Targeted emission reductions from global super-polluting power plant units

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There are more than 30,000 biomass- and fossil-fuel-burning power plants now operating worldwide, reflecting a tremendously diverse infrastructure, which ranges in capacity from less than a megawatt to more than a gigawatt. In 2010, 68.7% of electricity generated globally came from these power plants, compared to 64.2% in 1990. Although the electricity generated by this infrastructure is vital to economic activity worldwide, it also produces more CO_2 and air pollutant emissions than infrastructure from any other industrial sector. Here, we assess fuel- and region-specific opportunities for reducing undesirable air pollutant emissions using newly developed emission dataset at the level of individual generating units. For example, we find that retiring or installing emission control technologies on units representing 0.8% of the global coal-fired power plant capacity could reduce levels of $PM_{2.5}$ emissions by 7.7-14.2%. In India and China, retiring coal-fired plants 1.8% and 0.8% of total capacity can reduce total $PM_{2.5}$ emissions from coal-fired plants by 13.2% and 16.0%, respectively. Our results therefore suggest that policies targeting a relatively small number of "super-polluting" units could substantially reduce pollutant emissions and thus the related impacts on both human health and global climate.

The past two decades have witnessed an unprecedented expansion of fossil fuel combustion by the global power sector (fossil energy production worldwide grew 94% from 1990 to 2010)[1,2], driven primarily by population growth, industrialization and urbanization in developing countries[3-5]. Accompanying the growth of fossil energy use, greenhouse gases and air pollutant emissions from the power sector have also surged[6-10]; globally, the power sector accounted for ~40% of energy-related CO_2, ~7% of primary $PM_{2.5}$ (fine particulate matter with an aerodynamic diameter of 2.5μm or less) emissions, ~48% of SO_2 emissions and ~28% of NO_x emissions in 2010[11-13]. SO_2 and NO_x can be oxidized to secondary $PM_{2.5}$ in the atmosphere, which in turn has large impacts on air quality, health, and climate[14-16]. Power production thus contributes more to health impacts and climate change than any other industrial sector[17,18]. However, there is large variation in the environmental and health impacts of power generation across regions. In particular, environmental regulation in developed regions has greatly reduced emissions of criteria pollutants (for example, SO_2, NO_x, and $PM_{2.5}$) by power-generating units[19-22], largely decoupling economic activity from air quality. Meanwhile rapid rises in fossil fuel power generation and lax emission regulations and regulation enforcement[23] in some developing countries have led to increasing emissions, local violations of WHO outdoor air quality standards[15] and offsetting air quality improvements in downwind regions[24].

The impacts of global power plants on energy supply[25], air quality[26], health[27], and climate[28] are of broad interest and have been investigated previously. A publicly available, consistent global power plant emission dataset with detailed information can provide a firm basis for such discussions, for example, by highlighting effective ways to mitigate air pollution. Previous studies have compiled global and regional power plant CO_2 emission databases[8,29-31] or regional databases for air pollutant emissions[6,9,10], and noted the potential for substantial emission reductions from addressing a disproportionately small share of power plants[32–34]. Here, we develop a new global database of CO_2, SO_2, NO_x, and primary $PM_{2.5}$ emissions from fossil-fuel- and biomass-burning power-generating units as of 2010, which we name the Global Power Emissions Database (GPED); use it to identify the most-polluting units by region, fuel type and pollutant; quantify the disproportionalities of generating capacity and air pollutant emissions; and in each case highlight the best opportunities for reducing those undesirable emissions.

Details in methods and data used to construct and analyze the GPED are available in the *Methods* section. In summary, we have compiled, combined and harmonized the available data related to power-generating units burning coal, natural gas, oil or biomass from national statistics and previous unit-level inventories[6,9,10,35,36] (Supplementary Table 1), and filled data gaps with modelled emissions. Although other global and regional power plant emission databases exist[6,8–10,35,36], GPED is the first publicly available global database of annual emissions of CO_2 and air pollutants from individual power-generating units (http://www.meicmodel.org/datasetgped.html). We conducted a comprehensive uncertainty analysis and validated our modelled estimates of emissions by comparing measured and modelled emissions for units where we have such measurements (See Supplementary Information). Finally, we analysed the generating capacity, fuel type, age, location and installed pollution-control technology in order to determine those units with disproportionately high levels of air pollutant emissions.

Figure 1 shows the geographical distribution, fuel type and capacity of 30,655 biomass- and fossil-fuel-burning power plants operating worldwide in 2010, which in turn consist of 75,223 generating units with a combined installed capacity of 3,570 GW. We estimate that 12.5 Gt CO_2, 38.8 Mt SO_2, 25.2 Mt NO_x, and 2.7 Mt $PM_{2.5}$ were emitted by these thermal power plants in 2010. We find that a large fraction of total air pollutant emissions was produced by a disproportionately small fraction of total capacity. For example, 14.2% of global primary $PM_{2.5}$ emissions from coal-fired power plants were produced by just 0.8% of total capacity. The most-polluting units are often older, smaller, coal-burning units located in developing countries, but this is not uniformly true. These super-emitters represent targeted opportunities to mitigate air pollutant emissions by installing the best available pollution-control technologies or replacing these units.

Age and emissions of power generating-units

Figure 2 shows the age distribution of global power-generating capacity in 2010 by coal (Fig. 2c) versus gas and oil (Fig. 2b), as well as the share of global CO_2, SO_2, NO_x and $PM_{2.5}$ emissions in 2010 related to age cohorts of coal- and gas/oil-fired units (Figs. 2d,a, respectively). Overall, the young age of generating units worldwide is striking; although units historically operate for 35-38 years[37], rapid economic growth in emerging markets has required corresponding growth in energy infrastructures such that 37% of operating units worldwide were less than 12 years old in 2010. New units in China and India are especially substantial, representing 71% and 13%, respectively, of new coal-fired generating capacity built worldwide in 2010. As of 2010, 40% of global generating capacity was from coal-fired units located in China. Coal-fired units operating in the US and Europe are much older: averaging 35.9 and 32.4 years in 2010, respectively. However, the average age of gas-fired units in the US is 18.8 years in 2010, and there is a large capacity of gas-fired units less than a decade old. These patterns largely reflect (1) periods of energy-intensive economic development during industrialization and (2) the transition of coal to natural gas in developed economies[38].

Figure 2 also shows that CO_2 emissions are distributed across age groups of coal- and gas-and-oil- and coal-fired in rough proportion to operating capacity (black curves in Figs. 2a, d) because of a lack of deployed carbon capture and storage systems on operating fossil-fuel power plants in 2010[39,40]. However, control measures for SO_2, NO_x, and $PM_{2.5}$ are widely deployed, with emission standards varying drastically across species and regions. These differences result in very different penetration of pollution-control technologies and emission intensities for each species across regions (Supplementary Table 2).

In the case of coal-fired units, control technologies for $PM_{2.5}$ emissions are common across the world and highly effective in US, Europe, and China, which can be seen by the relative shares of $PM_{2.5}$ and CO_2 emissions (Fig. 2d; brown and black curves, respectively) from units 30-41 years (which are mostly in the US and Europe; Fig. 2c) and 0-8 years old (mostly in China). In contrast, lower penetrations of high effective $PM_{2.5}$ control measures cause high $PM_{2.5}$ emission intensity in India (Supplementary Table 2). Controlling SO_2 emissions is now required in most regions. However, in 2010, only 5.6% of India's coal-fired capacity was equipped with SO_2 control measures (compared with the global average, 81.9%), resulting in an SO_2 emission intensity for India twice that of the global average. China began requiring plants to use flue-gas desulfurization in 2005, and, as of 2010, 84.5% of coal-fired units built after 2005 are equipped with the technology[6]. For this reason, younger coal-fired units produce a smaller share of SO_2 emissions than older units relative to CO_2 emissions (compare gray and black curves in Fig. 2d). Controls for NO_x emissions remain less common and are mainly required in developed countries. Only 13.0% and 4.2% of coal-fired units in China and India, respectively, were equipped with flue-gas denitrification technologies in 2010. Thus, younger coal-fired units—dominated by units in China and India—produce relatively more NO_x emissions than either CO_2 or SO_2 emissions. Globally, 32.6% of coal-fired capacity was equipped with different types of flue-gas denitrification technologies in 2010.

The emissions from gas- and oil-fired units depicted in Fig. 2a reflect mostly different emission characteristics of those units and the prevalence of these two fuel types across time and regions. SO_2 and $PM_{2.5}$ control technologies on gas- and oil-fired units are less common compared with coal-fired units (Supplementary Table 2). SO_2 and $PM_{2.5}$ emissions from gas-fired units are very small, so the SO_2 and $PM_{2.5}$ emission contributions from different age cohorts in Fig. 2a are primarily determined by the fraction of oil-fired generators. For instance, 38% of SO_2 emissions from all gas- and oil-fired capacity are produced by units between 21 and 32 years old, 28% of which are oil-fired (not shown). Moreover, these older (21-32 year-old) oil-fired units are mostly located in the Middle East and Africa (pink bars in Supplementary Fig. 2b), where the high sulfur content of oil burned causes higher SO_2 emissions per MWh of electricity than in other regions[41]. Shares of NO_x emissions in Fig. 2a represent combined contribution from both gas- and oil-fired units. NO_x control technologies on gas- and oil-fired units were only widely used in developed countries. Thus, younger gas- and oil-fired units, dominated by developed countries (6-11 years old in Fig. 2a) produced less NO_x than CO_2. For instance, although 13% of operating gas- and oil-fired capacity is 6-8 years old, these units produced only 4% of the SO_2 emissions from all gas- and oil-fired capacity because 93% of the units in this age range are gas-fired (Supplementary Fig. 2).

Disproportionalities of generating capacity and emissions

Large fractions of pollution are consistently produced by a disproportionately small fraction of power-generating capacity. Figure 3 shows the contribution of different-sized generating units to total operating capacity, CO_2, SO_2, NO_x, and $PM_{2.5}$ emissions, with separate panels for each fuel type (coal, gas, and oil) and region (China, India, US, Europe and world). In each case, the absolute magnitudes are also shown at the top of each bar. Across all regions, small coal-fired units (for example, <100 MW) represent a small share of total generating capacity, but a larger share of air pollutant emissions (SO_2, NO_x, and $PM_{2.5}$). For example, small coal-fired units represent 9% of generating capacity in China, 14% in India, 6% in the US, and 10% in Europe but produce 24%, 25%, 12%, and 33% of $PM_{2.5}$ emissions in those regions, respectively (Fig. 3, pink, purple and blue bars in left column). In contrast, gas-fired generators are seldom equipped with control measures for SO_2 and $PM_{2.5}$, so that the proportion of overall capacity and SO_2/$PM_{2.5}$ emissions is more consistent across different-sized units, varying only due to combustion and operating efficiencies. However, gas- and oil-fired units may be equipped with denitration measures to reduce NO_x emissions, which is especially common on larger generators in developed countries. These controls may result in a lower share of NO_x emissions from large gas- and oil-fired units (≥300 MW, orange and red bars in middle column) relative to their total capacity (see, for example, Europe in Fig. 3).

The share of emissions from small units is disproportionately large relative to their share of generating capacity because larger units tend to have more advanced and effective emission controls and higher operating efficiencies. This disproportionality is due to a combination of more rigorous emission standards applied to newer generating units as well as the economies of scale related to advanced control measures that make installation on smaller existing units more expensive.

Super-polluting power-generating units

Figure 4 shows the relationship between generating capacity and annual emissions of different air pollutants from coal-fired units in China, India, Europe and the US, and highlights "super-polluters" in each region, which we define as those units whose emission intensity (tonnes per MW) is more than two standard (2σ) deviations greater than the region's mean. Globally, 14.2%, 12.6% and 28.3% of global primary $PM_{2.5}$, SO_2, and NO_x emissions from coal-fired units in GPED were respectively produced by 0.8%, 1.6%, and 11.2% of the total capacity. 26.8% of global super-polluters were super-polluting units for multiple pollutants, further emphasizing the importance of mitigating emissions from those units.

There are relatively few units that are super-polluters of SO_2 and $PM_{2.5}$, but the large imbalance in emissions and generating capacity (Fig. 3) means that these super-polluting units represent a leveraged opportunity to reduce those emissions. Further, because SO_2 and $PM_{2.5}$ control technologies have been widely required on coal-fired units across the world, the super-polluting units for SO_2 and $PM_{2.5}$ emissions mainly represent the small (and old) units with less effective control measures. In contrast, NO_x super-polluters represent a large fraction of units as a result of smaller variation in NO_x emissions across units in developing regions (Supplementary Fig. 4a,b). In developing regions, variations in NOx emissions among units were dominated by combustion and operating efficiencies due to a lack of emission controls.

The importance of super-polluting units is particularly striking in some regions. For example, 0.8% (333 units) and 1.8% (66 units) of coal-fired capacity in China and India, respectively, produced 16.0% and 13.2% of $PM_{2.5}$ emissions from all coal-fired units in 2010 (Figs. 4a,b). Perhaps surprisingly, super-polluting units are not confined to developing regions; 0.1% and 1.2% ((34 and 59 units) of coal-fired capacity in Europe and the US, respectively, produced 14.6% and 11.8% of $PM_{2.5}$ emissions from all the coal plants in those regions (Figs. 4c,d).

Targeted opportunities to mitigate air pollutant emissions

We estimate the potential reductions of air pollutants ($PM_{2.5}$, SO_2, and NO_x) if super-polluting coal-fired units in different regions were updated with control measures, improved fuel quality or replaced by large units that brought their emissions down to the regional mean intensity, as shown in Fig. 5 (for $PM_{2.5}$) and Supplementary Figs. 5 and 6 (for SO_2 and NO_x). Globally, installing current emissions control technologies on super-polluting units or retiring them could reduce $PM_{2.5}$, SO_2, and NO_x emissions by 7.7-14.2%, 4.6-12.6%, and 5.2-28.3%, respectively. Applying current pollution control technologies to the super-polluting coal-fired units (that is, light red; corresponding to dark gray area in Fig. 4) could reduce larger fractions of $PM_{2.5}$ and SO_2 emissions than NO_x in each region, and these controls have a larger effect than changes in coal quality or unit efficiency (darker shades of red) in most regions. Perhaps more surprisingly, the proportion of $PM_{2.5}$ emissions that could be avoided if all coal-fired units achieved the mean intensity for their respective region (cumulative emissions shown by the darkest blue, red, orange and green bars in Fig. 5a) are substantially greater in Europe than any other region (56% as compared to 41% in China, 44% in all other regions, and 26% in India and 25% in the US). This is explained by the inclusion of both a relatively large number of high-emitting units in areas of eastern Europe and a similarly large number of very low-emitting units in western Europe, which acts to establish a low mean intensity with a large range (see spread of points in Fig. 4).

Discussion

Our study constructed a unit-based global plant emission dataset and explored the mitigation opportunity from a small sub-group of the most polluting units. In the future, our database of global power plant emissions, GPED, can help prioritize cost-effective actions for further emission reductions and thereby regional and global impacts of outdoor air pollution on human health[27,42,43]. The potential impacts on the climate are also deserving of further study; power plants emit a range of CO_2 and other precursor gases simultaneously[28,44]. Our database can be used to support model analyses on potential air quality and climate co-benefits of global power plants.

Regional and international efforts to reduce both air pollution and CO_2 emissions are increasing. For instance, China has implemented strict emission standard since 2015[45] and plans to increase the share of non-fossil power to 31% by 2020[46] to tackle the severe air pollution problem, and the Clean Power Plan in the US aims to reduce CO_2 emissions by 32% in 2030 compared with 2005. Such efforts can contribute to international agreements on climate change. Our results can be applied not only to prioritize retrofits but to prioritize retirement and replacement of super-polluting power-generating units with non-emitting energy sources. In developing countries such as China, excess emissions were always a problem due to a lack of effective regulation enforcement[23,47]. Strengthened supervision systems should be developed and operated to avoid such undesirable emissions. In addition, there are still substantial disparities between the mean emission intensities in developed and developing countries (Supplementary Table 2), underscoring the potential of efforts to strengthen international collaboration and technology transfer to decrease the global impacts of air pollution[48,49] and accelerate the transition to 'clean' and/or non-fossil sources of power in developing countries. In turn, such progress could avoid further 'lock-in' of fossil energy technologies in both developing and developed economies[50,51].

The GPED is subject to uncertainties and limitations. A detailed description of uncertainties is presented in the Supplementary Information. In summary, the average uncertainties of global emissions are estimated to be −14% to 15% for CO_2, −20% to 21% for SO_2, −26% to 27% for NO_x, and −21% to 32% for $PM_{2.5}$. Uncertainties of unit-level emissions vary among units and regions, with larger uncertainties for smaller units and developing regions due to incomplete information. GPED might be still incomplete because the World Electric Power Plant (WEPP) database may have omitted some small units6. More regional databases should be collected and incorporated in the future. The accuracy of GPED may vary regionally due to integration of regional datasets of differing data quality. Inter-comparison initiatives among different regions could help to narrow the gap. At present, GPED is only available for 2010 given that collecting underlying data is a challenging task. Building transparent data reporting systems in developing countries and continuous efforts under international collaboration frameworks could help to deliver more complete and reliable data. Our database will be updated and improved in the future as more and better data become available.

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Methods

Global Power Emissions database.

GPED encompasses 231 countries or regions (aggregated into nine world regions for this study; Supplementary Fig. 1) and all generating units that burn coal, oil, natural gas, biomass or other fuels (65 specific fuel types; further details about fuels included in these five categories are shown in Supplementary Table 3).

There are a few databases of global power plants available for CO_2 emissions (for example, the Carbon Monitoring for Action (CARMA) database[8] and an improved version of Fossil Fuel Data Assimilation System (FFDAS) database[31]). CARMA has been widely used in bottom-up emission inventories to allocate power plants emissions[6], which estimated plant-level CO_2 emissions for 2004, 2009, and the “future” by using the commercially available Platt’s WEPP database[36]. A regression model was used in CARMA for predicting the capacity factor, heat rate, and CO_2 emission factor of each power plant, and then calculating CO_2 emissions based on these inputs[8]. As an update of FFDAS utilize an updated and improved global power plant emission data product that includes improved location information and individual power plant uncertainties[31], which uses data from both the public disclosure data and the WEPP database.

Here, we developed a new global power plant emission database including both CO_2 and air pollutant emissions (SO_2, NO_x, and primary $PM_{2.5}$). When constructing GPED, we chose 2010 as the base year for the database, because it was the latest year for which detailed data were publicly available in the national databases we used. We began by using the WEPP database to compile unit-based information of generators in service as of 2010 (for example, unit capacity, start year of operation, physical address, fuel type) as well as technologies in place for desulfurization, denitration and dust removal. Next, we cross-checked and where necessary overwrote unit-based information and emissions for units operating in the US, China and India using what we think are the more comprehensive and reliable data contained in the national databases: The Emissions and Generation Resource Integrated Database (eGRID)[35], the China Coal-Fired Power Plant Emissions Database (CPED)[6] and the India Coal-Fired Power Plant Database (ICPD)[9,10]. CPED considers the unit-level fuel qualities (for example sulfur and ash content) and removal efficiency of control measures, which significantly improve the accuracy of emission data[6]. ICPD also applies unit- or plant-level information (for example, specific coal consumption and boiler type)[9,10]. eGRID is based on available plant-specific data for all US power plants that provide power to the electric grid and report data to the US government[35]. The eGRID data include both unit- and plant-level emission data (CO_2, SO_2 and NO_x) for 2010. CPED includes unit-specific activity data and net emissions factors for CO_2, SO_2, NO_x and $PM_{2.5}$ for the period of 1990-2010 for Chinese coal-fired generators. ICPD includes generator-level SO_2 emissions during 2005-2012 and NO_x emissions from 1996 to 2010. Note that the CPED includes only coal-fired units and that the ICPD excludes both privately owned generators and smaller (<20 MW) publicly owned coal-fired units. Thus, where WEPP includes data not in the above regional databases, we retain that information such that our GPED represents an integration of the best available data.

Because geographical locations (exact latitudes and longitudes) are not included in the WEPP database, we obtained the locations of 19,105 generating units (25.4% of the total 75,223 units) from the eGRID, CPED and ICPD. We then geolocated one-by-one all remaining units at plants with a total capacity ≥10 MW using either data from the Global Energy Observatory (http://globalenergyobservatory.org/) or Google Earth, which represent locations for an additional 19,001 units (25.3%). For the remaining, smaller units, we obtain locations by using Google Maps to map the physical address provided in the WEPP database. Further details of this analysis and a summary of units and their total installed capacities are shown in Supplementary Table 1.

Unit-based CO_2, SO_2, NO_x and $PM_{2.5}$ emission estimation

As described above, where available, we adopt unit-based estimates of CO_2, SO_2, NO_x and $PM_{2.5}$ emissions for 2010 from existing databases. For example, CO_2, SO_2, NO_x emissions of American units from eGRID; CO_2, SO_2, NO_x and $PM_{2.5}$ emissions of Chinese coal-fired units from CPED; and SO_2, NO_x emissions of Indian coal-fired power plants from ICPD. For units not included in those databases, we estimate emissions of CO_2 and air pollutants ($E_{\mathrm{s},i}$) using the following equation:

$$E_{s,i} = A_{i,j} \times EF_{s,k} \times (1 - \eta_{s,m}) \times 10^{-3} \qquad (1)$$

where s, k, i, j, and m represent emission species, country, generating unit, fuel type and emission control technology, respectively. E represents unit-based emissions (kg), A represents specific fuel consumption for each unit (kg for solid- or liquid-fired units and m^3 for gas-fired units); EF represents the unabated emissions factors (g/kg for solid- or liquid-fired units and g/m^3 for gas-fired units); and η represents the removal efficiency of control technology, $\eta > 0$ when the control equipment is present, otherwise $\eta = 0$.

Activity rates and electric efficiencies. Because detailed activity data for each generating unit is not available, we estimate unit-based activity data from country-level fuel consumption by the power sector as reported by the International Energy Agency (IEA)[1,2].

Unit-level fuel consumption is a function of installed capacity, annual operating hours and fuel consumption per unit power generation[6], but of these, only installed capacity data are readily available. We therefore make the simplifying assumption that annual average operating hours of generating units burning the same fuel (65 fuel types) are consistent at the country level. Although this assumption may bias our findings at the country and unit levels, the assumption does not apply to the largest emitting countries (for which we have unit-level data). A detailed description and evaluation of results is presented in the Supplementary Information. Fuel consumption per unit power generated is inversely related to electric efficiency. Electric efficiencies in different utilities range from 25–45% for coal-fired power plants, 35–50% for oil-fired power plants, and 35–60% for natural-gas-fired power plants[52], corresponding to different technology and operating conditions. Instead, we estimate electric efficiency using a function we built based on data in eGRID, CPED and ICPD, as well as measurements collected from various electric reports or companies' websites. Our function reflects an obvious nonlinear relationship between installed capacity and electric efficiency in coal-, gas-, oil- and biomass-fired units, respectively, as illustrated in Supplementary Fig. 7.

Thus, we calculate unit-level fuel consumption from country-level fuel consumption by the equation:

$$A_{i,j} = A_{k,j} \times \frac{\frac{C_i}{e_i}}{\sum \frac{C_{k,j}}{e_{k,j}}} \qquad (2)$$

where A represents the fuel consumption; C represents the installed capacity of generating unit and e represents the corresponding electric efficiency. Note that whereas the GPED differentiates 65 fuel types (including many sub-types of solid biofuels and biogases), the IEA database estimates country-level fuel consumptions for 36 types, requiring us to aggregate the GPED data to these 36 types in order to use the IEA data on sources (details of this aggregation are shown in Supplementary Table 3).

Supplementary Fig. 7 shows further details of electric efficiency across units burning different fuel types. In general, electric efficiency increases with unit capacity, but the marginal rate of efficiency gains declines as units become larger, and efficiency gains eventually disappear. Using these samples, we build functions to estimate coal-, gas-, oil-, biomass-fired generating units' electric efficiencies where local information is not available (Supplementary Fig. 7a–d). Although most units burn coal, gas, oil or biomass, there are some other generating units fueled by less common and/or mixtures of fuels (for example, waste, peat and coke oven gas) where we lack sufficient samples to build functions. We categorize these fuel types as solids, liquids or gaseous fuels and constructed piecewise constant functions to estimate their electric efficiencies and differentiate the fuel consumptions per kWh supplied on the different range of unit capacity. The detailed values for each fuel type are also shown in Supplementary Table 4. In this way, we derive electric efficiencies of all units, which in turn allowed us to calculate unit-level fuel consumptions by equation (2).

CO_2 emissions. The CO_2 emissions factors were estimated by calculating the carbon content of the consumed fuel[53]. The following equation was used to calculate CO_2 emissions factors according to guidelines from the Intergovernmental Panel on Climate Change (IPCC)[54]*:*

$$EF_{CO_2,j,k} = CA \times O \times 44/12 \times H_{j,k} \qquad (3)$$

where *j*, *k* represent fuel type, and the country, respectively; EF_{CO_2} represents the CO_2 emissions factor in g/kg for solid and liquid fuels, kg/m^3 for gaseous fuels; CA represents the carbon content in kg of carbon per GJ (kg-C/GJ), O represents carbon oxidation factor; $44/12$ is the molecular weight ratio of CO_2 to carbon; H is the heating value in kJ/g for solid and liquid fuels, MJ/m^3 for gaseous fuels. In this study, the carbon oxidation factor assumed to be 1, the carbon contents were obtained from the IPCC guidelines[54]. The heating value data for each fuel type and country are from IEA[1,2].

SO_2 emissions. In the absence of desulphurization technology, emissions of SO_2 are directly related to the sulfur content of the fuel. Therefore, we estimate the unabated SO_2 emissions factors as follows:

$$EF_{SO_2,j,k} = 2 \times S_{j,k} \times \left(1 - SR_{j,k}\right) \times 10 \qquad (4)$$

where *j*, *k* represent sub fuel type (for example, anthracite, bituminous, subbituminous or lignite), and the country, respectively; EF_{SO_2} represents the unabated SO_2 emissions factor; *S* represents the sulfur content of fuel; and *SR* represents the sulfur retention in ash.

For coal-fired units, because unit-level data on fuel sulfur content is not available, we reflect differences in coal quality by assuming the national average sulfur content of different types of coal obtained from the United States Geological Survey (USGS). Where a national average sulfur content is not available, we instead use an average of all the countries in the same region for which sulfur content data was available. Using the default values derived from USEPA AP-42[55] and other previous works[56,57], *SR* was assumed to be 5% for bituminous-fired units, 12.5% for sub-bituminous-fired ones, 2.5% for anthracite-fired units, 25% for lignite-fired units and 15% for other coal-fired unit without specific sub type[55]. The effects of combustion technology and boiler age on *SR* were not taken into account because we lack sufficient data about their effects on SO_2 emissions[6]. For oil-fired units, the *SR* ratios were also taken from USEPA AP-42[55] for different fuel sub-types and country-level estimates of the sulfur contents of oil are derived from previous literature[57-60]. For gas-fired units, we neglect these differences between countries/regions and apply a global average emissions factor from AP-42[55] due to low SO_2 emissions from gas-fired units and insufficient data. The SO_2 emissions factors of biomass and other fuel combustion were based on the measurements from AP-42[55] and previous works[60,61].

The net emissions factor of SO_2 is also strongly dependent on the removal efficiency of desulfurization devices[10]. At present, flue gas desulfurization (FGD) technologies are most common and widely used desulfurization devices. From GPED, we can see desulfurization devices were widely used in coal- and oil-fired units. Moreover, we differentiate 55 specific desulphurization technologies from GPED (Supplementary Table 5). For each technology, removal efficiencies were derived from USEPA AP-42[55] and others' works[62,63] and applied to each country depending on emission standards and economic development because of the lack of unit-specific data. Higher removal efficiency for the same control technology was applied in developed countries. In this study, we assumed that the removal efficiency of SO_2 for wet scrubbers is 20%[6].

NO_x emissions. NO_x emissions factors of power-generating units vary primarily by type of fuel and combustion, and NO_x control technology[6,9]. In this study, we used the same size classification in CPED and ICPD to differentiate the NO_x emissions factors between boiler sizes[6,9]. National measurement data have been gradually reported in literatures[64,65]. However, due to the absence of country-specific measurement data for all the fuel types and countries, default NO_x emissions factors by fuel type were obtained from AP-42[55], EMEP[66] and various literatures[56,61,67] and then applied to all countries without specific measurements. In this study, boiler-size-specific and fuel-type-specific emissions factors were applied to units without taking boiler type into consideration.

NO_x emissions were regulated in some developed countries in 2010, such as the US, Japan and western Europe. Some developing countries, like China and India, also regulated NO_x emissions and began to control NO_x emissions according to local emission standards but with much lower penetration rates for NO_x-emission-control technologies. Most developing countries, like some in Africa, are not regulated NO_x emissions in 2010. There are two types of NO_x-emission controls: combustion controls (e.g., low-NO_x burners for coal-fired units, dry low-NO_x combustors for gas-fired units, and wet controls using water or steam injection to reduce combustion temperatures) and post-combustion controls (e.g., selective catalytic reduction and selective non-catalytic reduction)[62,68]. In total, we differentiate 34 types of NO_x-control technologies from GPED (Supplementary Table 6). Removal efficiencies for NO_x-emission-control technologies were derived from USEPA AP-42[55].

$PM_{2.5}$ emissions. PM emission levels are a complex function of boiler firing configuration, boiler operation, pollution control equipment, and fuel properties[51]. Because $PM_{2.5}$ emissions are mainly from coal-fired generating units (due to the much larger proportion of non-combustible components in the fuel relative to other fuel types), we estimate unabated emissions factors of $PM_{2.5}$ for coal-fired units as per previous analyses[69]:

$$EF_{PM2.5,k} = AC_{k,j} \times \left(1 - ar_{k,j}\right) \times f \qquad (5)$$

where k and j stand for the country and coal sub-type; AC represents the ash content of coal, ar represents the mass fraction of retention ash, f represents the $PM_{2.5}$ mass fraction to the total particulate matter in fly ash. Given the sparse number of country-level samples counted from USGS, excluding some countries with sufficient samples, we use the corresponding regional average ash content for each coal sub-type. The $PM_{2.5}$ mass fraction f, was obtained from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) database[70,71]. In addition, the mass fractions of retention ash of anthracite, bituminous, lignite and subbituminous were also derived from the GAINS[70,71]. Combining these parameters, we calculate the unabated emissions factors of coal-fired units. For the relatively small proportion of $PM_{2.5}$ produced by units burning other fuels, a global average emissions factor for each fuel type from AP-42[55] was applied due to small national differences and scarce data.

Dust-removal technologies were installed in nearly all the coal-fired generating units worldwide with different options such as mechanical collectors, wet scrubbers, electrostatic precipitators, wet electrostatic precipitators, fabric filters and combined precipitators. GPED differentiates 15 different control technologies (Supplementary Table 7). The removal efficiencies of each technology were obtained from previous studies considering operation differences between countries[6,55,70]. Note that particulate matter can also be removed via wet FGD as a co-benefit of SO_2 removal[6]. In this study, we assume the same $PM_{2.5}$ removal efficiency for wet FGD equipment as we have previously[6,65].

Dust removal technology data was relatively complete in the WEPP database for large coal-fired units (≥100 MW) but not for small units (<100 MW). In this study, we therefore assume all coal-fired units are equipped with some type of dust-removal technology. Where data are missing from WEPP, we assume country-specific average removal efficiency of dust from coal-fired units according to existing coal-fired units with installed capacity less than 100 MW. This assumption may underestimate the emission contribution of super-polluting units if some coal-fired units are not equipped with dust-removal equipment. Because oil-fired units produce much less PM emissions than comparably sized coal-fired units, many oil-fired units do not use $PM_{2.5}$ control measures. Similarly, PM emissions from gas-fired units are typically low because of the gaseous nature of the fuel. For units that burn biomass or waste, $PM_{2.5}$ can be significant but emission standards are often lacking. In these cases, unless we have specific data of control technologies in GPED, we assume zero removal efficiency.

Emissions factors for SO_2, NO_x and $PM_{2.5}$ can be substantially reduced by the installation and operation of control technologies, which are in turn determined by environmental policy. Most countries have their own emissions standards for air pollution (for example, the US, China, Japan and Europe), with limits on SO_2, NO_x and $PM_{2.5}$ emissions varying by country and fuel type. However, unit-specific data on installed control technologies are incomplete; we therefore make estimates regarding the different pollutants and different units as described above.

Potential mitigation of coal-fired units emissions estimated

We defined super-polluting coal-fired units as those with air pollutant emission intensities (that is, emissions per unit of generating capacity) that are two standard deviations greater than the mean in their respective region (here, the regions are China, India, Europe, the US and ‘all other regions’; Supplementary Fig. 1). We then evaluated the potential reductions in air pollutant emissions from these units as well as the corresponding effect of such mitigation on generating capacity. Based on equations (2), (4) and (5), the main levers for reducing unit-based $PM_{2.5}$ and SO_2 emissions are: (i) improving coal quality, (ii) installing advanced emission control measures, (iii) replacement with fossil-fuel-burning units of comparable capacity but higher electric efficiency, or (iv) retirement with no fossil fuel replacement. The main levers for reducing unit-based NOx emissions are (ii)–(iv). Based on related parameters and emissions in GPED, we evaluate the relative potential emission reduction related to each of these main levers for units in each region by assuming the ash content or sulfur content of coal is equal to the best level in the country acquired from the USGS database; assuming installation of SO_2, NO_x and $PM_{2.5}$ removal efficiency equivalent to the best available technology in 2010 in each region from GPED; assuming electric efficiencies equal to the mean level in the country. Residual emissions after all these measures are taken, we assume can be mitigated by retirement of the unit without replacement.

Characteristics of power-generating units

The GPED database includes The GPED database includes 11,484 coal-fired units, 23,865 natural-gas-fired units, 30,357 oil-fired units, 3,070 biomass-fired units and 6,447 other-fuel-fired units, with total capacities of 1,658 GW (47% of total), 1,284 GW (36%), and 440 GW (12%), 43 GW (1%), and 145 GW (4%), respectively. Worldwide, coal-fired units have the largest mean capacity, 144 MW, and gas- and oil-fired plants are considerably smaller: 54 and 15 MW, respectively.

Different fuel types and unit sizes are dominant in different regions. Here, we focus our analyses on four regions: China, India, the US and Europe (Fig. 1b–e). Our GPED database is global in its scope, but these four regions account for 64% of global generating capacity (2,284 GW) and also reveal the full extent of variation in power sector infrastructure and emissions. For instance, Fig. 1c,e shows the dominance of mid-sized coal-fired plants in India and China, with mean nameplate capacities of 112 and 117 MW, representing 78% and 93% of total generating capacity in those countries, respectively. In contrast, Fig. 1b shows the joint reliance on gas and coal power in the US, which represent 52% and 40% of US capacity, respectively. Europe has the greatest variation in fuel types, with capacity made up of 40% coal, 35% gas, 14% oil, 9% other and 3% biomass-fired units (Fig. 1d; the other category here reflects less-common types of fossil fuels such as waste, peat and coke oven gas). Such differences in the fuel mix of regional power sectors are primarily determined by resource structure, public policy and economic structure. Regional energy policies and availabilities to renewable energy resources can also affect the penetrations of renewable and nuclear power plants, which in turn lead to the regional differences in power generation mix.

Data availability

The database GPED that supports the findings of this study is available at http://www.meicmodel.org/dataset-gped.html

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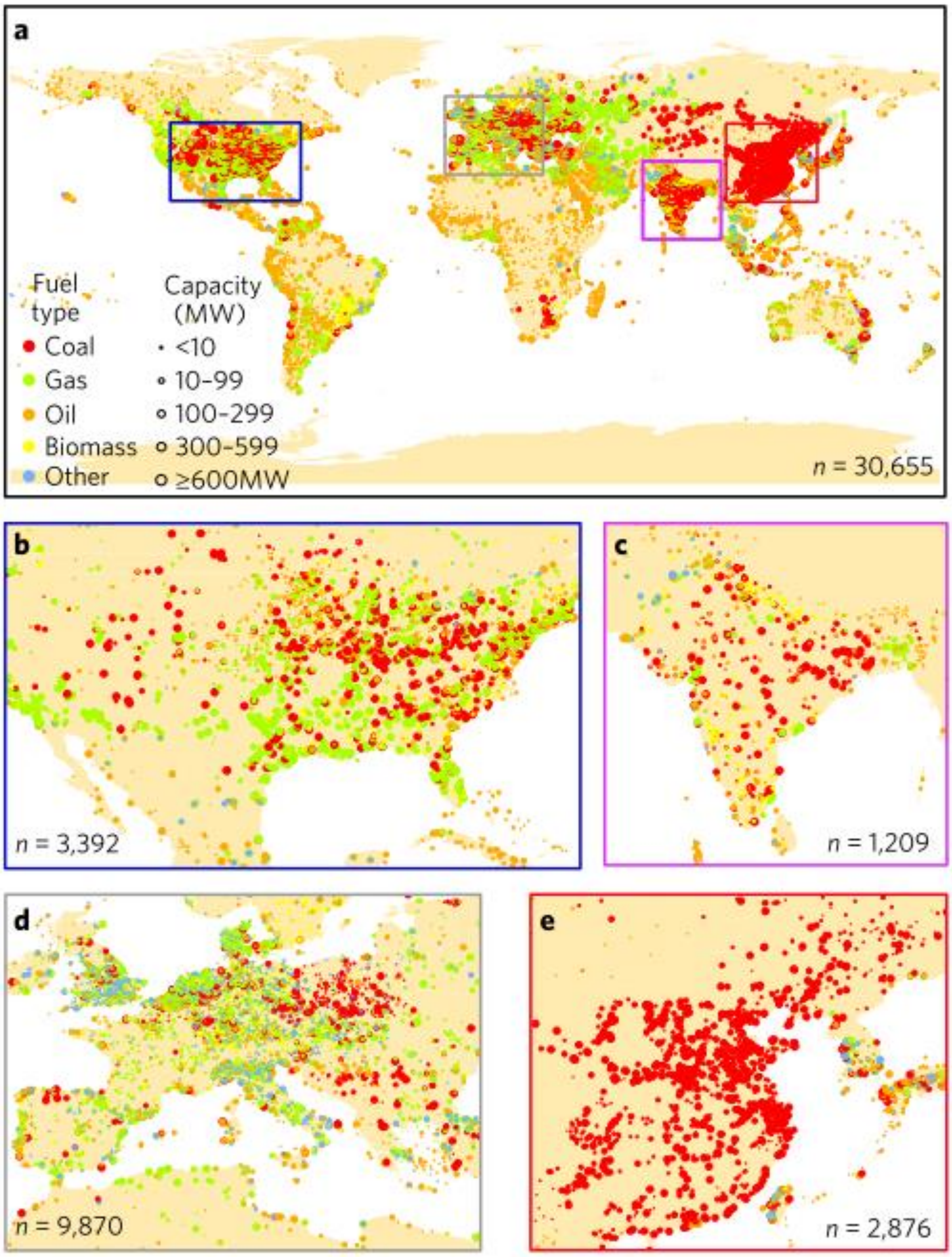

Fig. 1 | Maps of biomass- and fossil-fuel-fired power-generating units worldwide. a, Location, fuel type and nameplate capacity of 30,655 generating units worldwide. **b–e**, The US is dominated by mid-sized gas- and larger coal-fired units (**b**), India by mid-sized coal-fired units (**c**), Europe by a mix of mid-to-large units of different fuel types (**d**), and China by mid-sized coal-fired units (**e**). Generating units are classified by nameplate capacities (<10 MW, 10–99 MW, 100–299 MW, 300–599 MW, ⩾600 MW; Supplementary Table 2) and fuel types (coal, gas, oil, biomass, and other fuels such as waste, peat and coke oven gas; see Supplementary Table 3).

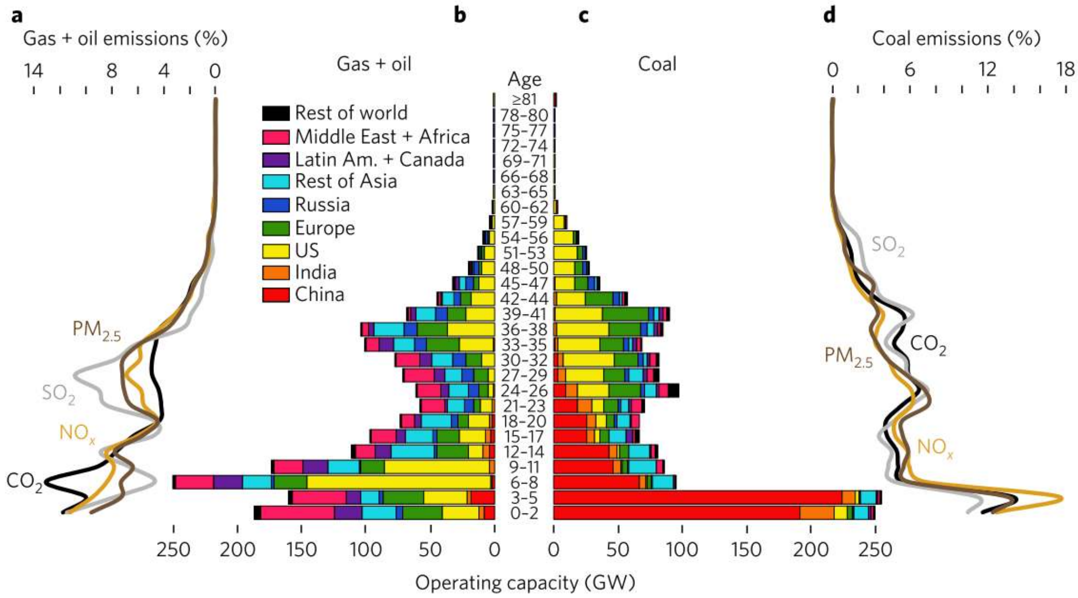

Fig. 2 | Age structure of global power-generating capacity and emissions. a,d, Curves indicate the estimated percentage of emissions from each age cohort of gas- and oil-fired units (**a**) and coal-fired units (**d**). **b,c**, The operating capacity of gas- and oil-fired units (**b**) and coal-fired units (**c**) where the youngest units are at the bottom. The dominance of young Chinese coal-fired units and US gas-fired units is apparent. Note that 0 years old means the power units began operating from 2010 in this study. See Supplementary Fig. 1 for the definition of regions.

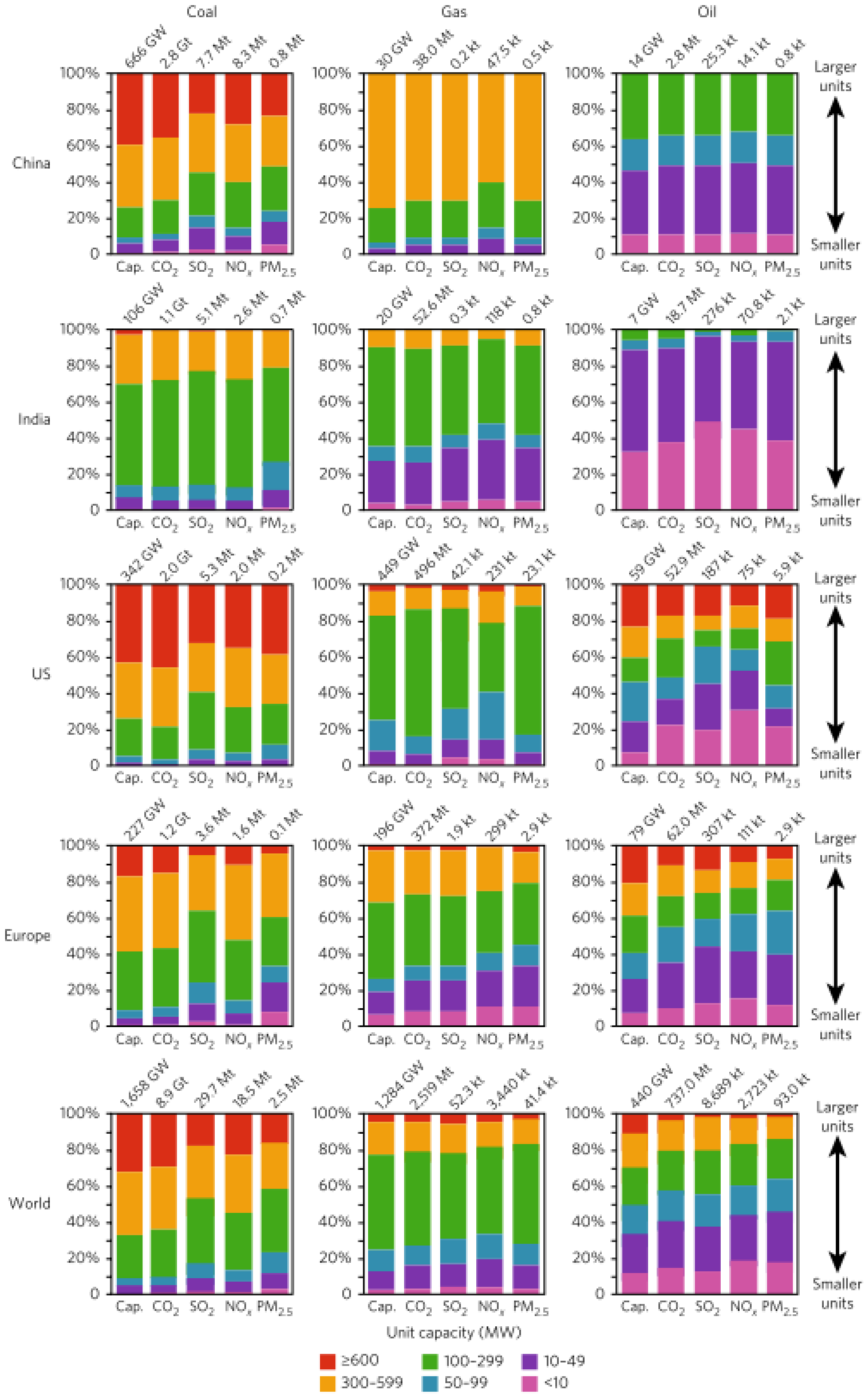

Fig. 3 | Shares of total capacity and estimated emissions by unit capacity. In each panel, bars from left to right show the fraction of capacity, CO_2, SO_2, NO_x and $PM_{2.5}$ accounted for by units in six categories of nameplate capacity (that is, size). Panels are organized by region (rows) and fuel type (columns).

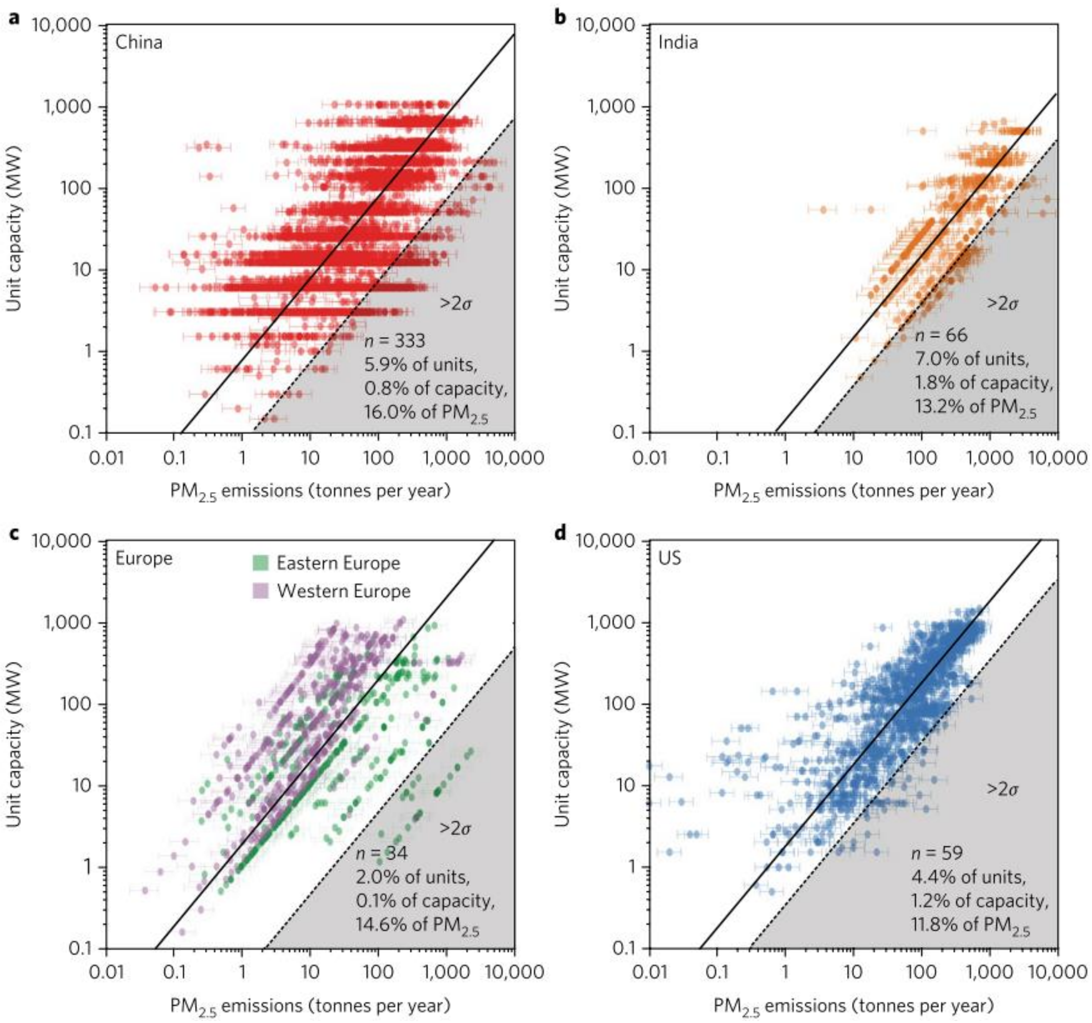

Fig. 4 | Super-polluting units. a–d, The data points represent individual coal-fired units in China (**a**), India (**b**), Europe (**c**), and the US (**d**), in each case plotted according to nameplate capacity (y axis) and annual $PM_{2.5}$ emissions (x axis). Solid diagonal lines indicate the mean emission intensity (tonnes $PM_{2.5}$ per MW) and shaded triangles indicate units whose emission intensity is 2σ above the mean. As noted in the panels, these units in each case represent < 7% of all coal-fired units but at least 12% of the $PM_{2.5}$ emissions from all coal-fired units. Unit-level uncertainty ranges (95% confidence interval) of emission estimates in this work are also provided. Supplementary Figs. 3 and 4 show analogous plots for SO_2 and NO_x.

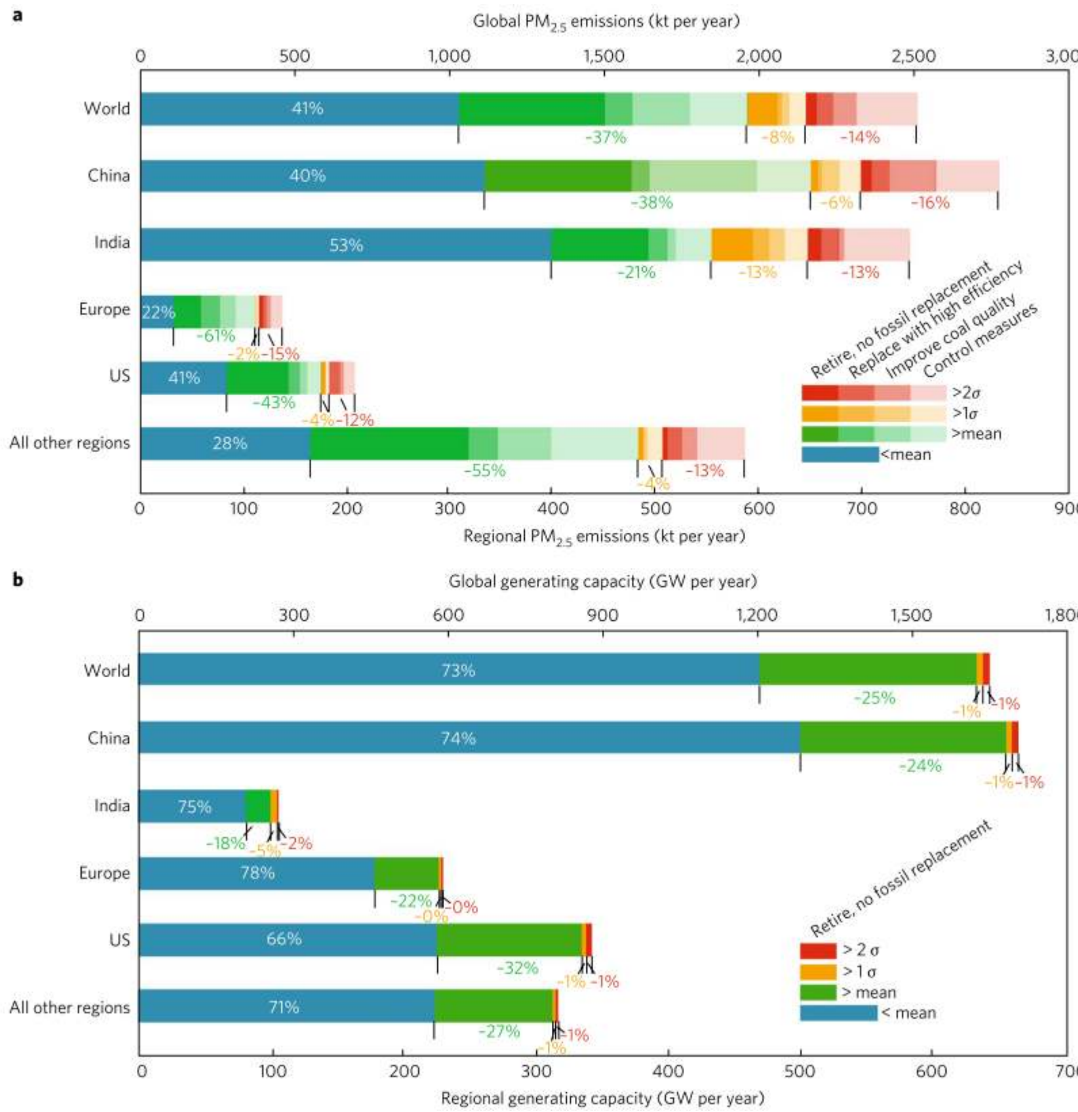

Fig. 5 | Potential reductions of PM$_{2.5}$ emissions and the associated coal-fired generating capacity. a, Bars show the estimated magnitude of PM$_{2.5}$ emissions that could be avoided if the super-polluting (units with emissions per unit capacity 2σ greater than the mean) and above-average-emitting units were improved by various methods (for example, control measures installed, higher-quality coal or replacement with higher electric efficiency). The darkest coloured bars show the potential reductions if the super-polluting and above-average-polluting coal-fired units are retired and not replaced by fossil-fuel-fired units. **b**, Large reductions are possible across all regions, and in each case the fraction of generating capacity affected is relatively less than the fraction of avoided of PM$_{2.5}$ emissions (**a**). Here we show potential reductions for the world (top x axis), China, India, all other regions (see list in Supplementary Fig. 1), US, and Europe (bottom x axis).