nature energy

SUPPLEMENTARY INFORMATION
https://doi.org/10.1038/s41560-019-0468-1

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

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Supplementary Information

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Supplementary Note 1 | Previous research.

To the best of our knowledge, previous studies have not yet used nationwide CEMS data. The available unit- or plant-level databases on air pollutant emissions from Chinese power plants were the Global Power Emissions Database (GPED)[1], the China coal-fired Power plant Emissions Database (CPED)[2] and some bottom-up emission inventories for Chinese power plants[3-6]. However, these existing datasets lacked actual measurements of stack concentrations (which are the ultra-low emissions (ULE) standards targets). Instead, they estimated emissions based on average emission factors at a very aggregated level, i.e., the mass of emitted pollutants per unit of fuel consumption (in g kg^{-1} for solid- and liquid-fired units and g m^{-3} for gas-fired units). These emission factors were not the results of measurements but, rather, were proxied using broad technology classes and associated with numerous assumptions and sensitive parameters (such as the pollutant content of fuel, the net heating value, the oxidation rate and the removal efficiency of control technology), leading to high uncertainty[7]. Furthermore, the emission factors used in these cited inventories were generally uniform and invariable values, which cannot capture the heterogeneous, time-varying features of individual generating units that vary with the real operational status. Moreover, these emission factors were evaluated before 2012 and have not been yet updated using ex post measurements; however, the implementation of the GB13223-2011 standards and introduction of the ULE policy in 2014 have led to renovations and technological changes to Chinese power plants, thereby largely changing the associated emission factors. This poses a particular problem for evaluating changes due to the stricter regulations imposed in 2014 and the associated renovations and technological changes.

The proposed China Emissions Accounts for Power plants (CEAP) database makes it possible to estimate power emissions directly using actual measurements of stack concentrations rather than average emission factors, by incorporating the data from Chinese continuous emission monitoring systems (CEMS) network. This approach addresses the above limitations of the existing inventories in three ways. First, the CEMS network targets the stack concentrations of different air pollutants (which are the targets of the new ULE standards), allowing us to determine the compliance behaviours of Chinese power plants with the ULE standards and the associated impacts of the ULE policy. Second, the use of actual measurements provides a direct estimation for emission factors and absolute emissions thereby avoiding the indirect parameters used in previous research, which substantially reduces the uncertainty in estimates. Third, the real-time (hourly) measurements by the CEMS network present the dynamics of the polluting behaviours of Chinese power plants and their compliance behaviours with respect to the ULE standards over time, updating the emission factors and absolute emissions based on ex post measurements.

Karplus et al. (2018) used the CEMS data for four provinces (i.e., Guangdong, Hubei, Shandong and Shanghai) in China to investigate the compliance behaviours of coal-fired power plants with the GB13223-2011 standard on SO_2 emission concentration[8], finding a substantial reduction in the SO_2 emission concentration since the policy implementation deadline[9]. However, they did not estimate the associated changes in emission factors and absolute emissions due to a lack of detailed activity data (e.g., fuel consumption and power generation), nor did they estimate the nationwide effect. In comparison, our CEAP database couples CEMS data with unit-based information (on activity levels, geographic location, fuel type, operating capacity and pollution control technologies), allowing us to investigate not only the polluting and compliance behaviours of Chinese power plants but also the associated mitigation effects, as well as the techniques and operating procedures that were used to meet the new ULE standards[10,11,12,13].

Supplementary Note 2 | Mechanisms to meet ULE standards.

The popular mechanisms by which coal-fired power plants reduced stack concentrations include installing and running emission control systems, upgrading system efficiency, switching to low-sulphur coal, shutting down old units and constructing new units. Installing and running emission control systems have been demonstrated to be an efficient and prevailing measure to meet the GB13223-2011 standards (with operating costs for controlling SO_2, NO_X and PM of RMB 11.7, 6.9, and 4.3 per MWh, respectively, for a typical 300 MW coal-fired unit)[10,11,14]. Therefore, to further reach the tighter ULE standards, updating the removal efficiency of such systems became an easy and economical method (incurring an acceptable additional cost of RMB 2.1, 1.3 and 3.6)[10]. Given that upgrading small-capacity units to meet the ULE standards has been shown to be far more costly than that for large-capacity units (with an operating cost of NO_X control for a 100 MW unit that is approximately twice that for a 1000 MW unit)[10], shutting them down entirely and constructing new ULE technology-installed units is likely to be cost-effective in many cases[1]. Using low-sulphur coal has been shown to be relatively inefficient and has a limited application globally[14]. Not surprisingly, we find that Chinese coal-fired power plants reduced stack concentrations to meet the ULE standards mainly by the three cost-effective mechanisms: renovating preexisting traditional units for ULE (by operating pollution control systems and upgrading their removal efficiency), shutting down small inefficient units and constructing new units with state of the art ULE control technology.

According to the existing relevant regulations[15,16], coal-fired power plants can obtain a combination of financial incentives if they meet the ULE standards, including the following: subsidies of RMB 10 and 5 per MWh for preexisting units (connected to the grid before January 1, 2016) and new units (after January 1, 2016), respectively; a 200-hour extension of operating time for each unit; a 50% discount on sewage charges if the emission concentrations are 50% lower than the current limits from 2003 to 2017 or a 25% (50%) discount on environmental tax if the emission concentrations are 30% (50%) lower than the current limits since 2018; financial support (in terms of special funds for air pollution control); and preferential bank loans for technology improvement. These benefits can completely offset (and in many cases exceed) the compliance costs, which could have encouraged many coal-fired power plants to comply with the ULE standards even earlier than the compliance period.

Based on the aforementioned mechanisms and policy, the stack concentrations of Chinese coal-fired power plants have substantially decreased since 2014, leading to extensive early compliance ahead of the policy deadlines (2020 and 2030). 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 all three ULE standards (surpassing the 2020 target of 580 million kW[15]). 72.30% of Chinese coal-fired capacity had achieved early compliance 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 easily met ahead of schedule.

Supplementary Note 3 | Changes in stack concentrations at non-coal-fired units.

Non-coal-fired power-generating units also experienced general declines in stack concentrations, in spite of the fact that they are not targeted by the ULE regulation (third to fifth rows in Figure 2). The concentration reductions of units burning other fuels (such as waste, peat and coke oven gas) were particularly substantial, with average monthly rates of decrease of 4.07% (exceeding the coal-fired level), 1.61% and 3.83% (exceeding the coal-fired level) for SO_2, NO_X and PM, respectively, from 2014 to 2017 (last row). The corresponding figures for biomass-fired units were 2.53%, 1.39% and 2.51%, which were all slightly more moderate than the coal-fired levels (fourth row). In comparison, the policy influence on gas and oil-fired units seemed the weakest. Gas-fired units were very clean, with emission concentrations averaging 7.96, 33.68 and 2.81 mg m^{-3} for SO_2, NO_X and PM, respectively, between 2014 and 2017. These levels are far below the required levels (i.e., 35, 50 and 10 mg m^{-3} for SO_2, NO_X and PM, respectively, equivalent to the ULE levels for coal-fired units) and the coal-fired levels (averaging 75.41, 96.04 and 16.20 during 2014-2017; Supplementary Data 3). Accordingly, the concentration reductions of gas and oil-fired units (third row) were mainly from oil-fired units that achieved high reduction rates (averaging 3.90%, 2.76% and 3.52% per month from 2014 to 2017) but accounted for a small fraction (representing only 1.29% of gas and oil-fired plant stacks in 2017).

Supplementary Note 4 | Potential emission reductions from 2017 to 2020.

We assess fuel-, region- and capacity-specific opportunities for further reducing Chinese power emissions by progressively enhancing ULE compliance. In general, 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 for all fuel types achieve compliance in 2020 (Figure 4).

From the perspective of fuel type, in the extreme scenario assuming all thermal units achieve compliance in 2020, gas-fired units are projected to still be far cleaner than coal-fired units even with the same levels of emissions standards (with projected stack concentrations averaging 3.79, 22.63 and 1.37 mg m^{-3} for SO_2, NO_X and PM, respectively, vs 23.41, 41.38 and 5.57 mg m^{-3} for coal-fired units). Therefore, coal-fired generators (with large room for improvement and the largest proportion of total capacity) are projected to still contribute the largest shares to potential emission reductions for 2017-2020 (for example, 93.08%, 141.48% and 24.11% for SO_2, NO_X and PM, respectively, in the extreme case). In contrast, emissions from gas and oil-fired units might otherwise increase and make a negative contribution to future emission reductions from 2017 to 2020 (-0.08%, -3.11% and -5.87% for SO_2, NO_X and PM, respectively), mainly due to high compliance rates having been achieved by the end of 2017 (99.53%, 99.53% and 99.85% for SO_2, NO_X and PM, respectively;

Supplementary Data 3) and a large new capacity planned to be built from 2017 to 2020 in China's 13th Five-Year Plan (2016-2020)[18]. In addition, with the lowest compliance rate at the end of 2017 (15.60% for all three ULE targets; Supplementary Data 3), other fuel-fired units (burning waste, peat, coke oven gas, etc.) are projected to make the second largest shares of contribution to future emission reductions (6.89%, 48.09% and 75.87% for SO_2, NO_X and PM, respectively).

The northern region is projected to make the largest contribution to nationwide emission reductions from 2017 to 2020 (22.74%, 23.85% and 107.07% for SO_2, NO_X and PM, respectively, if all thermal units meet the ULE standards in 2020). The southwestern region, with the longest timeframe[15], would also play an important role in reducing future emissions (contributing 41.21%, 17.89% and 24.74% to the national reductions in SO_2, NO_X and PM emissions, respectively).

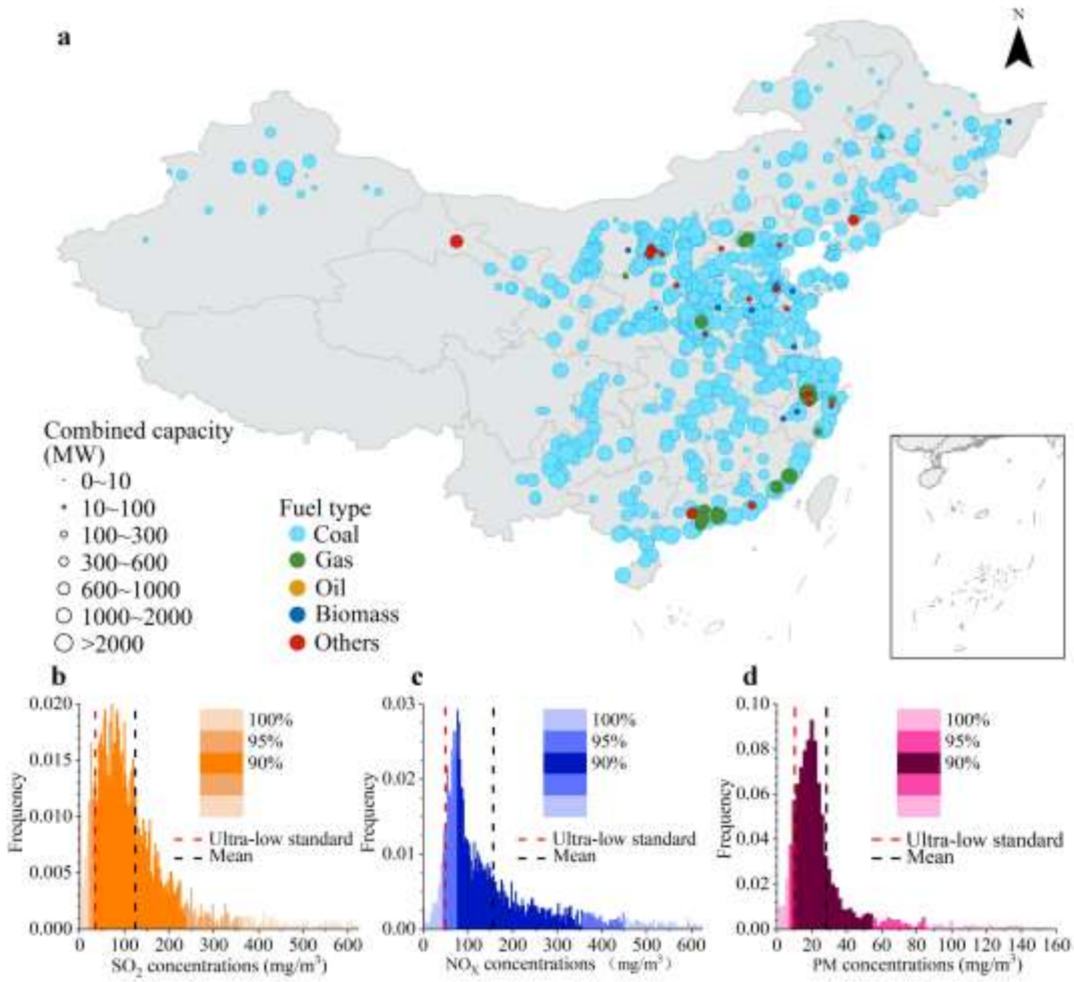
Small-capacity units below 100 MW were often super-polluting units that accounted for a small fraction of capacity (representing 7.38% of total thermal power capacity on average during 2014-2017; Supplementary Data 2) but generated disproportionately large quantities of emissions (representing 23.00%, 23.43% and 23.13% of total SO_2, NO_X and PM emissions, respectively). Thus, targeting small-capacity units can be considered an effective measure for cutting power emissions in the future[1], with units below 100 MW contributing 23.64% (the second largest share), 58.18% (the largest share) and 100.42% (the largest share) to future emission reductions for SO_2, NO_X and PM, respectively, from 2017 to 2020 in the extreme scenario.

Supplementary Note 5 | CEMS-related regulations.

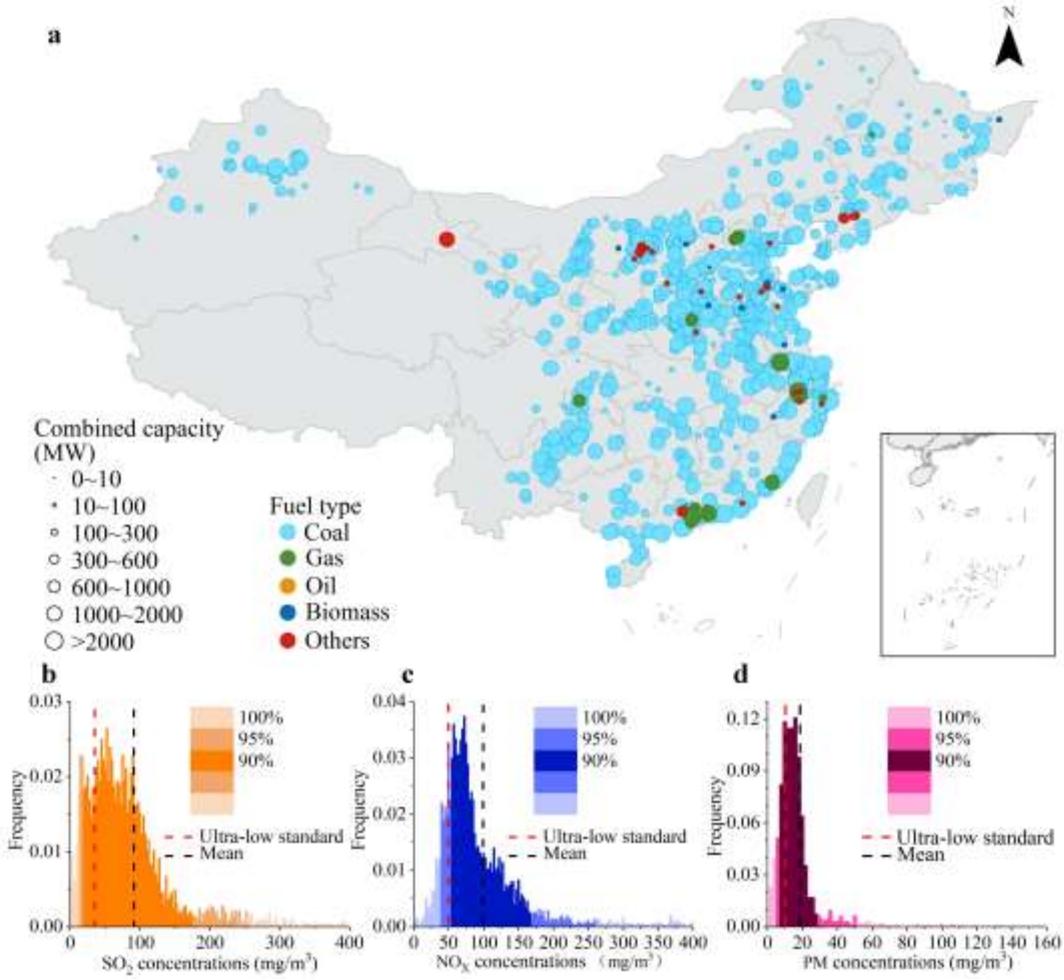
The data quality of the CEMS network must be taken seriously, and China has developed a series of detailed specifications and technical guidelines for power plants and local governments to perform and supervise, respectively, throughout all processes in the CEMS network (such as CEMS operations and maintenance and

CEMS data recording, collection, processing and storage)[19,20]. From the end of 2013, the CEMS regulation has required each state-monitored firm to automatically report CEMS-monitored data to a publicly available, online platform for the corresponding province (the left column in Supplementary Data 9). To guarantee the credibility and quality of the data, local entities at the provincial and city levels are required to conduct an inspection of every pollution source on at least a quarterly basis; such inspections involve performing random spot-checking and comparing the results with the levels reported by the firms[21,22]. Furthermore, local governments need to conduct a quarterly data comparison across different firms, with the objective of identifying outliers, abnormalities and data manipulation[23]. The verification results are released in an online platform (the right column in Supplementary Data 9) for public scrutiny[24,25]. The CEMS regulation includes a substantial punishment mechanism, in that the financial penalties and criminal punishments for actions of deleting, distorting and forging CEMS data are very severe[26,27].

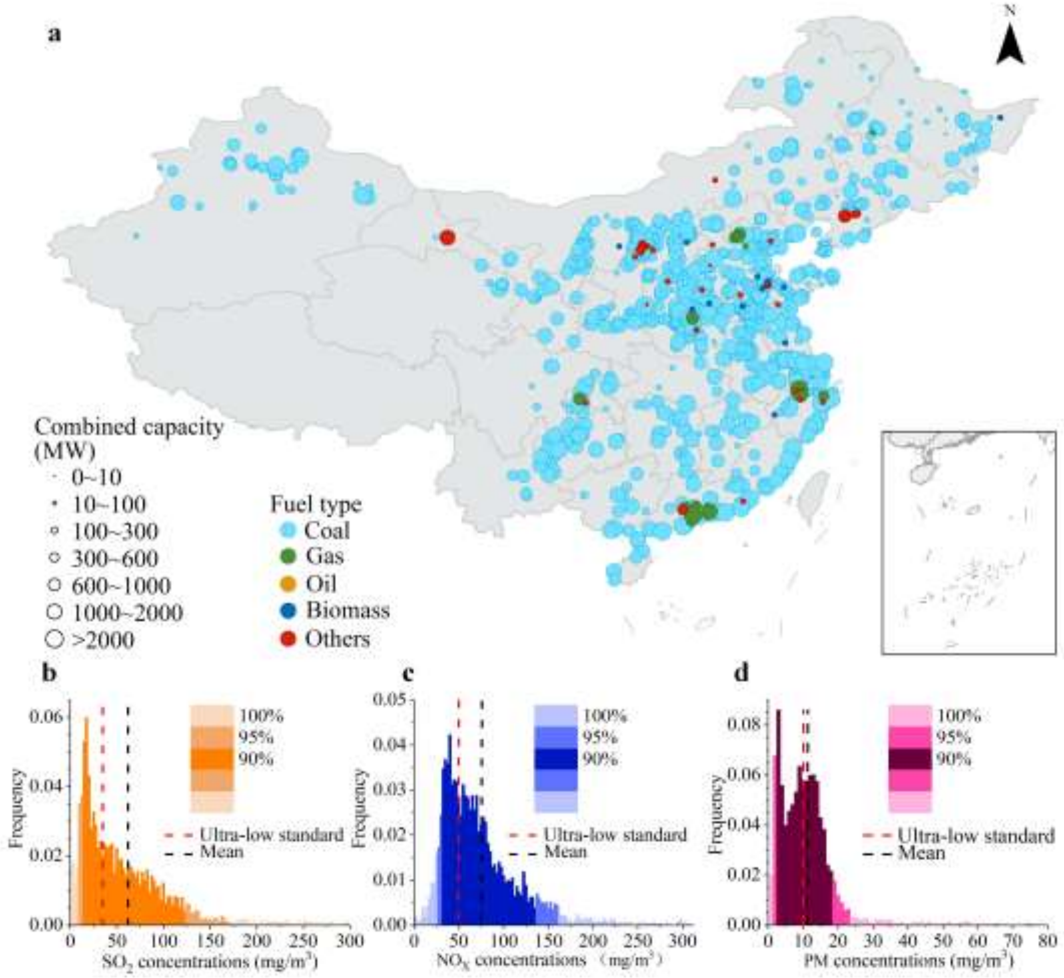
CEMS data might suffer uncertainties stemming from the technologies used to measure pollutant concentrations at China's power plants, in terms of zero drift, span drift and indication errors in the process of operation, the failure to conduct calibration and reference tests in the process of maintenance, and invalid data communication and data loss in the process of data reporting[19]. Governments have been aware of these uncertainties, and they have required each thermal power plant to undertake at least an A-, B- and C-grade shutdown every 4-6, 2-3 and 1 year(s), with each taking 32-80, 14-50 and 9-30 days, respectively, for maintaining and updating their technologies[28]. Furthermore, if needed, thermal power plants can conduct a D-grade overhaul, taking 5-15 days, every year[28].



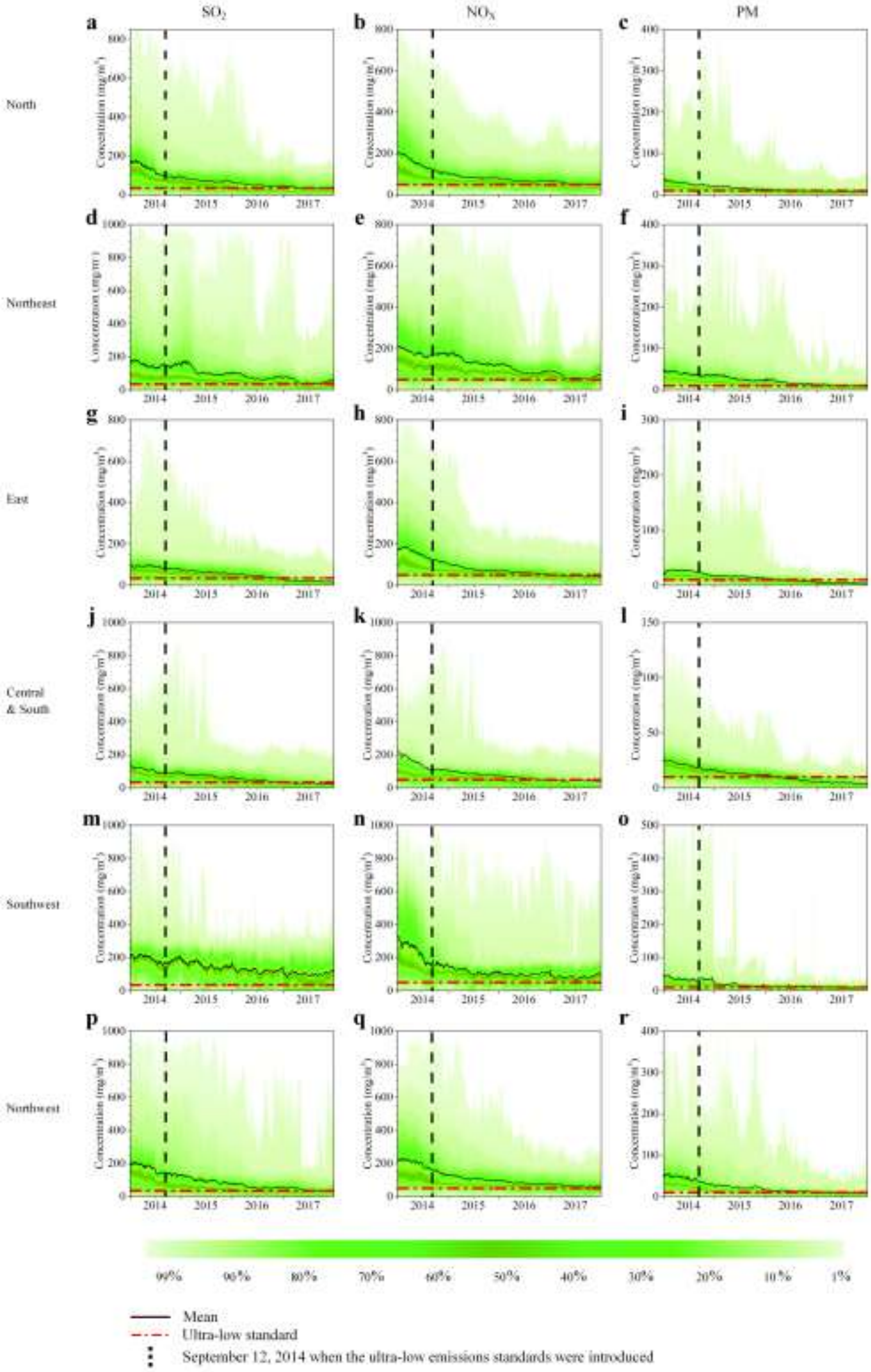
Supplementary Figure 1 | Chinese power plant stacks with continuous emissions monitoring systems in 2014. **a**, Locations, fuel types and combined capacities of the involved generating units totalling 3,192 power plant stacks nationwide. The stacks are classified by fuel type and combined capacity of 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 2014 of SO_2 (**b**), NO_X (**c**) and PM (**d**) for different stacks. The red dashed lines show the ultra-low emissions standards, the black dashed lines indicate the mean, and the shading represents the 90% and 95% intervals.



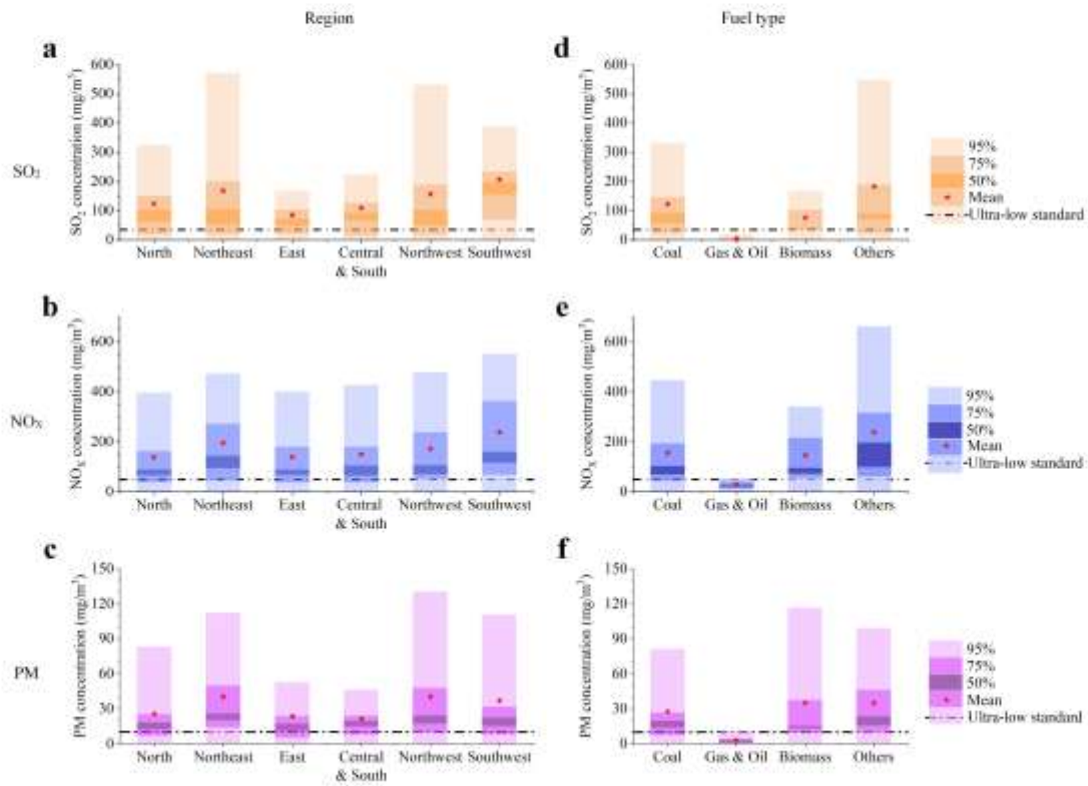
Supplementary Figure 2 | Chinese power plant stacks with continuous emissions monitoring systems in 2015. **a**, Locations, fuel types and combined capacities of the involved generating units totalling 3,527 power plant stacks nationwide. The stacks are classified by fuel type and combined capacity of 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 2015 of SO_2 (**b**), NO_X (**c**) and PM (**d**) for different stacks. The red dashed lines show the ultra-low emissions standards, the black dashed lines indicate the mean, and the shading represents the 90% and 95% intervals.



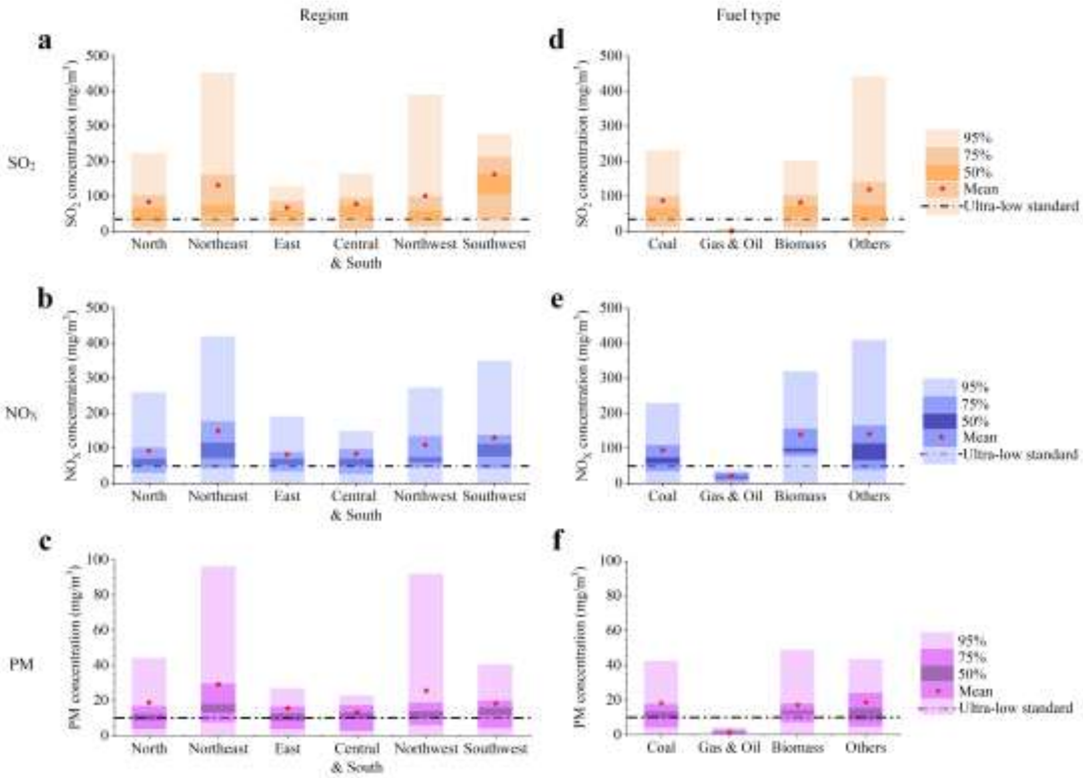
Supplementary Figure 3 | Chinese power plant stacks with continuous emissions monitoring systems in 2016. **a**, Locations, fuel types and combined capacities of the involved generating units totalling 3,749 power plant stacks nationwide. The stacks are classified by fuel type and combined capacity of 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 2016 of SO_2 (**b**), NO_X (**c**) and PM (**d**) for different stacks. The red dashed lines show the ultra-low emissions standards, the black dashed lines indicate the mean, and the shading represents the 90% and 95% intervals.



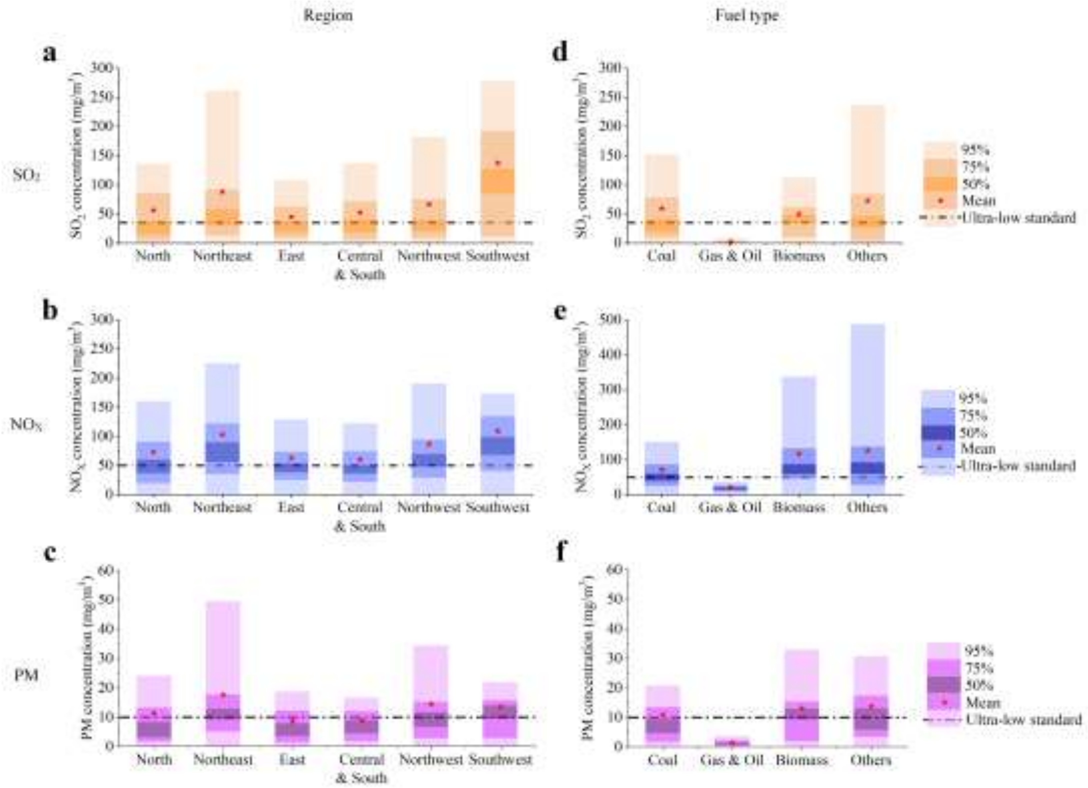
Supplementary Figure 4 | Daily distributions of stack concentrations at Chinese power plant stacks in different regions 2014-2017. a-r, Distributions of daily average stack concentrations of Chinese power plant stacks located in the northern (**a-c**), northeastern (**d-f**), eastern (**g-i**), central and southern (**j-l**), southwestern (**m-o**) and northwestern regions (**p**-**r**) for SO_2 (**a**, **d**, **g**, **j**, **m**, **p**), NO_X (**b**, **e**, **h**, **k**, **n**, **q**) and PM (**c**, **f**, **i**, **l**, **o**, **r**). The red dashed horizontal lines show the ultra-low emissions 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.



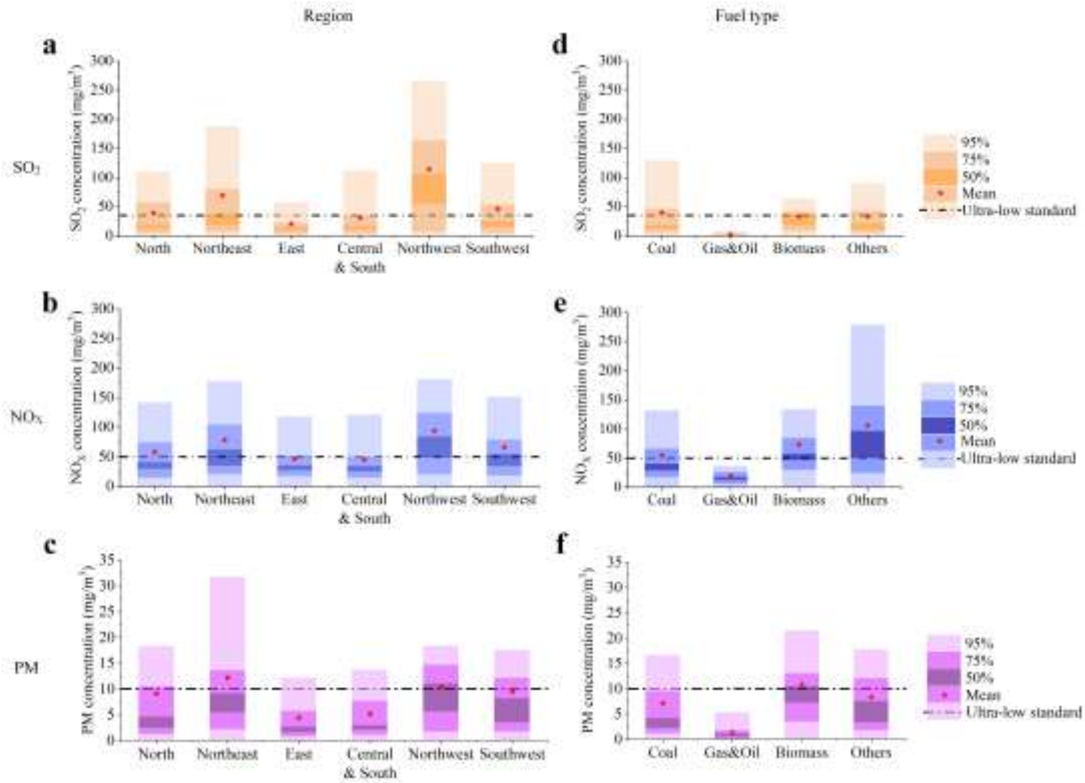
Supplementary Figure 5 | Boxplots of annual average stack concentrations at Chinese power plant stacks in 2014. **a-f**, The distributions of 2014 annual average stack concentrations by region (**a-c**) and fuel type (**d-f**). The dashed lines show the ultra-low emissions standards, the asterisks indicate the mean, and the shading represents the 50% and 75% intervals.



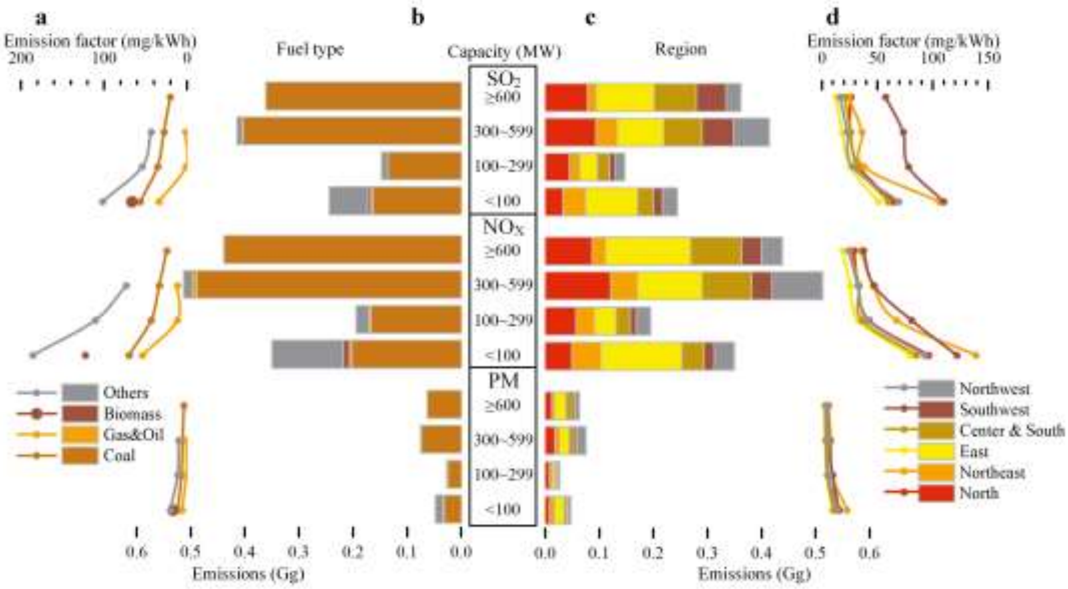
Supplementary Figure 6 | Boxplots of annual average stack concentrations at Chinese power plant stacks in 2015. **a-f**, The distributions of 2015 annual average stack concentrations by region (**a-c**) and fuel type (**d-f**). The dashed lines show the ultra-low emissions standards, the asterisks indicate the mean, and the shading represents the 50% and 75% intervals.



Supplementary Figure 7 | Boxplots of annual average stack concentrations at Chinese power plant stacks in 2016. **a-f**, The distributions of 2016 annual average stack concentrations by region (**a-c**) and fuel type (**d-f**). The dashed lines show the ultra-low emissions standards, the asterisks indicate the mean, and the shading represents the 50% and 75% intervals.



Supplementary Figure 8 | Boxplots of annual average stack concentrations at Chinese power plant stacks in 2017. **a-f**, The distributions of 2017 annual average stack concentrations by region (**a-c**) and fuel type (**d-f**). The dashed lines show the ultra-low emissions standards, the asterisks indicate the mean, and the shading represents the 50% and 75% intervals.



Supplementary Figure 9 | Structures of emission factors and absolute emissions from Chinese power-generating units by capacity, fuel type and region in 2016. **a,d,** The curves indicate the splined interpolation of estimated average emission factors associated with different fuel types (**a**) and regions (**d**) for each capacity category (in mg/kWh; top axes). **b,c,** The bars show the estimated absolute emissions associated with different fuel types (**b**) and regions (**c**) for each capacity category (in Gg; bottom axes).

Supplementary References

1. Tong, D. et al. Targeted emission reductions from global super-polluting power plant units. *Nature Sustainability* **1**(1), 59-68 (2018).
2. Liu, F. et al. High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010. *Atmos. Chem. Phys.* **15**(23), 13299-13317 (2015).
3. Chen, L. et al. Unit-based emission inventory and uncertainty assessment of coal-fired power plants. *Atmos. Environ.* **99**, 527-535 (2014).
4. Zhao, Y. et al. Primary air pollutant emissions of coal-fired power plants in China: Current status and future prediction. *Atmos. Environ.* **42**(36), 8442-8452 (2008).
5. Wang, S. et al. Growth in NO_X emissions from power plants in China: Bottom-up estimates and satellite observations. *Atmos. Chem. Phys.* **12**(10), 4429-4447 (2012).
6. Tian, H. et al. Nitrogen oxides emissions from thermal power plants in china: Current status and future predictions. *Environ. Sci. Technol.* **47**(19), 11350-11357 (2013).
7. Liu, Z. et al. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* **524**, 335-338 (2015).
8. Ministry of Ecology and Environment of the People's Republic of China. *Emission Standard*

of Air Pollutants for Thermal Power Plants (GB13223-2011) (China Environmental Press, 2011). (*in Chinese*)

9. Karplus, V.J., Zhang, S. & Almond, D. Quantifying coal power plant responses to tighter SO_2 emissions standards in China. *Proc. Natl Acad. Sci. USA* **115**(27), 7004-7009 (2018).Yang, H. et al. Cost estimate of the multi-pollutant abatement in coal-fired power sector in China. *Energy* **161**, 523-535 (2018).
10. Yang, H. et al. Cost estimate of the multi-pollutant abatement in coal-fired power sector in China. *Energy* **161**, 523-535 (2018).
11. Wang, C., Olsson, G. & Liu, Y. Coal-fired power industry water-energy-emission nexus: A multi-objective optimization. *J. Clean. Prod.* **203**, 367-375 (2018).
12. De Gouw, J.A., Parrish, D.D., Frost, G.J., & Trainer, M. Reduced emissions of CO_2, NO_X, and SO_2 from U.S. power plants owing to switch from coal to natural gas with combined cycle technology. *Earth's Future* **2**(2), 75-82 (2014).
13. Pétron, G., Tans, P., Frost, G., Chao, D. & Trainer, M. High-resolution emissions of CO_2 from power generation in the USA. *J. Geophys. Res. Biogeosci.* 113, G4 (2008).
14. Lin, C. et al. A global perspective on sulfur oxide controls in coal-fired power plants and cardiovascular disease. *Scientific Reports* **8**(1), 2611 (2018).
15. Ministry of Ecology and Environment of the People's Republic of China, National Development and Reform Commission & National Energy Administration. *Work Plan of Full Implementing Ultra-low Emission Policy and Energy Saving Transformation for Coal-fired Power Plants* (Ministry of Ecology and Environment of the People's Republic of China, 2015). (*in Chinese*)
16. National People's Congress of the People's Republic of China. *Environmental Protection Tax Law* (National People's Congress of the People's Republic of China, 2016). (*in Chinese*)
17. National Development and Reform Commission & National Energy Administration. *Revolutionary Strategy for Energy Production and Consumption (2016-2030)* (National Development and Reform Commission, 2016). (*in Chinese*)
18. National Development and Reform Commission & National Energy Administration. *China's 13th Five-Year Plan (2016-2020) for Power Sector Development* (National Development and Reform Commission, 2017). (*in Chinese*)
19. Zhang, X. & Schreifels, J. Continuous emission monitoring systems at power plants in China: Improving SO_2 emission measurement. *Energy Policy* **39**(11), 7432-7438 (2011).
20. Ministry of Ecology and Environment of the People's Republic of China. *Measures for Environmental Monitoring Management* (Ministry of Ecology and Environment of the People's Republic of China, 2007). (*in Chinese*)
21. National Development and Reform Commission, Ministry of Ecology and Environment of the People's Republic of China & National Energy Administration. *Upgrade and Retrofit Plan for Coal-fired Power Plants Aiming at Energy Savings and Emissions Reduction for 2014-2020* (National Development and Reform Commission, 2014). (*in Chinese*)
22. Ministry of Ecology and Environment of the People's Republic of China et al. *Notice of Issuing the Statistics and Monitoring Methods for Total Emission Reductions of Major Pollutants in the 12th Five-Year* (Ministry of Ecology and Environment of the People's Republic of China, 2013). (*in Chinese*)
23. China National Environmental Monitoring Centre. *Technical Regulations for Comparing*

Monitoring results of Automatically Monitoring Devices for Pollution Sources (on trial) (China National Environmental Monitoring Centre, 2010). (*in Chinese*)
24. Ministry of Ecology and Environment of the People's Republic of China. *Measures of Supervisory Monitoring and Information Disclosure for Pollution Sources in China's Key State-Monitored Enterprises* (on trial) (Ministry of Ecology and Environment of the People's Republic of China, 2013). (*in Chinese*)
25. Ministry of Ecology and Environment of the People's Republic of China. *Measures of Self-monitoring and Information Disclosure for China's Key State-Monitored Enterprises* (on trial) (Ministry of Ecology and Environment of the People's Republic of China, 2013). (*in Chinese*)
26. General Office of the Communist Party of China & General Office of the State Council of the People's Republic of China. *Suggestions to Deepen the Reform of Environmental Monitoring and Improve the Quality of Environmental Monitoring Data* (General Office of the Communist Party of China, 2017). (*in Chinese*)
27. The Supreme People's Court of the People's Republic of China & The Supreme People's Procuratorate of the People's Republic of China. *Explanations for Some Questions about Applicable Laws for Criminal Cases of Environmental Pollution* (The Supreme People's Court of the People's Republic of China, 2016). (*in Chinese*)
28. Ministry of Commerce of the People's Republic of China. *Guide of Maintenance for Power Plant Equipment* (Ministry of Commerce of the People's Republic of China, 2003). (*in Chinese*)