Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards

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In 2014, China introduced an ultra-low emissions (ULE) standards policy for renovating coal-fired power-generating units to limit SO_2, NO_X and PM emissions to 35, 50 and 10 mg m^{-3}, respectively. The ULE standard policy had ambitious levels (surpassing those of all other countries) and implementation timeline. We estimate emission reductions associated with the ULE policy by constructing a nationwide, unit-level, hourly-frequency emissions dataset using data from a continuous emission monitoring systems network covering 96-98% of Chinese thermal power capacity during 2014-2017. We find that between 2014 and 2017 China's annual power emissions of SO_2, NO_X and PM dropped by 65%, 60% and 72%, respectively. Our estimated emissions using actual monitoring data are 18-92% below other recent estimates. We detail the technologies used to meet the ULE standards and the determinants of compliance, underscoring the importance of *ex-post* evaluation and providing insights for other countries wishing to reduce their power emissions.

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China is currently suffering from severe air pollution, with the highest country level values globally for population-weighted annual average concentration of fine particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) (53 μg m^{-3})[1-3] and number of deaths (0.85 million) attributable to $PM_{2.5}$ in 2017[1]. Thermal power plants combusting coal, oil, natural gas, biomass or other fuels are one of the major contributors to ambient air pollution: between 2010 and 2017, they accounted for 16-39%, 19-51% and 5-23% of Chinese anthropogenic emissions of SO_2[4-10], NO_X[4-11] and total particulate matter (PM) or dust[4-6], respectively, with ranges depending on the estimation method and the time period covered. SO_2 and NO_X are essential precursor gases for secondary $PM_{2.5}$[12], and PM contains a 46-53% mass fraction of primary $PM_{2.5}$[5].

In 1991 China began imposing progressively lower limits on emission concentrations at power plants (Supplementary Data 1), with the most ambitious regulation in terms of maximum emission levels and timing for implementation: ultra-low emissions (ULE) standards. The current standards (GB13223-2011) that are still valid now went into effect on July 1, 2014, limiting SO_2, NO_X and PM emissions from Chinese coal-fired power plants to 100, 100 and 30 mg m^{-3}, respectively[13]. These levels are already low relative to those in other large jurisdictions, such as the US (184, 135 and 20 mg m^{-3} for SO_2, NO_X and PM, respectively) and the EU (200, 200 and 30 mg m^{-3}). Nevertheless, on September 12, 2014, China proposed introducing even tougher emission standards that are equivalent to those of natural gas-fired units, i.e., ULE standards: 35, 50 and 10 mg m^{-3} for SO_2, NO_X and PM, respectively[14,15]. These stricter ULE standards cover the full fleet of existing and future coal-fired power-generating units, requiring that at least 580 million kW installed capacity of existing units (accounting for 71% of the total in 2014) meet the ULE standards by 2020[16], that new units meet the ULE standards since 2015[14], and that at least 80% of capacity (including both preexisting and new units) achieve compliance by 2030[17]. The ULE standards policy would result in significant abatement costs to both governments (particularly in monitoring power plants and supporting subsidies)[18] and power plant owners (in updating technologies, installing and operating control equipment, shutting down inefficient units and building new units)[14,19,20]. However, the ULE policy was expected to substantially reduce Chinese power emissions[21], thereby leading to considerable social benefits in terms of environmental improvement[22], health co-benefits[23] and technological progress in emission control[20].

This substantial increase in the policy stringency of the ULE policy on Chinese coal-fired power emissions has raised the interests of researchers and policy makers[5,20-22,24]. However, most research to date has relied on *ex-ante* studies estimating how the introduction of the ULE standards *may* affect power emissions based on assumptions about what changes in emission concentrations may take place and when they would occur[22]. There have been no *ex-post* studies based on actual measurements. Although there are a handful of global or Chinese power plant emissions databases providing information at a unit or plant level[25-30], they do not involve actual measured data on emission concentrations (which are the targets of the new, stricter ULE standards).

Here, we assess in a highly spatially and temporally disaggregated manner the mitigating effects of the new ULE standards, even ahead of the compliance period, as well as the technologies used for abatement and the factors associated with early compliance. We develop and analyse a Chinese power emissions database, named the China Emissions Accounts for Power plants (CEAP) (which we make available here: http://www.ieimodel.org/). The CEAP database presents, organizes and analyses data from China's continuous emission monitoring systems (CEMS) network (http://www.envsc.cn/): the direct, actual, real-time measurements of emission concentrations for a variety of air pollutants at power plant stacks nationwide (the right targets of the ULE standards). We expand on the work of Karplus et al. (2018), which used CEMS data for four provinces in China to study the changes in stack SO_2 concentration at coal-fired power plants associated with the GB13223-2011 standard. The use of nationwide, detailed and continuous CEMS data provides a direct estimation for emission factors and absolute emissions at high spatial (unit-specific) and temporal (hourly-frequency) resolutions. This differentiates the CEAP database from other power emissions databases[25-30] that were based on average, invariable and outdated (without *ex-post* measurements) emission factors (Supplementary Note 1). We conduct a comprehensive uncertainty analysis and validate our estimates. We use the CEAP dataset to conduct an analysis of overall, unit-specific, time-varying effects of the new ULE standards on Chinese power emissions from 2014 to 2017. We compare our estimates using actual measurements with previous estimates using average emission factors and show that the previous methods significantly overestimated Chinese power emissions for 2014-2017. Furthermore, we detail the mechanisms used to meet the ULE standards and factors associated with a greater probability of early compliance. These analyses not only highlight fuel-, region- and capacity-specific opportunities to further reduce Chinese power emissions in the near future but also provide insights for countries looking to reduce their power emissions.

Early compliance with ultra-low emissions standards

CEMS data suggest encouraging news about the systematic reductions in stack concentrations at Chinese thermal power plants after the introduction of the ULE standards in 2014. Figure 1 displays the geographic distribution, fuel type and operating capacity of the 4,622 power plant stacks monitored by the CEMS network in 2017. The corresponding information for 2014, 2015 and 2016 is presented in Supplementary Figures 1, 2 and 3, respectively. From the histograms, a clear, continuous decline in stack concentrations at Chinese thermal power plants can be observed from 2014 to 2017, with mean annual reductions of 33.34%, 28.29% and 38.06% for SO_2, NO_X and PM, respectively (the non-red dashed lines of Figure 1). The overall compliance rates, i.e., the percentages of total capacity decreasing the annual average concentrations of SO_2, NO_X and PM below the respective ULE criteria (the samples on the left of the red dashed lines in the histograms of Figure 1 and Supplementary Figures 1-3), increased from 15.63%, 10.47% and 15.79% in 2014 to 74.54%, 70.64% and 87.50% in 2017, respectively (Supplementary Data 2).

As the main ULE targets, the stack concentrations of Chinese coal-fired power plants have substantially decreased since 2014, leading to an extensive early compliance at the end of 2017. Figure 2 shows the daily distributions of stack SO_2, NO_X and PM concentrations for different fuel types during 2014-2017. In general, a striking downtrend in the coal-fired power emission concentrations can be observed, with average monthly decreases of 2.82%, 2.79% and 3.65% for SO_2, NO_X and PM, respectively, from 2014 to 2017 (the 2nd row in Figure 2). Crucially, these rates of reduction suddenly increased in July 2014 (the deadline for implementing the GB13223-2011 limits); specifically, they reached 10.97%, 11.43% and 3.54% for SO_2, NO_X and PM, respectively. For the next two months, the rates of decrease in monthly stack concentrations rapidly dropped to 0.69%, 3.20% and 2.29%, respectively, on average. Nevertheless, after the introduction of the ULE standards in September 2014, such declining trends persisted at steady monthly rates averaging 2.81%, 2.47% and 3.87% for SO_2, NO_X and PM, respectively, over the whole ULE period from November 2014 to December 2017. At the end of 2017, the mean SO_2, NO_X and PM concentrations from Chinese coal-fired power plants hit 35.30, 52.00 and 5.70 mg m^{-3}, respectively (Supplementary Data 3). Overall, 72.30% of Chinese coal-fired capacity had achieved early compliance with all three ULE emission limits by December 2017. Given that the 2030 target was to achieve compliance in 80% of coal-fired capacity[17], it seems likely that this target will be met ahead of schedule. Early compliance was encouraged by provisions in the ULE regulations themselves[16,32]: coal-fired power plants in China have access to a wide range of financial incentives if they meet the ULE standards, which can largely offset (and in many cases exceed) the costs of compliance (Supplementary Note 2).

We find that Chinese coal-fired power plants reduced stack concentrations to meet the ULE standards mainly through three mechanisms (Supplementary Note 2): renovating preexisting traditional units for ULE (by installing and turning on pollution control equipment and upgrading their removal efficiency), shutting down small inefficient units and constructing new units with state of the art ULE control technology[16,31,33]. From 2014 to 2017, a total of 591.47 million kW of preexisting coal-fired capacity that had been built before 2015 was renovated to meet the ULE standards (surpassing the 2020 target of 580 million kW[16]). Meanwhile, the combined installed capacity of small coal-fired units below 300 MW was cut by 16.9 million kW. As a result, the stack concentrations of preexisting units built before 2015 declined significantly, with mean monthly decreases of 3.05%, 2.28% and 3.61% for SO_2, NO_X and PM, respectively, from 2015 to 2017 (the blue lines in the insets of Figure 2). Since 2015, 96.07 million kW of new coal-fired capacity has been built by the end of 2017 (which had to install ULE technologies to achieve compliance according to the ULE regulation[16]), with stack concentrations averaging 27.27, 47.70 and 6.27 mg m^{-3} for SO_2, NO_X and PM, respectively (below the ULE standards; green lines).

By the end of 2017, nearly all coal-fired capacity in China had installed SO_2 control equipment[34], and were running such systems on average 97.02% of the total operating time between 2014 and 2016. Typical SO_2 control systems include limestone-gypsum wet desulfurization (deployed in 84.40%, 86.85% and 87.71% of coal-fired capacity in 2014, 2015 and 2016, respectively), flue gas circulating fluidized bed desulfurization (6.47%, 5.24% and 4.89%), seawater desulfurization (2.65%, 2.52% and 2.45%) and ammonia absorption (0.76%, 0.88% and 0.84%). These methods have been technically improved to achieve ultra-high removal efficiencies (even reaching 99.70%; Panel A in Supplementary Data 4). These improvements contributed to 80.15% of Chinese coal-fired capacity achieving early ULE compliance for SO_2 in December 2017 (Supplementary Data 3).

In reducing NO_X emissions, China has experienced considerable progress: the installation of relevant control technologies increased from 13% of total coal-fired capacity in 2010[25] to 98.40% in 2017[34]. The most prevalent equipment used to reduce NOx emissions is flue gas denitrification technologies. One such technology, selective catalytic reduction, was used in 80.49%, 88.19% and 88.67% of coal-fired capacity in 2014, 2015 and 2016, respectively. This equipment is not turned on as frequently as the SO_2 control equipment: on average it was functioning during 94.22% of the total operating time between 2014 and 2016. Relying to a large extent on these technologies, which have removal efficiencies reaching 90.00% (Panel B in Supplementary Data 4), 75.63% of coal-fired capacity had met the ULE NO_X limit by the end of 2017 (Supplementary Data 3).

Control measures for PM were already prevalent in Chinese coal-fired power plants before the ULE policy[25], and recent improvements have primarily focused on upgrading the efficiency of existing equipment. For example, through technological improvements, commonly used technologies, e.g., electrostatic dust removal technology (used in 77.30%, 69.08%, 68.40% and 65.90% of coal-fired capacity in 2014, 2015, 2016 and 2017, respectively), electrostatic-bag dust removal technology (13.70%, 22.24%, 23.20% and 25.40%), and bag-type dust removal technology (9.00%, 8.68%, 8.40% and 8.70%)[34] that removed 99.75% of PM on average, ended up removing over 99.90% (Panel C in Supplementary Data 4)[15]. With the largest penetration of control technologies (100% in 2017)[34], the highest removal efficiencies (over 99.90%)[15] and the longest running time (representing 99.15% of the total operating time on average during 2014-2016), the compliance rate for PM was the highest (90.17% in December 2017; Supplementary Data 3).

Non-coal thermal power plants also experienced general declines in stack concentrations, in spite of the fact that they are not targeted by the ULE regulation (from the 3rd to 5th rows in Figure 2; Supplementary Note 3). These reductions were largely attributable to the age structure shift towards younger units with higher energy efficiency and lower emission intensities: 29.63%, 25.70% and 25.08% of gas and oil-, biomass- and other fuel-fired capacities, respectively, were built after 2014, compared with 15.97% of coal-fired capacity. Overall, the stack concentrations across all fuel types declined over the sampling period (the 1st row) at average monthly rates of 2.95%, 2.55% and 3.63% for SO_2, NO_X and PM, respectively (Supplementary Data 3).

Mitigation effect of ultra-low emissions standards

Figure 3 shows the calculated time-varying emission factors and total emissions of SO_2, NO_X and PM from Chinese power plants between 2014 and 2017, revealing a substantial mitigation effect of the ULE policy. The monthly emission factors of Chinese power plants declined from 2014 to 2017 by 75.33%, 76.03% and 83.31% for SO_2, NO_X and PM, respectively, for coal-fired units, by 69.20%, 25.06% and 64.90% for biomass-fired units, and by 52.35%, 46.87% and 76.94% for gas-fired units (lines in the left column). Although Chinese thermal power generation increased by 3.49% every year from 2014 to 2017 (blue bars in the right column; right axis), the positive effect on emissions was completely offset by the decline in emission factors. Therefore, Chinese power emissions show a downward trend over the four years, decreasing from 2.21, 3.11 and 0.52 Mt in 2014 to 0.77, 1.26 and 0.14 Mt in 2017 by 1.44, 1.85 and 0.37 Mt (i.e., 65.03%, 59.50% and 72.37%) for SO_2, NO_X and PM, respectively (red lines in the right column; left axis). We find that our estimates using actual emission measurements are considerably (17.55-91.86%) lower than other previous estimates that primarily depended on emission factors without considering the ULE effect (datapoints in the right column; left axis).

Using the CEAP database, we analyse the factors associated with early ULE compliance (determining early vs late compliers and identifying the top contributors to the emission reductions). We focus on three determinants of compliance, fuel, region and size, to explore the operational feasibility and technical viability of the ULE limits and to highlight specific opportunities for future emission reductions. Figure 4 shows the estimated reductions in SO_2, NO_X and PM emissions for power plants using different fuel types, located in different regions and of different generating capacities from 2014 to 2017, as well as the potential reductions from 2017 to 2020 under an extreme scenario assuming that all power-generating units meet the ULE standards in 2020.

As for fuel type, coal-fired generators contributed the largest shares (89.27%, 95.37% and 92.82%, respectively) to the reductions in SO_2, NO_X and PM emissions from Chinese power plants between 2014 and 2017, whereas biomass-fired generators made the smallest contributions (0.17%, 0.11% and 0.23%) (the top row in Figure 4). These findings can be primarily explained by the proportion of total thermal power capacity (averaging 92.79% for coal-fired units vs 0.17% for biomass-fired units during 2014-2017; Supplementary Data 2) and the extent of emission mitigation (with annual coal-fired SO_2, NO_X and PM emissions (the targets of the ULE regulation) declining by 64.06%, 62.64% and 73.11%, respectively, from 2014 to 2017, vs biomass-fired emissions declining by 37.11%, 19.05% and 37.97%). Perhaps surprisingly, the annual SO_2 and NO_X emissions from biomass- and other fuel-fired units increased from 2014 to 2015. The hidden reason for these trends might be the age structure shift towards younger units (Supplementary Note 3), i.e., the emissions from newly built units offset the emission reductions from preexisting units.

The power sector emissions from all six Chinese regions (as defined in Supplementary Data 5) declined drastically from 2014 to 2017, with the eastern region contributing the largest shares to nationwide emission reductions (27.67%, 28.69% and 35.13% for SO_2, NO_X and PM, respectively), closely followed by the northern (23.22%, 20.28% and 18.90%) and central and southern regions (17.25%, 17.48% and 14.25%) (the middle row in Figure 4). From 2014 to 2017, these three regions accounted for the largest percentages of thermal power capacity (averaging 74.51% for 2014-2017; Supplementary Data 2) and contributed 68.15%, 66.45% and 68.28% to the nationwide reductions in SO_2, NO_X and PM power emissions, respectively. Furthermore, the eastern, northern and central and southern regions faced the toughest policy stringency, involving 21, 7 and 11, respectively, out of 47 key regions defined and prioritized by the GB13223-2011 standards in terms of levels[13] and having 3, 4 and 1, respectively, out of 9 tight local emission standards (Supplementary Data 1). The ULE policy prioritized East China over Central China in terms of timelines, followed by West China[16]. Under considerable pressure, the eastern region made the greatest effort to meet the standards (achieving the highest compliance rates of 92.51%, 88.29% and 96.15% of total thermal power capacity for SO_2, NO_X and PM, respectively, in 2017). In comparison, the southwestern region, which had the fewest thermal power units (representing 6.65% of the nationwide capacity on average between 2014 and 2017; Supplementary Data 2) and the longest timeline[16], contributed the least to nationwide emission reductions (9.26%, 10.10% and 8.18% for SO_2, NO_X and PM, respectively).

The capacity-specific analysis reveals a clear shift in reduction contributions from large-capacity units (representing a large fraction of total capacity) to small-capacity units (dominated by super-polluting units) (the bottom row in Figure 4). The majority of Chinese power-generating units were large-capacity units (with units larger than 300 MW representing 80.95% and 83.12% of total thermal power capacity and coal-fired capacity, respectively, for 2014-2017; Supplementary Data 2). The ULE standards prioritize key (high-emitting) coal-fired units[16], such that large-capacity units above 300 MW emitting the largest shares of power emissions (63.26%, 60.79% and 62.02% for SO_2, NO_X and PM, respectively, on average between 2014 and 2017) and dominated by coal-fired units (representing 95.27% of large-capacity units in unit capacity between 2014 and 2017; Supplementary Data 2) fell into the main ULE target. Accordingly, large-capacity units achieved compliance faster than small-capacity units (with the ULE compliance rates of 68.59% for thermal units larger than 300 MW vs 43.29% for thermal units smaller than 100 MW, in 2017) and became a large contributor to power emission reductions (with units larger than 300 MW contributing 58.60%, 60.11% and 60.56% to total emission reductions for SO_2, NO_X and PM, respectively, from 2014 to 2017). Nevertheless, retiring small-capacity units (with the combined installed capacity of units smaller than 100 MW declining from 2014 to 2017 by 19.8 million kW) was also an efficient mechanism for abatement. These small-capacity units were often super-polluting units that accounted for a small fraction of capacity (representing 7.38% of total thermal power capacity during 2014-2017; Supplementary Data 2) but generated disproportionately large quantities of emissions (representing 23.00%, 23.43% and 23.13% of total SO_2, NO_X and PM emissions, respectively).

We also assess fuel-, region- and capacity-specific opportunities for further reducing Chinese power emissions by progressively enhancing ULE compliance (Supplementary Note 4). From 2017 to 2020, the annual SO_2, NO_X and PM emissions are projected to decline by 22.13%, 8.28% and 2.04%, respectively, if all coal-fired units meet the ULE standards in 2020 and by 23.21%, 15.49% and 2.69%, respectively, if all thermal units achieve compliance.

Discussion

We develop a Chinese power plant emissions database using CEMS data for 2014-2017 and conduct analysis of the nationwide, unit-specific, time-varying effects of the new ULE standards. The findings of this study indicate the efficacy of the ULE standards: it resulted in a systematic reduction in emission factors for all fuel types by 25-83% and in absolute emissions by over 60%, underscoring the importance of *ex-post* evaluation. We find an overall early compliance of coal-fired power plants that was encouraged by significant financial incentives according to the ULE regulations: by the end of 2017, the 2020 target for updates to preexisting units has been met and even surpassed, and 90% of the compliance 2030 target has been achieved. The dominant mechanisms of early compliance included switching on and upgrading control equipment and shutting down small super-polluting units. The early ULE compliers or large contributors to emission reductions were the power-generating units burning coal, located in the eastern region and on a large capacity scale, with each group representing a large fraction of unit capacity and facing tough policy stringency in levels and timelines. We highlight that a focus on coal-fired units (still with large room for improvement and the largest proportion of total capacity), West China (with the longest timeframe) and small-capacity units (dominated by super-polluting units) can further reduce annual SO_2, NO_X and PM power emissions by 23%, 15% and 3%, respectively, from 2017 to 2020.

The CEAP database and *ex-post* measurements can be used to investigate air quality improvements[22] and health co-benefits[35] associated with the ULE standards and to improve the modelling accuracy by offering nationwide, unit-based and high-frequency power emission inventories[36]. Actually, the Chinese CEMS network covers both air and water pollutants from different industrial sectors (encompassing over 30,000 pollution-emitting sources), with air pollutants from the power sector just as one small part. We plan to extend the CEAP database and produce a multisector dataset in the near future. Such a dataset can be used to identify the top polluting sources in China and to design the corresponding policies for addressing the severe environmental pollution[37].

The CEAP database is subject to uncertainties and limitations. The CEMS network has not covered all Chinese thermal power-generating units (with an average annual gap of 3.8% in unit capacity for 2014-2017), and these samples will be collected to update the CEAP database in the future. The use of theoretical flue gas rates assumes a constant boiler utilization rate and fuel requirement for each combination of fuel type, boiler type and capacity scale. If it becomes available, future research can incorporate high-frequency operational data (especially flue gas volume) for each unit to improve the estimation accuracy. Uncertainty ranges of our estimates are estimated to be within ±9.03% for emission factors and ±2.47% for total emissions, in terms of 2 standard deviations. To enhance the reliability of CEMS data, the CEMS system can be verified using aerial concentration measurements[31], and the CEMS network can be subject to independent audits such as those deployed in India[38]. There is still large room to improve the existing methods of detecting and processing outliers in CEMS data.

Methods

Construction of the CEAP database. The CEAP database uses systematic, detailed, real-time monitoring data from China's CEMS network to estimate nationwide, unit-based, time-varying emission factors and absolute emissions of SO_2, NO_X and PM (the air pollutants covered by the new ULE standards) from Chinese power plants (http://www.ieimodel.org/).

We have been granted exclusive access by the MEE to comprehensive nationwide data from the Chinese CEMS network (http://www.envsc.cn/). In China, power plants (including combined heat-and-power plants) operating coal-fired boilers with an output above 65 tons of steam per hour (excluding stoker-fired boilers and spreader stoker-fired boilers), pulverized coal-fired boilers, oil-fired boilers with an output above 65 tons per hour and gas turbines are required to install CEMS[39]. The national CEMS network covers most Chinese thermal (including fuel- and biomass-fired) power-generating units and measures the emission concentrations of diverse air pollutants in flue gas (g m^{-3}) at power plant stacks. The monitoring data are collected in terms of hourly averages and are further revised to the standard values based on a standard oxygen level[40]. In total, CEMS data involve 3,192, 3,527, 3,749 and 4,622 power plant stacks for 2014, 2015, 2016 and 2017, respectively. In turn, these stacks are associated with 5,248, 5,606 and 5,367 separate power-generating units and account for 96.01%, 97.15% and 95.91% of total thermal power capacity for 2014, 2015 and 2016, respectively (Supplementary Data 2). For the small fraction of power-generating units without CEMS, we assume that their polluting concentrations are at the average level of units that have similar fuel types, that are located in the same region and that are involved in the CEMS network. In some cases, several units share one smokestack, and they are assumed to have similar stack concentrations.

The CEAP dataset also involves unit-specific information for each individual operating unit for 2014-2016 regarding activity levels (such as fuel consumption and power generation; yearly), fuel type, operating capacity, geographic location and pollution control technology, and this information is similarly derived from the MEE. By coupling this unit-specific information with CEMS data, we can detail the technologies that were used to meet the ULE standards and the determinants (fuel, size, or region) of early compliance. The CEAP database encompasses all thermal power-generating units that burn coal, oil, natural gas, biomass and other fuels in 26 Chinese provinces and 4 municipalities, excluding Tibet, Hong Kong, Macao and Taiwan (Supplementary Data 5). In total, 5,943, 6,267, and 6,015 operating units (with total installed capacities of 878,240, 958,308 and 983,857 MW) are involved for 2014, 2015 and 2016, respectively (Supplementary Data 2).

Preprocess of CEMS data. Chinese government has made a great effort to regulate the CEMS network and to ensure the reliability of CEMS data (Supplementary Note 5). However, there still exist null observations and abnormal values (including zeroes during operation and extreme values) in the CEMS dataset, which should be treated carefully according to the related official regulations and guidelines. Plants report nulls or zeroes during downtime for maintenance, such that we omit successive null- or zero-value samples lasting for no less than 5 days (the shortest period of a maintenance shutdown according to the regulation 41) in the estimation. Our estimates for downtime are generally consistent with the official statistics that for a thermal power plant, the downtime on average accounted for 19.45% of the time for 2015[9] (17.11% in our estimation). We treat missing data lasting for less than 5 days (representing 1.15%, 1.03%, 1.05% and 1.04% of total hours in 2014, 2015, 2016 and 2017, respectively) in two different ways according to the guideline HJ/T 75-2007[42]: we assume successive missing data for above 24 hours during operation at similar levels to the points near the time (in terms of monthly averages), and we set missing data lasting for 1-24 hour(s) to the arithmetic mean of the two nearest valid values before and after.

We conducted a data preprocessing step that involved carefully reviewing each observation via a data visualization and removing abnormal values, including the zeroes during operation periods and the impossible values beyond the measurement ranges of the CEMS monitors (Supplementary Data 6). The percentage of these abnormal values is 0.18%, 0.10%, 0.04% and 0.03% for 2014, 2015, 2016 and 2017, respectively. According to the regulation HJ/T 75-2007[42], abnormal values in CEMS data should be treated similarly to null observations. Missing data and abnormal data are not considered a substantial problem, not only because they are only around 1% and 0.1%, respectively, but also because their distributions are random, i.e., we do not observe a higher occurrence of them in particular regions or times of the day/year. Accordingly, we generate daily average stack concentrations by averaging the valid hourly measurements (which are the resulting dataset after dealing with nulls, zeroes and outliers) within the 24-h period and then generate monthly averages by averaging the daily averages within the month[31].

Estimation of emission factors and absolute emissions. The use of the CEMS database offers a direct, simple estimation for nationwide, unit-based and time-varying emission factors and absolute emissions of SO_2, NO_X and PM from Chinese thermal power plants. This CEMS-based estimation method has two clear advantages over traditional methods using average and invariable emission factors (Supplementary Note 1). First, the CEMS database provides direct, actual measurements, which avoids using many indirect parameters and the associated assumptions and that were used in previous studies and enhances the estimation accuracy. Second, the real-time CEMS data are recorded at a high frequency (hourly), which improves the temporal resolutions of emission factors (hourly; the smallest unit of CEMS data) and absolute emissions (monthly; the smallest unit of activity data).

Based on CEMS stack concentration data, unit-level and hourly-frequency emission factors for SO_2, NO_X and PM can be estimated by Eq. (1), without using the uncertain parameters that are common in traditional methods (such as the pollutant content of the fuel, the net heating value, the oxidation rate and the removal efficiency of control technology)[27,43]:

$$EF_{s,i,y,m,h} = C_{s,i,y,m,h} V_{i,y}\,, \qquad (1)$$

where the subscripts s and i indicate the emission species and unit, respectively; y, m and h are the year, month and hour time indexes, respectively; EF represents the abated emission factor, which is expressed as the mass of emitted pollutant per unit of fuel consumption (g kg^{-1} for solid- or liquid-fired units and g m^{-3} for gas-fired units); C is the stack concentration in flue gas based on a standard oxygen level (g m^{-3}), which is available for 2014-2017 in the CEMS database; and V is the theoretical flue gas rate (i.e., the flue gas volume per unit of fuel consumption in m^3 kg^{-1} for solid- or liquid-fired units and m^3 m^{-3} for gas-fired units)[44,45]. Because CEMS monitors are installed at power plant stacks, abated emission concentrations after the effect of pollution control technology (if available) are measured, and abated emission factors are estimated here even without using the removal efficiency-related parameters.

Since the CEMS regulation mainly uses stack concentrations to evaluate the performance of a power plant, a large fraction of other measurements (such as those for flue gas volume) are missing in the CEMS dataset. Omitting these missing data will lead to a substantial underestimation of the actual flue gas volume coming out of China's thermal power plants[45]. Therefore, we resort to theoretical flue gas rates in the estimation[43], which are determined by fuel type, boiler type and installed capacity according to the China Pollution Source Census (Supplementary Data 7)[44]. Accordingly, the actual volume of flue gas for each unit is calculated by multiplying the theoretical flue gas rate by the actual fuel consumption. The use of theoretical flue gas rates to estimate total pollutant emissions can avoid the impact of flue gas leakage, which is known as a tough challenge in power plants and can largely distort the estimation for flue gas volume[45].

The absolute SO_2, NO_X and PM emissions of each power-generating unit are estimated by multiplying the activity data by the emission factors[46]:

$$E_{s,i,y,m} = A_{i,y,m} EF_{s,i,y,m}, \tag{2}$$

where E represents the unit-based emissions during power generation (g) and A is the activity level, represented by the amount of fuel consumption (kg for solid- or liquid-fired units and m^3 for gas-fired units). In this study, power plant emissions are calculated on a monthly basis. Notably, real-time CEMS data are hourly data, whereas the activity data are annual for each unit, such that we need to use the monthly provincial thermal power generation as a proxy to allocate the monthly unit-level fuel consumption (A)[26]:

$$A_{i,y,m} = \frac{F_{p_i,y,m}}{\sum_{m=1}^{12} F_{p_i,y,m}} A_{i,y}, \tag{3}$$

where p_i indicates the province of unit i and F is the provincial thermal power generation available in the Chinese Energy Statistics Yearbooks[47]. Monthly emission factors are estimated by averaging hourly emission factors at the monthly scale.

The unit-specific activity data (A) are available only up to 2016 and are projected for 2017 according to the growth in provincial thermal power generation from 2016 to 2017. This projection, however, assumes that the activity level of a power-generating unit follows the overall development of provincial thermal power generation and that the new units built in 2017 hold fuel type, installed capacity and region structures similar to those of the existing units in 2016. With the assumption of homogenous growth rates in power generation for different plants in a province, this method works well only in places where marginal changes in demand lead to an increase in equal shares of supply from all plants in a province. However, the electricity market reform[48] has changed this since 2017 in the eight pilots, where spot electricity markets were introduced to determine the shares of supply. Thus, the results for 2017 are associated with additional uncertainties.

Uncertainty analysis. A series of uncertainty analyses are conducted to verify the reliability of our estimates based on CEMS data. First, to address the uncertainty from the volatility in high frequency CEMS data, statistical analysis is employed to fit the probability distribution (in a normal form) of the stack concentrations of each emission species by each power-generating unit in each month based on the associated daily averages[49,50]. For units without CEMS, a bootstrap simulation method is employed to randomly select samples from units that have similar fuel types, that are located in the same regions, and that are involved in the CEMS network at equal probabilities. A Monte Carlo approach is employed to produce stack concentrations based on the corresponding distributions, and 10,000 simulations are performed to assess the uncertainty ranges of the estimated emission factors and absolute emissions[27,43]. The uncertainty analysis indicates that the uncertainty ranges in our estimates are relatively small (with 2 standard deviations within ±8.65% for emission factors and ±1.09% for absolute emissions; error bars in Figure 3).

Second, uncertainty might also arise from the use of theoretical flue gas rates due to the technology, feedstock and other heterogeneities of power-generation units. Fortunately, the CEMS database involves the measurements of flue gas rate for 1,516 units (Supplementary Data 8), sufficing to generate a rough estimation of the likely ranges of flue gas rates by fuel type, boiler type and unit capacity. The likely ranges are estimated at a small level under the confidence level of 95% (with the maximal level of ±10%; Supplementary Data 7), finely supporting the use of theoretical flow rates. We let the flue gas rate for every unit change randomly on the corresponding likely ranges (for the types of units without flow rate samples, the largest likely range of ±10.07% estimated is used) by following a uniform distribution, and we run 10,000 simulations[51,52]. We found that even with random variations, our estimates appear quite robust (with 2 standard deviations within ±9.03% for emission factors and ±2.47% for absolute emissions).

Third, we conduct an uncertainty analysis on the unit-specific activity data for 2017 (which are not yet available and are projected using a homogenous growth rate for a province). The probability distribution of growth rates of activity level for each unit is fitted in a normal form[43], based on a total of 10,000 samples that are randomly selected by a bootstrap method from its previous values during 2014-2016. The heterogeneous unit-level growth rates for different units from 2016 to 2017 are produced by a Monte Carlo approach based on their own independent distributions and are then used to allocate the total provincial growth to different units. Relying on 10,000 simulations, the likely bound of total emissions for 2017 is estimated to ±0.03%, in terms of 2 standard deviations.

Estimation of future potential emission reductions. Our estimation for the 2014-2017 period reveals encouraging news about an overall early compliance of Chinese coal-fired power plants with the ULE standards: the 2020 target (renovating a combined 580 million kW of the installed capacity of coal-fired units to meet the ULE standards)[16] had been surpassed by 20 million kW by the end of 2017 (three years before the policy implementation deadline of 2020), and the 2030 target (with 80% of coal-fired capacity achieving compliance)[17] was approached (72% in 2017). We then evaluate future potential reductions under aggressive but feasible targets (considering the ever-increasing stringency of air pollution standards in China in recent years). We consider 2020 as the target year because there is sufficient time (three years from 2018 to 2020) left to accomplish tougher goals (in view of the satisfactory early compliance with respect to the ULE standards). Moreover, China's 13th Five-Year Plan (2016-2020) for Power Sector Development[53] provides predictions of the growth trends in the activity levels of Chinese power plants.

To explore the potential reductions in power emissions under different ULE targets in 2020, we design 2 scenarios: we assume that all Chinese coal-fired capacity has been retrofitted to meet the ULE limits by 2020; and we design an extreme case in which all thermal power-generating units achieve ULE compliance in 2020. The activity levels of different power-generating units in 2020 are projected according to China's 13th Five-Year Plan (2016-2020) for Power Sector Development[53]. The total power generation in 2020 is assumed to meet the expected total power consumption (7.20 trillion kWh)[53] and is then allocated to different fuel types according to the planned energy structure (with 31% of power generation from non-fossil-fired units[53] vs 100%-31%=69% (4.97 trillion kWh) from fossil-fired units). For fossil-fired units, the power generation from coal- and gas-fired units is assumed to follow the plans for the respective total installed capacities (growing to 1.10 and 0.11 billion KW, respectively, in 2020[53]), reaching 4.59 and 0.30 trillion kWh, respectively, in 2020; thus, the power generation from the other fossil-fired units is set to 4.97-(4.59+0.30)=0.08 trillion kWh. We assume that the new units built from 2017 to 2020 hold fuel type, installed capacity and region structures similar to those of the existing units in 2016.

Data availability

The CEAP database that supports the findings of this study is available at http://www.ieimodel.org/. Supplementary Data 2 presents a summary of the CEAP dataset. The data regarding the compilation of the CEAP dataset include CEMS data collected from the platforms listed in Supplementary Data 9, and the unit-specific information provided in Supplementary Data 10. The data regarding the estimation of emission factors and absolute emissions include the stack concentrations presented in Figure 1, Supplementary Figures 1-3 and Supplementary Data 3, the flue gas rates provided in Supplementary Data 7 and 8, and the unit information provided in Supplementary Data 10 and 11. The data regarding the analysis of the determinants of early ULE compliance (region, fuel and capacity) are presented in Supplementary Figures 4-9.

Code availability

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

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Additional information

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Acknowledgements

This work was supported by the grants from the National Science Foundation for Outstanding Young Scholars (71622011), the National Program for Support of Top Notch Young Professionals and the National Research Program for Key Issues in Air Pollution Control (DQGG-05-07).

Author contributions

L.T., Z.M., X.B. and S.W. designed the research. X.B., S.L. and X.Z. processed and analysed the data of Continuous Emission Monitoring Systems. X.W. compiled and analysed the unit-specific information for Chinese power plants. L.T., J.Q., X.C. and X.X. conducted the experimental work. L.T., Z.M. and L.D.A. wrote the paper. All authors contributed to developing and writing the manuscript.

Competing interests

The authors declare no financial or non-financial competing interests.

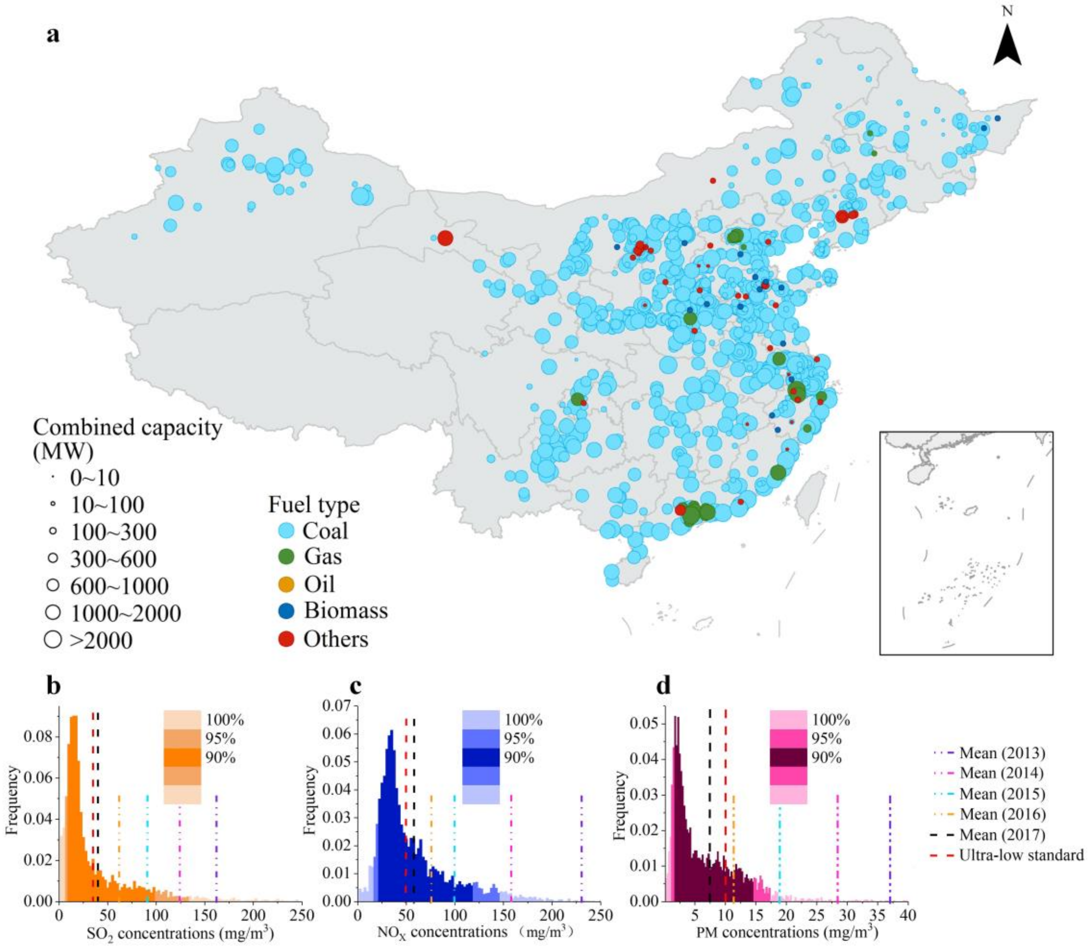

Figure 1 | Chinese power plant stacks with continuous emissions monitoring systems in 2017. **a**, Locations, fuel types and combined capacities of the involved generating units totalling 4,622 power plant stacks nationwide. In turn, these stacks consist of 1,501 thermal (including fossil fuel- and biomass-burning) power plants or 5,367 power-generating units, with a combined installed capacity of 943.60 GW, i.e., 95.91% of total thermal power capacity in 2017. The stacks are classified by fuel type and combined capacity of the associated units. The inset at the lower right corner shows islands in the South China Sea, for which there is no data. **b-d**, Histograms of annual average concentrations in 2017 of SO$_2$ (**b**), NO$_X$ (**c**) and PM (**d**) for different thermal power plant stacks. The red dashed lines show the ultra-low emissions standards, the dashed lines in different non-red colours indicate the mean for different years, and the shading represents the 90% and 95% intervals.

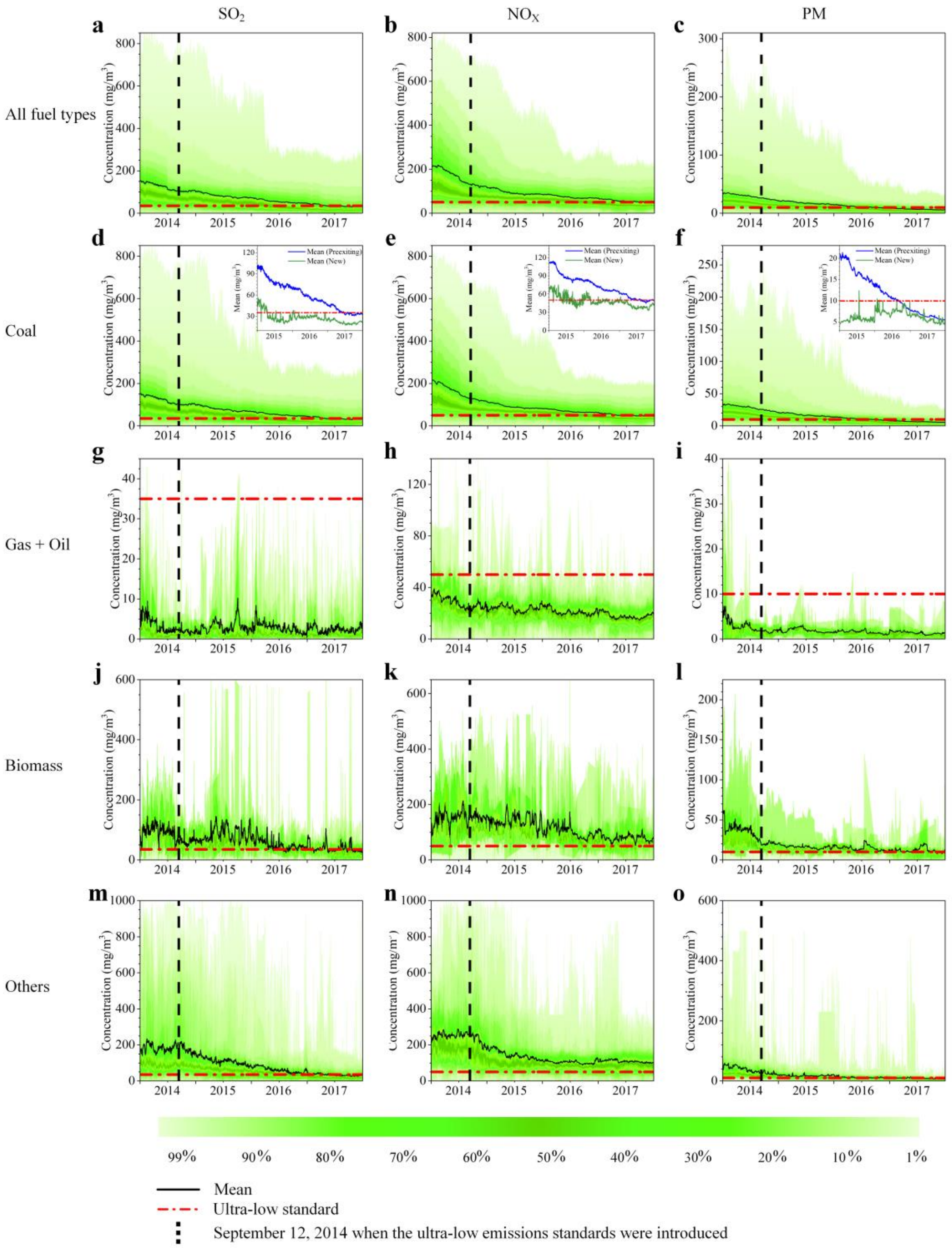

Figure 2 | Daily distributions of stack concentrations at Chinese power plant stacks 2014-2017. a-o, Distributions of daily average stack concentrations of all Chinese power plant stacks (**a-c**) and those associated with coal- (**d-f**), gas and oil- (**g-i**), biomass- (**j-l**) and other fuels-fired units (**m-o**) for SO_2 (**a**, **d**, **g**, **j** and **m**), NO_X (**b**, **e**, **h**, **k** and **n**) and PM (**c**, **f**, **i**, **l** and **o**). The red dashed horizontal lines show the ultra-low emission standards, the black dashed vertical lines mark September 12, 2014 when the ultra-low emissions standards were introduced, the black full lines indicate the mean, and the shading shows the intervals of percentiles. The insets in the 2nd row show the mean of preexisting units built before 2015 (blue lines) and new units built after 2015 (green lines).

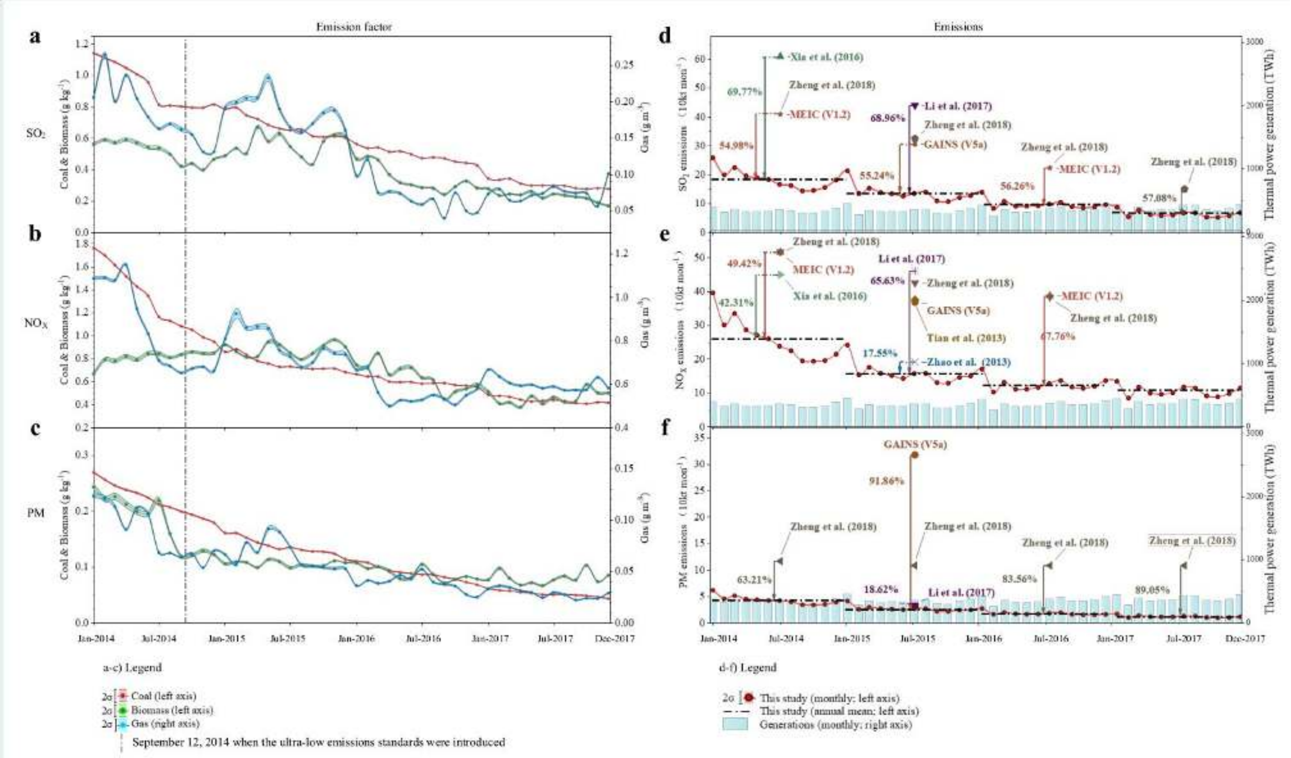

Figure 3 | Monthly emission factors and total emissions for Chinese power-generating units 2014-2017. a-c, Emission factors for coal- and biomass-fired units (g kg^{-1}; left axis) and gas-fired units (g m^{-3}; right axis) for SO_2 (**a**), NO_X (**b**) and PM (**c**). The dashed vertical lines mark September 12, 2014 when the ultra-low emissions standards were introduced. **d-f**, Estimated total power emissions (10 kt per month; left axis) for SO_2 (**c**), NO_X (**d**) and PM (**f**), together with total thermal power generation (TWh; right axis). The 2 sigma for the error bars means the 2 standard deviations. The datapoints in panels **d**, **e** and **f** are from Refs. 5, 8, 10, 11 and 30, and the Greenhouse Gas and Air Pollution Interactions and Synergies database (GAINS) (https://gains.iiasa.ac.at/models/gains_models3.html) and Multi-resolution Emission Inventory for China (MEIC) (http://meicmodel.org/). The percentages reflect the percentage reduction of our current estimates (dashed horizontal lines) relative to the corresponding previous estimates (discrete datapoints).

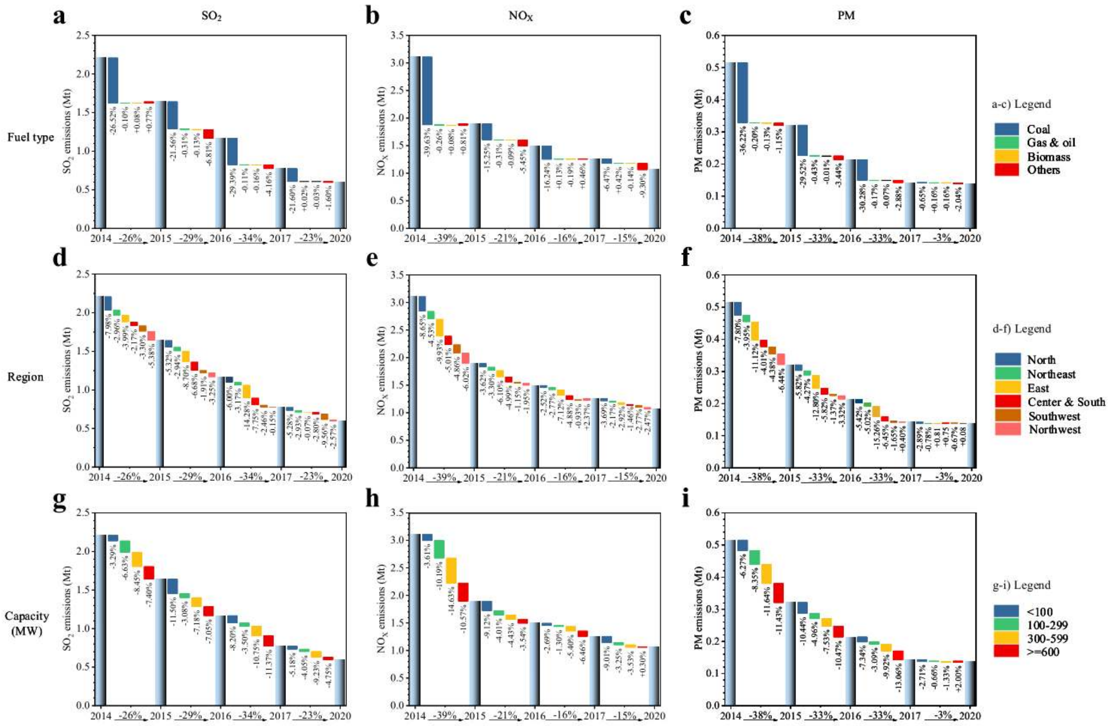

Figure 4 | Absolute emission reductions for 2014-2020. a-**i**, Estimated reductions in SO_2, NO_X and PM emissions from the power-generating units classified by fuel type (**a**-**c**), region (**d**-**f**) and capacity (**g**-**i**). The bars in blueish grey show the estimated annual power emissions, and the bars in bright colours represent the emission reductions of the associated unit categories. Absolute emission reductions from all units across years are shown in *x* axis. The results for 2017-2020 are projected based on China's 13th Five-Year Plan (2016-2020) for Power Sector Development[53] and the assumption that all units meet the ultra-low emissions standards in 2020 in the same way (using the same technologies and upgrades) as those used to meet the standards during 2014-2017.