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Targeted emission reductions from global super-polluting power plant units

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Supplementary Information of

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Supplementary Methods

Uncertainties and limitations

Emission estimates are subject to uncertainty due to incomplete knowledge of activity rates and emission factors[40,60,72]. In order to more completely assess uncertainties in our results, we undertook a comprehensive analysis of national and unit-level emission estimates. Following the method demonstrated by Liu et al.[6] for uncertainty analysis of coal-fired power plants in China, we performed a Monte Carlo analysis that varied key parameters. The term "uncertainty" in this study refers to the lower and upper bounds of a 95 % confidence interval (CI) around our central estimate. All of the input parameters of activity levels and emission factors, with corresponding statistical distributions, are placed in a Monte Carlo framework, and 10,000 simulations are performed to analyze the uncertainty of estimated emissions by species[6,73].

For the uncertainties of the national emission estimates, national activity rates are derived from IEA and local databases, and we assumed these activity rates are normally distributed, with coefficients of variations (CV, or the standard deviation divided by the mean) ranging from 0.05 to 0.33 according to the data sources and fuel types derived from previous literature[6,9,74]. Note that different species and different fuel types are estimated using different parameters. For example, input parameters such as sulfur content of fuel and pollution removal efficiencies were in some cases obtained from previous studies that assumed different statistical distributions (e.g., lognormal or triangular distributions). Furthermore, the ranges of parameter values vary by country in part due to the quality of their statistical infrastructure[75].

As a result, we calculate global average uncertainty of CO_2, SO_2, NO_x, and $PM_{2.5}$ emissions in 2010 based on aggregation of the uncertainties of 231 countries. We estimate applicable uncertainties of −14% to 15% for CO_2, −20% to 21% for SO_2, −26% to 27% for NO_x, and −21% to 32% for $PM_{2.5}$. The higher uncertainty range of the $PM_{2.5}$ emission estimates is dominated by the uncertainties of the unabated emission factors and the efficiencies of $PM_{2.5}$ control measures[6]. The development of a local database of actual removal efficiencies for emission controls in the future will help to reduce these uncertainties[6].

For the uncertainties of unit-level emission estimates, there are substantial differences in the sources of activity rates, which sometimes come from unit-level databases (e.g., for the US, China and India) but in other cases are derived using equation (2) (Supplementary Fig. 7). Therefore, uncertainties associated with emission estimates could vary with unit size, fuel types and countries. In previous study, Liu et al.[6] selected a specific, large generation unit to demonstrate how the emission uncertainties changed over time at the unit level. Here we followed this method, selecting coal-fired units from each country and each unit size category (<10 MW, 10-50 MW, 50-99 MW, 100-299 MW, 300-599 MW, and ≥600MW) from several key regions (China, India, the US and Europe) in order to evaluate the uncertainties of different species. For the uncertainties of unit-level energy consumption in China, India, and the US, where we obtained unit-level energy consumption directly from local database, we assume the coefficients of variation (CV) of activity rates are normally distributed with CV of 5%[6]. In Europe, where unit-level energy consumption data were not available, we again assume unit-level energy consumption are normally distributed, but with CV equal to one standard deviation (1σ) divided by the mean of energy consumption intensity in each category.

For the uncertainties of emission factors, we followed the method of previous studies and assume unit-level uncertainties are the same as national emission estimates. For the uncertainties of unit-level removal efficiencies of each species, note that specific control technologies were obtained from WEPP, eGRID, CPED and ICPD. In contrast to uncertainty analyses for national emissions, we used discrete distributions (i.e., "Yes/No" distributions) to represent the probability distributions of the technologies, which reflect uncertainty as to whether the databases are correct or incorrect about the technology in place at a specific unit.

As a result, as shown in Fig. 4 and Supplementary Figs. 3 and 4, larger uncertainties apply to smaller generating units (e.g., uncertainties for $PM_{2.5}$ emissions from Chinese coal-fired units ≥600MW are -34%-50% whereas uncertainties of similar units of only 10-49MW are -39%-55%). This reflects inconsistent data quality in the underlying databases, which tend to focus on larger units and thus contain incomplete information about the control measures and $PM_{2.5}$ removal efficiencies at smaller units. Super-polluting units of SO_2 defined in this study have larger uncertainty ranges in India than China due to the availability of unit-level data of sulfur content from CPED (e.g., -22%-23% for units ≥600MW in China compared to -40%-42% for units of the same size range in India).

Our study also subjects to several additional uncertainties and limitations. First, although we have tried our best to collect related information, the GPED database might be still incomplete given the tremendous amount of information are needed to derive a complete dataset. For instance, Liu et al.[6] found that the CARMA database (which is in turn based on the WEPP database) omitted many small power plants in China, suggesting that WEPP may also have omitted small units in other regions of the world. Because a disproportionately large share of air pollution is produced by small generating units that represent a small fraction of power generation, the effect of such omissions would be to even underestimate the contributions of super-polluting units to total operating capacity, CO_2, SO_2, NO_x, and primary

$PM_{2.5}$ emissions (i.e. to strengthen the conclusions of our study).

Second, the accuracy (or uncertainty) of emission estimates in GPED may vary among different regions due to integration of information from global (WEPP) and regional (eGRID, CPED and ICPD) database. In this work, we incorporated regional information where available because we expect the GPED could provide a consistent database for both global and regional studies. The accuracy of the GPED could be improved by incorporating more regional-specific data in the future. Here we estimated emissions from coal-fired power units in the US, China, and India by using unit-based information from the WEPP and compared with the estimates from eGRID, CPED, and ICPD. Supplementary Fig. 8 presented the contribution of different sized generating units to CO_2, SO_2, NO_x, and $PM_{2.5}$ emissions by using the information from global and regional databases. As shown in Supplementary Fig. 8, the distributions of emissions by different size categories are very similar (e.g., contribution of emissions from small units). Especially, for 59, 333, and 66 super-polluting units identified by regional databases in the US, China, and India respectively, 88%, 93%, and 86% of those units were also identified as super-polluting units by WEPP, indicating that the WEPP provides reasonable information for identifying a specific group of units.

Last but not least, although GPED is the first publicly accessible database which provides emissions of CO_2 and air pollutants for global power plants, it is only available for the year 2010 at present. Understanding the evolution of global power plants and investigating their environmental and health impact are of great interests; we will aim to regularly update the GPED to recent years, hindcast to historical years, and incorporate best available regional information in the future.

Supplementary References

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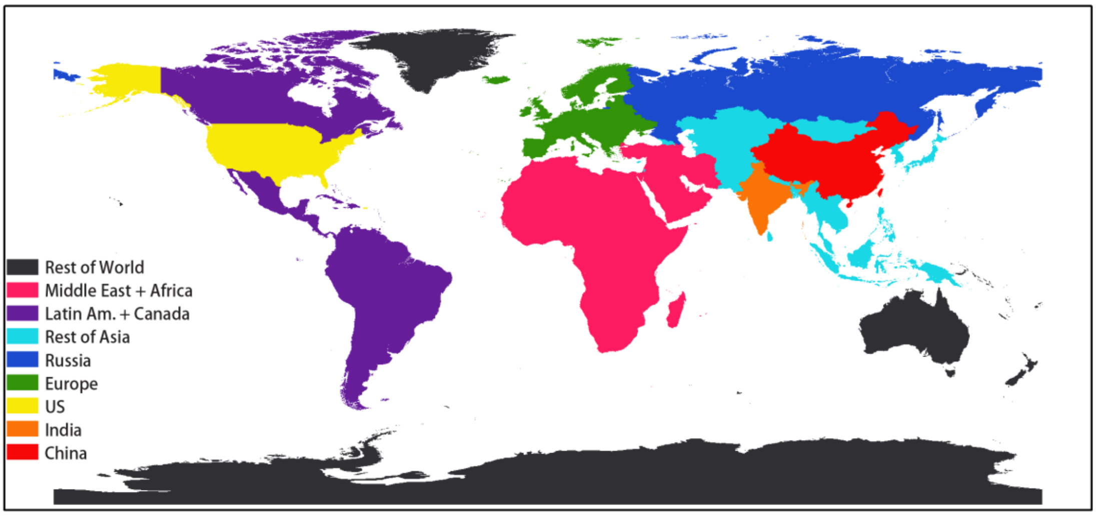
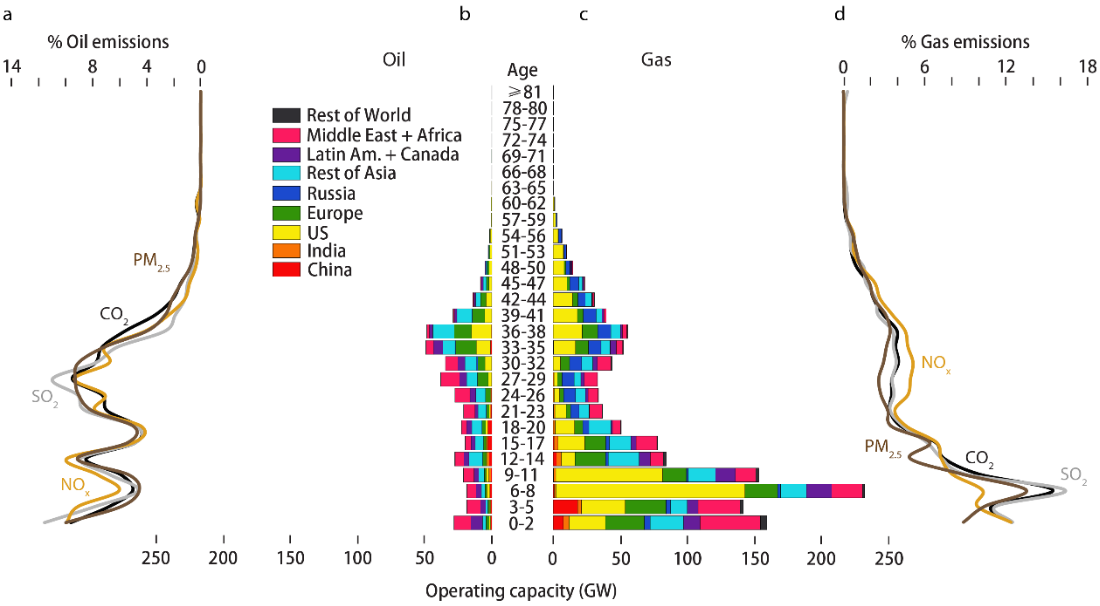
Supplementary Figures

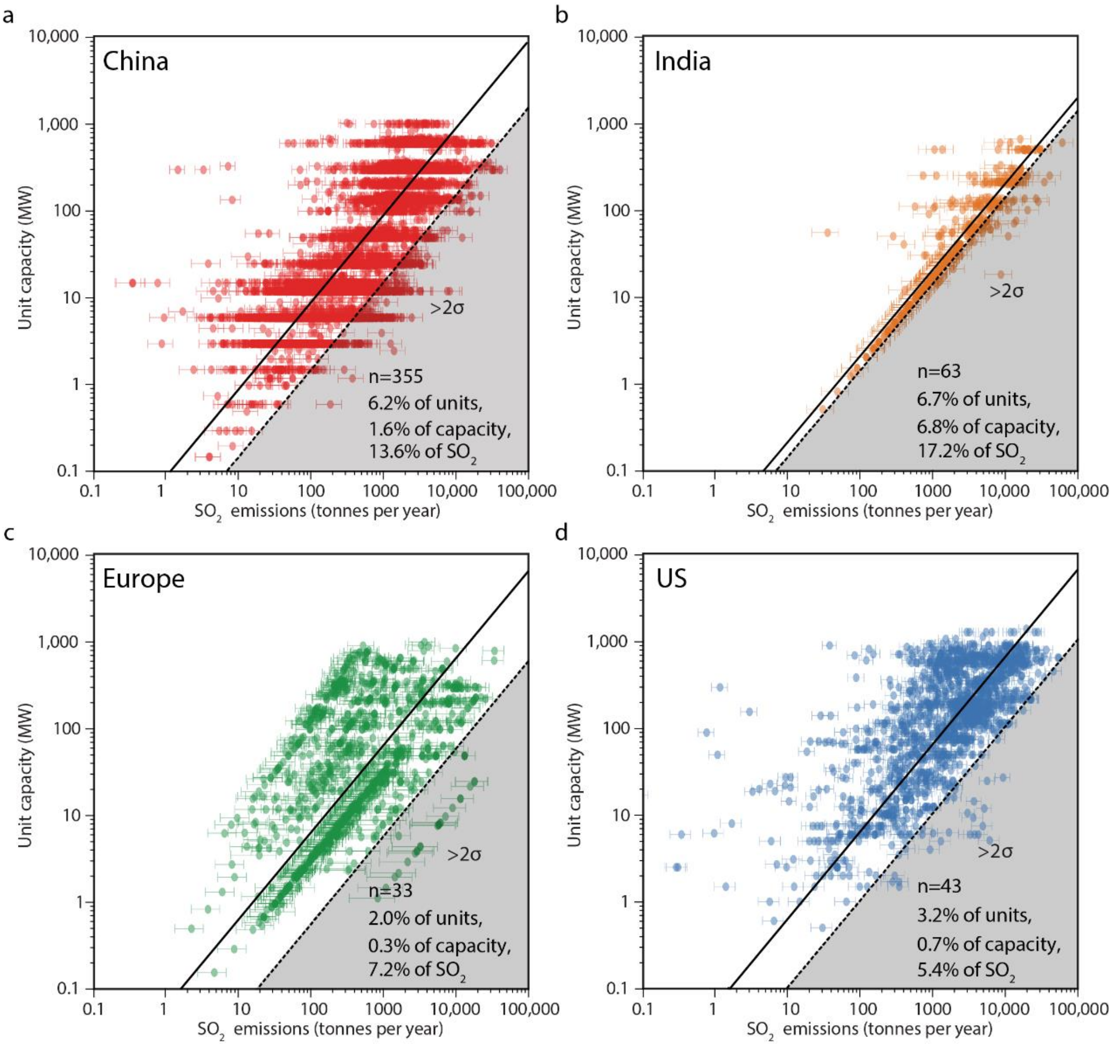
Supplementary Figure 1 | Definition of 9 regions in this study, note that "All Other Regions" in this study include Russia, Rest of Asia, Latin America + Canada, Middle East + Africa, and Rest of World.



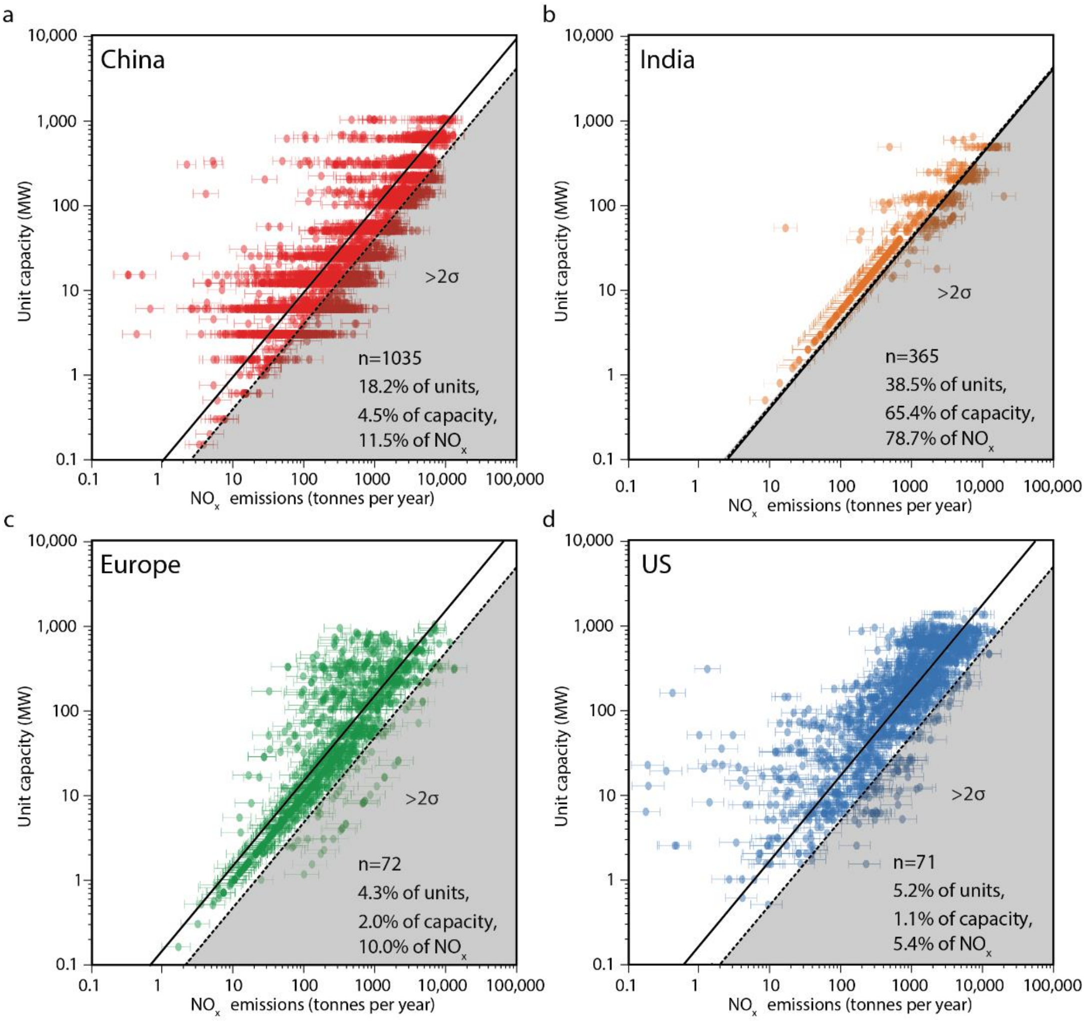
Supplementary Figure 2 | Age structure of global power-generating capacity and emissions for gas- and oil-fired units.



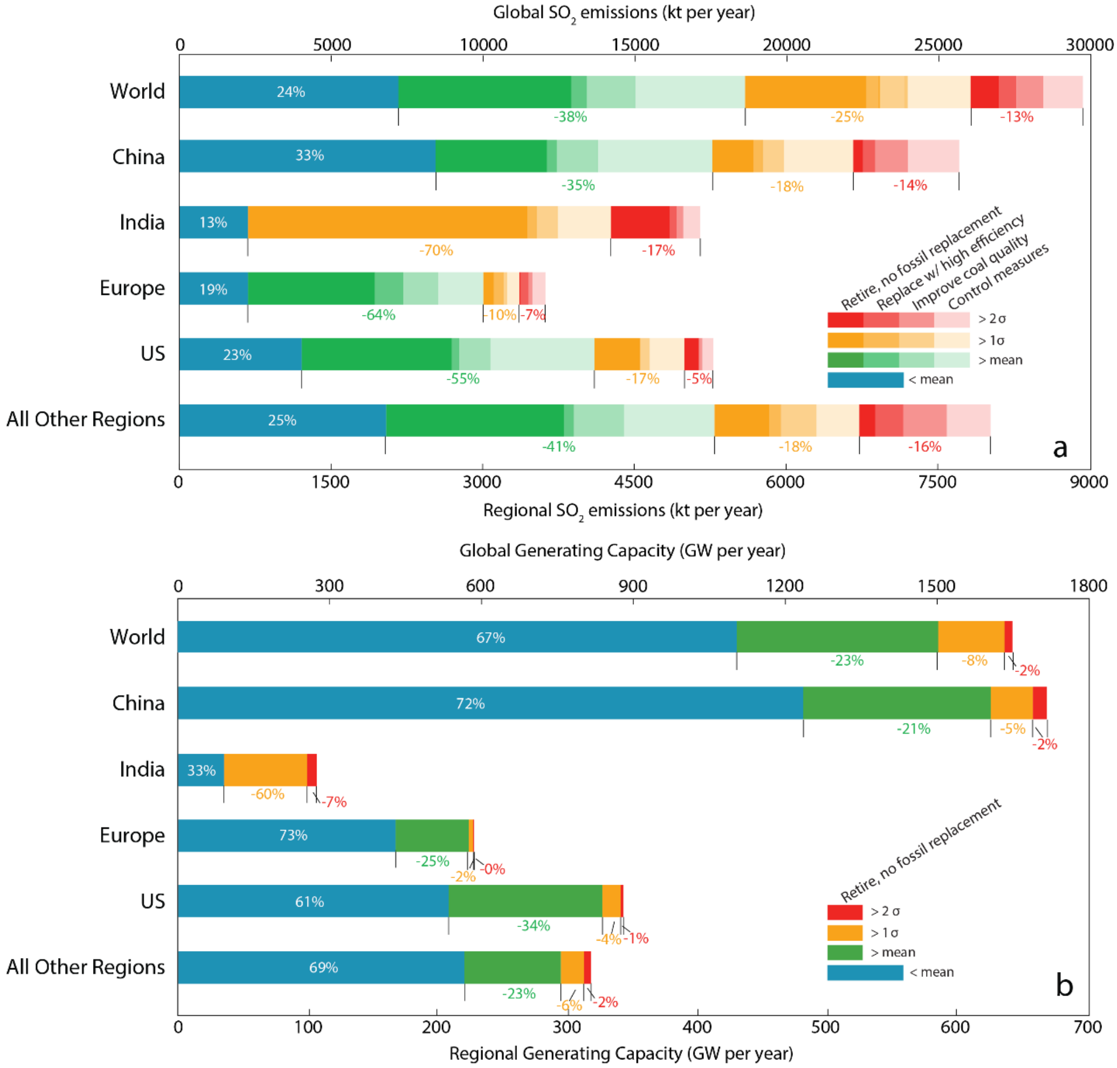
Supplementary Figure 3 | Super-polluting units. a–d, Points represent individual coal-fired units in China (a), India (b), Europe (c), and the US (d), in each case plotted according to nameplate capacity (*y*-axis) and annual SO_2 emissions (*x*-axis). Solid diagonal lines indicate the mean emission intensity (tonnes SO_2 per MW) and shaded triangles indicate units whose emission intensity is 2σ above the mean.



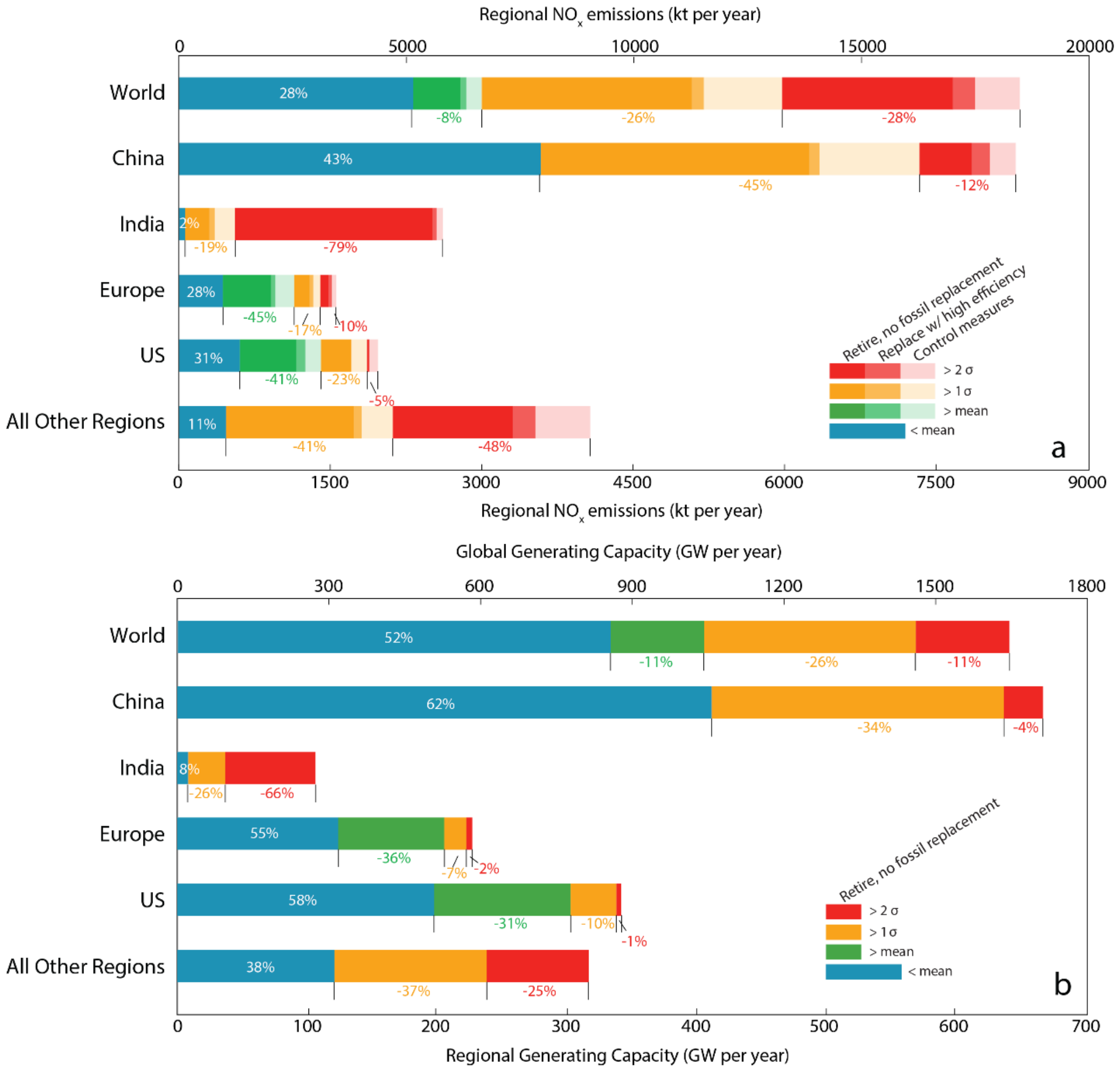
Supplementary Figure 4 | Super-polluting units. a–d, Points represent individual coal-fired units in China (a), India (b), Europe (c), and the US (d), in each case plotted according to nameplate capacity (*y*-axis) and annual NO_x emissions (*x*-axis). Solid diagonal lines indicate the mean emission intensity (tonnes NO_x per MW) and shaded triangles indicate units whose emission intensity is 2σ above the mean.



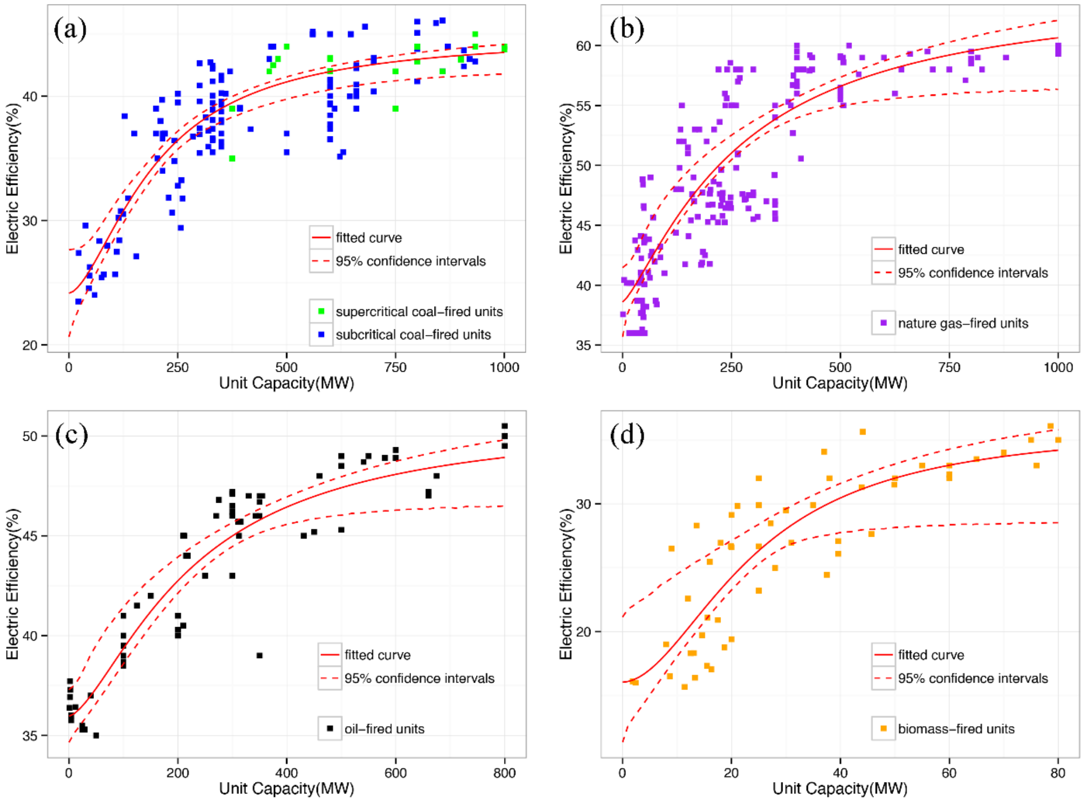
Supplementary Figure 5 | Potential reductions of SO_2 emissions and the associated coal-fired generating capacity.



Supplementary Figure 6 | Potential reductions of NO_x emissions and the associated coal-fired generating capacity.



Supplementary Figure 7 | The functions established between electric efficiency and installed capacity (MW) for different fuel types. (a) coal-; (b) gas-; (c) oil-; (d) biomass-fired generating units.



Supplementary Figure 8 | Shares of total capacity and emissions by using different databases.