary Note 4). Nevertheless, an assessment of how well the CEMS-related requirements [42,43,45-48] are implemented in the reality is an important topic for future research[44].

Evaluation of compliance with emission standards. The CEMS network measures the PM, SO_2 and NO_X concentrations at the emission source level, which are the targets of the emission standards policies in China, thus allowing us to study the individual compliance of Chinese iron- and steelmaking facilities[22,23].

The emission standards policies were designed, approved and issued by the MEE and are enforced and supervised by the local entities of the MEE at the prefecture and above levels[11-15]. The 2015 standards are mandatory regulations that all iron- and steelmaking plants should comply with or face severe punishment (such as financial penalties of ¥ 0.1-1 million, doubled sewage charges, production reductions or bans and plant suspension or shutdown[25,49]). There are also financial incentives for firms to control smokestack concentrations to be lower than the 2015 standards: a 50% discount on sewage charges if the emission concentrations are 50% lower than the standards before 2018[25]; a 25% (or 50%) discount on environmental taxes if the emission concentrations are 30% (or 50%) lower than the standards since 2018[26]; and benefits from surplus pollution permits for sale or transfer if the actual emissions are below the quotas allowed[27]. Therefore, the cost of compliance (primarily for introducing, upgrading and operating pollution control equipment) is quite small relative to the punishment for noncompliance as well as the additive incentives for overcompliance. The ULE standards are not mandatory but are encouraged through financial incentives for ULE renovations (such as financial rewards and credit and loan support), as well as penalties for plants not reaching the ULE levels (such as increased electricity prices and production reductions or bans during heavy air-pollution days)[18].

We quantify compliance based on compliance rate and compliance ratio. Compliance rate is defined as the percentage of complying observations (that is, smokestack concentrations of or below the associated emission standards) in total valid observations, with a 100% value standing for compliance and a value of [0%, 100%) for noncompliance[22,23]. Compliance ratio measures the extent to which an observation complies with the corresponding emission standard, defined as:

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

where f, u, s, p and h are the indexes for the pollutant species, facility, emission source, production process and hour, respectively; S denotes the emission standard (g m^{-3}), which is the allowed upper limit of the pollution concentration in flue gas (Supplementary Table 1); C means the emission concentration in flue gas (g m^{-3}), which is measured by CEMS; and R is the estimated compliance ratio ranging from $(-\infty, 1)$, with a positive (or negative) value corresponding to compliance (or noncompliance) and a higher (or lower) value corresponding to better (or poorer) compliance.

Estimation of emission factors and emissions. Using the real measurements from the CEMS network, we estimate the source-level and hourly emission factors of PM, SO_2 and NO_X in a direct way that avoids using many indirect parameters and the associated assumptions[22,36]:

$$\mathrm{EF}_{f,u,s,p,h} = C_{f,u,s,p,h} V_{u,s,p,y} \qquad (2)$$

where the index y indicates the year, V means the theoretical flue-gas rate, which is expressed as the volume of flue gas per unit of production (m^3 kg^{-1}), and EF stands for the emission factor (or emission intensity), the amount of emissions per unit of production (g kg^{-1}). Abated emission factors that already incorporate the effect of pollution control technologies (if any) can be directly obtained here because CEMS monitors are installed at smokestacks and measure the abated emission concentrations[47].

Given that the emission standards policy and related regulations focus on emission concentrations, the CEMS dataset has high-quality data regarding emission concentrations but lacks a large proportion of other emissions data (particularly on flue-gas rates). Thus, we introduce theoretical flue-gas rates, which were estimated based on sufficient field research by the MEE[50] (Supplementary Table 8). Fortunately, some actual flue-gas rates for 210 facilities have been measured and recorded in the CEMS dataset (Supplementary Table 9), which allows a rough exploration of the likely ranges of theoretical flue-gas rates. Comparing CEMS-monitored samples and theoretical values, we find that the actual flue-gas rates generally approximate their theoretical values within a likely range of ±12.1% at a 95% confidence level. The results are consistent with the findings of Tang et al.[36] and verify the use of theoretical flue-gas rates. Furthermore, the introduction of theoretical flue-gas rates can effectively avoid substantial underestimation if flue-gas leakage occurs[22,36,51].

Using the detailed emission factors, iron- and steelmaking emissions can be estimated on a source and monthly basis[22,36,41]:

$$E_{f,u,s,p,m} = \mathrm{EF}_{f,u,s,p,m} A_{u,p,m} \qquad (3)$$

where the subscript m indicates the month, E represents the absolute emissions (g), and A

denotes the activity level, which is defined as the amount of production (kg). We estimate absolute emissions on a monthly basis, in which hourly emission factors are averaged on a monthly scale and yearly facility-level activity data (offered by the MEE) are allocated at the monthly levels using monthly provincial data on crude steel production (which are available in the *China Statistical Yearbooks*[7]) as the weights[22,36]. Future research involves incorporating hourly operational data (particularly on production and flue gas rates) to improve the accuracy of emissions estimates.

Uncertainty analysis. An uncertainty analysis is conducted to verify the reliability of our estimates. First, we consider the uncertainty stemming from the variability in the hourly frequency CEMS data. We fit probability distributions of smokestack concentrations for each pollutant on a source and monthly basis using the associated hourly CEMS-monitored observations[52,53]. For an emission source without CEMS, we employ the bootstrap method to select random samples at an equal probability from the hourly observations in the CEMS dataset that have the same types of facility, emission source and production process and that are located in the same region. Second, the use of theoretical flue-gas rates might add to uncertainty due to the heterogeneities in technology, feedstock, operation and other conditions across individual facilities[22,36]. In the uncertainty analysis, each flue-gas rate is generated using a uniform distribution around its theoretical value (Supplementary Table 8) within the likely range estimated based on the CEMS-measured samples (Supplementary Table 9). Third, activity level, an important model input in emission estimation, is also considered in the uncertainty analysis, and we assume normal distributions with a 5% coefficient of variation (defined as the standard deviation divided by the mean) for plant process-specific production[3,41,54]. The Monte Carlo approach is performed to generate random values for emission concentrations, flue-gas rates and activity levels based on their respective distributions. A total of 10,000 simulations are run to estimate the uncertainty ranges of our estimates[3,8,55]. The results show that our estimations are relatively stable, with 2 s.d. all within ±4.0% for emission factors and ±1.6% for total emissions (Fig. 2).

Data availability

The CEAIS database that supports the findings of this study is available in Supplementary Tables 1-10 or at http://www.ieimodel.org/. Supplementary Table 2 presents a summary of the CEAIS dataset. The data used in the estimation for emission intensities and total emissions include the smokestack concentrations presented in Fig. 1, Supplementary Figs. 1, 2 and 5 and Supplementary Table 4, the flue-gas rates provided in Supplementary Tables 8 and 9 and the plant-level information provided in Supplementary Table 10.

Code availability

All computer codes generated during this study are available from the corresponding authors on reasonable request.

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Additional information

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Author contributions

X.B., L.T., Z.M. and S.W. planned the project. X.B., W.C. and X.C. processed and analysed the data of Continuous Emission Monitoring Systems. G.D., M.J. and X.X. compiled and analysed the facility-based information for Chinese iron- and steelmaking plants. S.W., M.J., X.X., J.R. and B.Z. conducted the experimental work. X.B., L.T. and Z.M. wrote the paper. S.J.D. polished the paper. All authors contributed to developing and writing the manuscript.

Competing interests

The authors declare no competing interests.

Figure

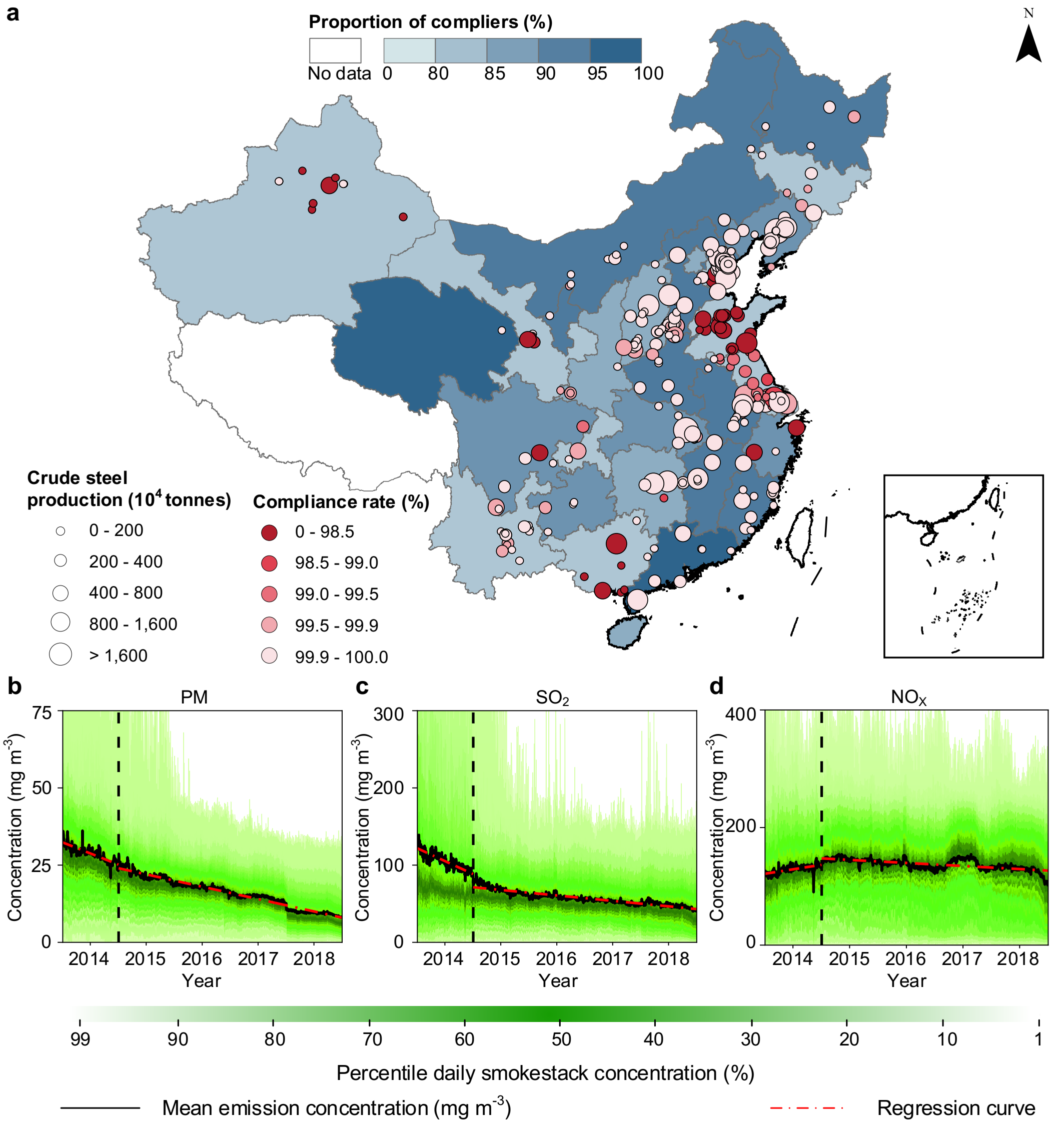

Figure 1 | Geographic and temporal distributions of Chinese iron- and steelmaking smokestack concentrations, 2014-2018. **a**, The iron- and steelmaking plants operating nationwide in 2018, with a total of 1,885 plant processes, of which 73.1% were monitored by the CEMS network (representing 83.5%, 68.5%, 90.3%, 84.9%, 87.8% and 84.9% of the total production of sinter, pellet, coke, pig iron, crude steel and rolled steel, respectively). The sizes of the dots indicate the crude steel production of individual plants (in 10^4 tonnes), the intensities denote the compliance rates (which are defined as the percentage of compliers with the associated standards, in %) with the 2015 standards, and the coloured background represents the proportion of compliers in the associated provinces. **b-d**, Daily distributions of smokestack concentrations (in mg m^{-3}) of PM (**b**), SO_2 (**c**) and NO_X (**d**). The color gradation shows the intervals of percentiles for daily smokestack concentrations, ranging from the 1% quantile (in the lightest green) to the 50% quantile (namely median; in the darkest green) and then to the 99% quantile (in the lightest green); the black dashed vertical lines mark 1 January 2015, when the emission standards were strengthened, the black solid curves represent the mean smokestack concentrations and the red dashed lines are the regression curves for the mean before or after the emission standards were strengthened. The results imply a skewed distribution for smokestack concentrations, as the median values (falling in the darkest-green areas) are offset from the corresponding mean values (represented by black solid curves), particularly for SO_2.

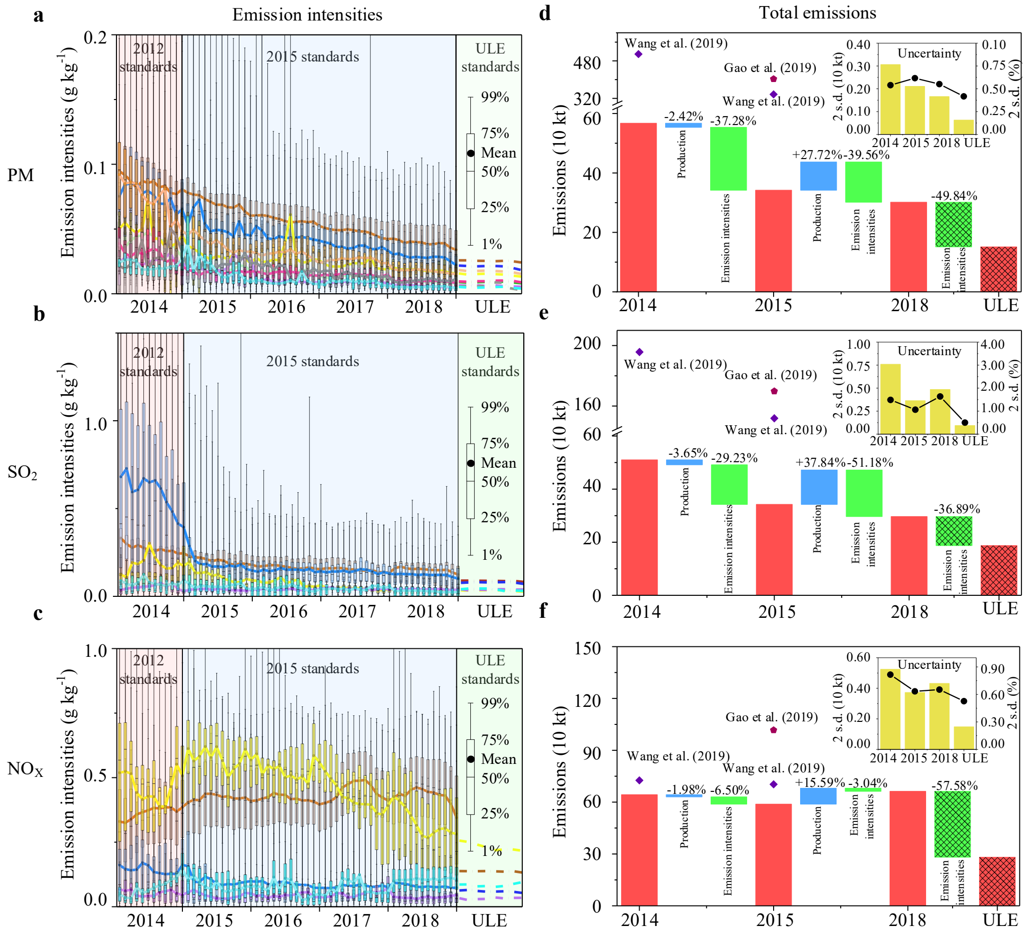

Figure 2 | Emission intensities and total emissions for Chinese iron- and steelmaking facilities, 2014-2018. a-c, Monthly quartiles of the emission intensities (in g kg^{-1}) for PM (**a**), SO$_2$ (**b**) and NO$_X$ (**c**). The colours indicate the emission sources: sinter machine heads in sintering (tan), sinter machine tails in sintering (green), pellet firing in pelletizing (blue), coke oven chimneys in coking (yellow), hot stoves in ironmaking (purple), blast furnace casting in ironmaking (orange), secondary basic oxygen furnace off-gases in steelmaking (pink), electric arc furnaces in steelmaking (grey) and reheating furnaces in steel rolling (cyan). The solid curves indicate the mean emission intensities, and the dashed curves show the projected results under the assumption that all facilities met the ULE levels in 2018. **b-f**, Total emissions (in 10 kt; red bars) and emission changes driven by the variances in production (blue bars) and emission intensities (green bars). The emission changes by production are estimated under the assumption that emission intensities remained at the base levels, while the emission changes by emission intensities are calculated under the assumption that production remained at the base levels. The patterned bars indicate the projected results under the assumption that all facilities met the ULE levels in 2018. The discrete data points are the previous estimates (in 10 kt). Right column insets: the uncertainty ranges of our estimated emissions, represented by the 2 s.d. of simulation results in the uncertainty analysis (bars; in 10 kt, left *y* axis) and the relative 2 s.d. compared with the associated mean (dots; in %, right *y* axis).

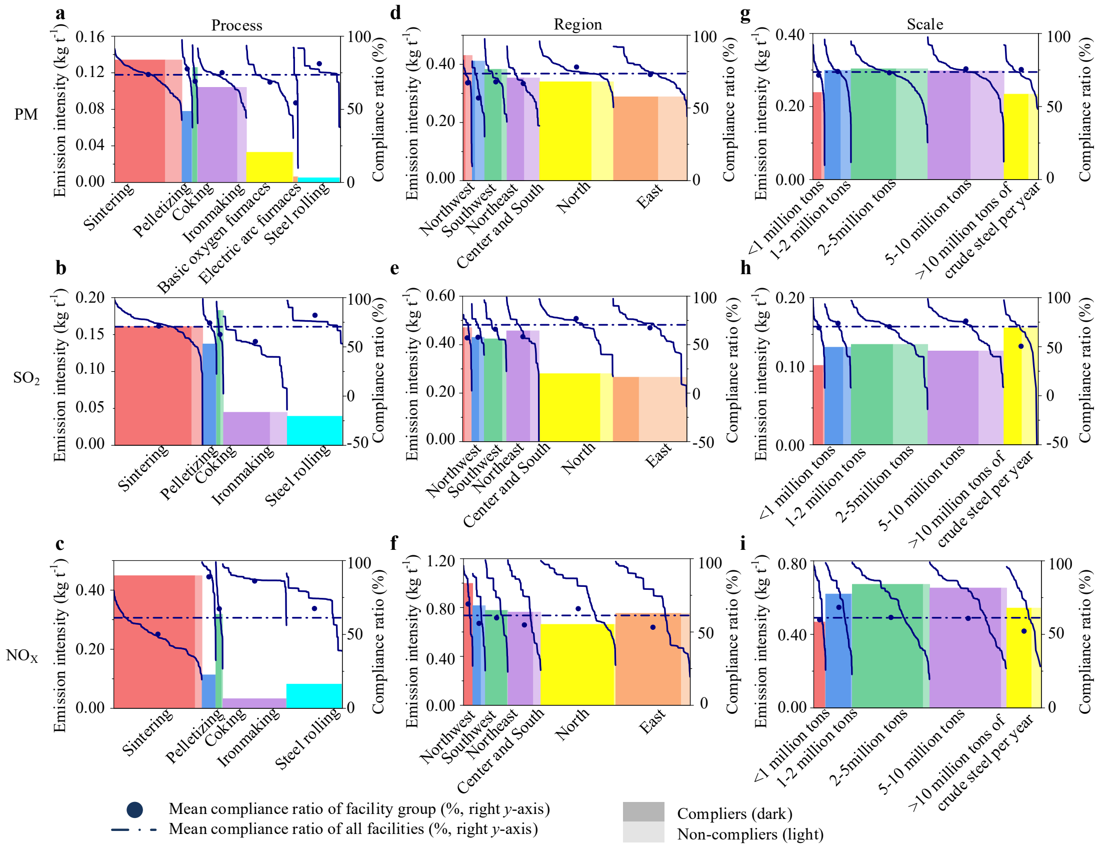

Figure 3 | Emissions from Chinese iron- and steelmaking facility groups in 2018. **a-i**, The mean per-production emissions (kg t^{-1}; left *y* axis) across the iron- and steelmaking facilities grouped by process (**a-c**), region (**d-f**) and scale (**g-i**), with the colours of bars denoting the 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 solid curves indicate the distributions of compliance ratios (defined as the exceedance of the associated standard for a smokestack concentration, in %; right *y* axis) for the facilities in the given groups, the points represent the mean compliance ratios across the facilities in the given groups, and the dashed lines represent the mean compliance ratios across the facilities in all groups.

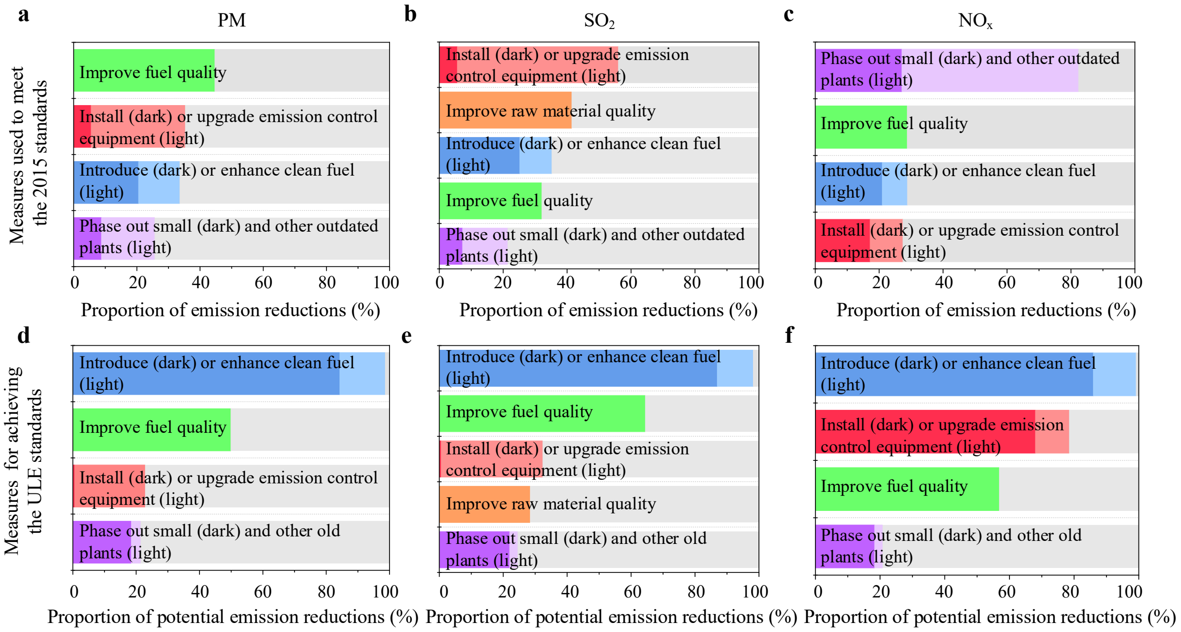

Figure 4 | Measures to meet the strengthened emission standards. a-c, Proportions of reductions in PM (**a**), SO_2 (**b**) and NO_X (**c**) emissions from the iron- and steelmaking facilities that have been improved via the associated measures from 2015 to 2018 (coloured bars) versus those without implementation of such measures (pale bars). More than one measure can apply to a facility. **d**-**f**, Proportions of potential reductions in PM (**d**), SO_2 (**e**) and NO_X (**f**) emissions from improving ULE-noncompliant facilities via the associated measures, where the measure-related factors, (for example, the fuel mixture (blue), fuel quality (green), emissions control technology (red), raw material quality (orange) and scale or age structure (purple)) were inferior to the corresponding mean levels of ULE-compliant facilities in 2018.