

1

2

3 **Targeted emission reductions from global super-polluting power plant**
4 **units**

5

6

7 Dan Tong^{1,2}, Qiang Zhang^{1,*}, Steven J. Davis^{1,3,*}, Fei Liu², Bo Zheng², Guannan Geng¹,8 Tao Xue¹, Meng Li¹, Chaopeng Hong¹, Zifeng Lu⁴, David G. Streets⁴, Dabo Guan^{1,5}, and9 Kebin He²

10

11

12 ¹ Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System
13 Science, Tsinghua University, Beijing 100084, People's Republic of China14 ² State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment,
15 Tsinghua University, Beijing 100084, People's Republic of China16 ³ Department of Earth System Science, University of California, Irvine, California 92697, USA17 ⁴ Energy Systems Division, Argonne National Laboratory, Argonne, IL 60439, USA18 ⁵ School of International Development, University of East Anglia, Norwich NR4 7TJ, UK

19 **There are more than 30,000 biomass- and fossil-fuel-burning power plants now operating**
20 **worldwide, reflecting a tremendously diverse infrastructure, which ranges in capacity from**
21 **less than a megawatt to more than a gigawatt. In 2010, 68.7% of electricity generated**
22 **globally came from these power plants, compared to 64.2% in 1990. Although the**
23 **electricity generated by this infrastructure is vital to economic activity worldwide, it also**
24 **produces more CO₂ and air pollutant emissions than infrastructure from any other**
25 **industrial sector. Here, we assess fuel- and region-specific opportunities for reducing**
26 **undesirable air pollutant emissions using newly developed emission dataset at the level of**
27 **individual generating units. For example, we find that retiring or installing emission**
28 **control technologies on units representing 0.8% of the global coal-fired power plant**
29 **capacity could reduce levels of PM_{2.5} emissions by 7.7-14.2%. In India and China, retiring**
30 **coal-fired plants 1.8% and 0.8% of total capacity can reduce total PM_{2.5} emissions from**
31 **coal-fired plants by 13.2% and 16.0%, respectively. Our results therefore suggest that**
32 **policies targeting a relatively small number of “super-polluting” units could substantially**
33 **reduce pollutant emissions and thus the related impacts on both human health and global**
34 **climate.**

35 The past two decades have witnessed an unprecedented expansion of fossil fuel
36 combustion by the global power sector (fossil energy production worldwide grew 94% from
37 1990 to 2010)^{1,2}, driven primarily by population growth, industrialization and urbanization in
38 developing countries³⁻⁵. Accompanying the growth of fossil energy use, greenhouse gases
39 and air pollutant emissions from the power sector have also surged⁶⁻¹⁰; globally, the power
40 sector accounted for ~40% of energy-related CO₂, ~7% of primary PM_{2.5} (fine particulate
41 matter with an aerodynamic diameter of 2.5µm or less) emissions, ~48% of SO₂ emissions
42 and ~28% of NO_x emissions in 2010¹¹⁻¹³. SO₂ and NO_x can be oxidized to secondary PM_{2.5} in
43 the atmosphere, which in turn has large impacts on air quality, health, and climate¹⁴⁻¹⁶.
44 Power production thus contributes more to health impacts and climate change than any
45 other industrial sector^{17,18}. However, there is large variation in the environmental and health
46 impacts of power generation across regions. In particular, environmental regulation in
47 developed regions has greatly reduced emissions of criteria pollutants (for example, SO₂,
48 NO_x, and PM_{2.5}) by power-generating units¹⁹⁻²², largely decoupling economic activity from air

49 quality. Meanwhile rapid rises in fossil fuel power generation and lax emission regulations
50 and regulation enforcement²³ in some developing countries have led to increasing
51 emissions, local violations of WHO outdoor air quality standards¹⁵ and offsetting air quality
52 improvements in downwind regions²⁴.

53 The impacts of global power plants on energy supply²⁵, air quality²⁶, health²⁷, and
54 climate²⁸ are of broad interest and have been investigated previously. A publicly available,
55 consistent global power plant emission dataset with detailed information can provide a firm
56 basis for such discussions, for example, by highlighting effective ways to mitigate air
57 pollution. Previous studies have compiled global and regional power plant CO₂ emission
58 databases^{8,29-31} or regional databases for air pollutant emissions^{6,9,10}, and noted the potential
59 for substantial emission reductions from addressing a disproportionately small share of
60 power plants³²⁻³⁴. Here, we develop a new global database of CO₂, SO₂, NO_x, and primary
61 PM_{2.5} emissions from fossil-fuel- and biomass-burning power-generating units as of 2010,
62 which we name the Global Power Emissions Database (GPED); use it to identify the most-
63 polluting units by region, fuel type and pollutant; quantify the disproportionalities of
64 generating capacity and air pollutant emissions; and in each case highlight the best
65 opportunities for reducing those undesirable emissions.

66 Details in methods and data used to construct and analyze the GPED are available in the
67 *Methods* section. In summary, we have compiled, combined and harmonized the available
68 data related to power-generating units burning coal, natural gas, oil or biomass from
69 national statistics and previous unit-level inventories^{6,9,10,35,36} (Supplementary Table 1), and
70 filled data gaps with modelled emissions. Although other global and regional power plant
71 emission databases exist^{6,8-10,35,36}, GPED is the first publicly available global database of
72 annual emissions of CO₂ and air pollutants from individual power-generating units
73 (<http://www.meicmodel.org/datasetgped.html>). We conducted a comprehensive
74 uncertainty analysis and validated our modelled estimates of emissions by comparing
75 measured and modelled emissions for units where we have such measurements (See
76 Supplementary Information). Finally, we analysed the generating capacity, fuel type, age,
77 location and installed pollution-control technology in order to determine those units with
78 disproportionately high levels of air pollutant emissions.

79 Figure 1 shows the geographical distribution, fuel type and capacity of 30,655 biomass-
80 and fossil-fuel-burning power plants operating worldwide in 2010, which in turn consist of
81 75,223 generating units with a combined installed capacity of 3,570 GW. We estimate that
82 12.5 Gt CO₂, 38.8 Mt SO₂, 25.2 Mt NO_x, and 2.7 Mt PM_{2.5} were emitted by these thermal
83 power plants in 2010. We find that a large fraction of total air pollutant emissions was
84 produced by a disproportionately small fraction of total capacity. For example, 14.2% of
85 global primary PM_{2.5} emissions from coal-fired power plants were produced by just 0.8% of
86 total capacity. The most-polluting units are often older, smaller, coal-burning units located in
87 developing countries, but this is not uniformly true. These super-emitters represent targeted
88 opportunities to mitigate air pollutant emissions by installing the best available pollution-
89 control technologies or replacing these units.

90 **Age and emissions of power generating-units**

91 Figure 2 shows the age distribution of global power-generating capacity in 2010 by coal
92 (Fig. 2c) versus gas and oil (Fig. 2b), as well as the share of global CO₂, SO₂, NO_x and PM_{2.5}
93 emissions in 2010 related to age cohorts of coal- and gas/oil-fired units (Figs. 2d,a,
94 respectively). Overall, the young age of generating units worldwide is striking; although units
95 historically operate for 35-38 years³⁷, rapid economic growth in emerging markets has
96 required corresponding growth in energy infrastructures such that 37% of operating units
97 worldwide were less than 12 years old in 2010. New units in China and India are especially
98 substantial, representing 71% and 13%, respectively, of new coal-fired generating capacity
99 built worldwide in 2010. As of 2010, 40% of global generating capacity was from coal-fired
100 units located in China. Coal-fired units operating in the US and Europe are much older:
101 averaging 35.9 and 32.4 years in 2010, respectively. However, the average age of gas-fired
102 units in the US is 18.8 years in 2010, and there is a large capacity of gas-fired units less than
103 a decade old. These patterns largely reflect (1) periods of energy-intensive economic
104 development during industrialization and (2) the transition of coal to natural gas in
105 developed economies³⁸.

106 Figure 2 also shows that CO₂ emissions are distributed across age groups of coal- and
107 gas-and-oil- and coal-fired in rough proportion to operating capacity (black curves in Figs. 2a,
108 d) because of a lack of deployed carbon capture and storage systems on operating fossil-fuel

109 power plants in 2010^{39,40}. However, control measures for SO₂, NO_x, and PM_{2.5} are widely
110 deployed, with emission standards varying drastically across species and regions. These
111 differences result in very different penetration of pollution-control technologies and
112 emission intensities for each species across regions (Supplementary Table 2).

113 In the case of coal-fired units, control technologies for PM_{2.5} emissions are common
114 across the world and highly effective in US, Europe, and China, which can be seen by the
115 relative shares of PM_{2.5} and CO₂ emissions (Fig. 2d; brown and black curves, respectively)
116 from units 30-41 years (which are mostly in the US and Europe; Fig. 2c) and 0-8 years old
117 (mostly in China). In contrast, lower penetrations of high effective PM_{2.5} control measures
118 cause high PM_{2.5} emission intensity in India (Supplementary Table 2). Controlling SO₂
119 emissions is now required in most regions. However, in 2010, only 5.6% of India's coal-fired
120 capacity was equipped with SO₂ control measures (compared with the global average,
121 81.9%), resulting in an SO₂ emission intensity for India twice that of the global average.
122 China began requiring plants to use flue-gas desulfurization in 2005, and, as of 2010, 84.5%
123 of coal-fired units built after 2005 are equipped with the technology⁶. For this reason,
124 younger coal-fired units produce a smaller share of SO₂ emissions than older units relative to
125 CO₂ emissions (compare gray and black curves in Fig. 2d). Controls for NO_x emissions remain
126 less common and are mainly required in developed countries. Only 13.0% and 4.2% of coal-
127 fired units in China and India, respectively, were equipped with flue-gas denitrification
128 technologies in 2010. Thus, younger coal-fired units—dominated by units in China and
129 India—produce relatively more NO_x emissions than either CO₂ or SO₂ emissions. Globally,
130 32.6% of coal-fired capacity was equipped with different types of flue-gas denitrification
131 technologies in 2010.

132 The emissions from gas- and oil-fired units depicted in Fig. 2a reflect mostly different
133 emission characteristics of those units and the prevalence of these two fuel types across
134 time and regions. SO₂ and PM_{2.5} control technologies on gas- and oil-fired units are less
135 common compared with coal-fired units (Supplementary Table 2). SO₂ and PM_{2.5} emissions
136 from gas-fired units are very small, so the SO₂ and PM_{2.5} emission contributions from
137 different age cohorts in Fig. 2a are primarily determined by the fraction of oil-fired
138 generators. For instance, 38% of SO₂ emissions from all gas- and oil-fired capacity are

139 produced by units between 21 and 32 years old, 28% of which are oil-fired (not shown).
140 Moreover, these older (21-32 year-old) oil-fired units are mostly located in the Middle East
141 and Africa (pink bars in Supplementary Fig. 2b), where the high sulfur content of oil burned
142 causes higher SO₂ emissions per MWh of electricity than in other regions⁴¹. Shares of NO_x
143 emissions in Fig. 2a represent combined contribution from both gas- and oil-fired units. NO_x
144 control technologies on gas- and oil-fired units were only widely used in developed
145 countries. Thus, younger gas- and oil-fired units, dominated by developed countries (6-11
146 years old in Fig. 2a) produced less NO_x than CO₂. For instance, although 13% of operating
147 gas- and oil-fired capacity is 6-8 years old, these units produced only 4% of the SO₂ emissions
148 from all gas- and oil-fired capacity because 93% of the units in this age range are gas-fired
149 (Supplementary Fig. 2).

150 **Disproportionalities of generating capacity and emissions**

151 Large fractions of pollution are consistently produced by a disproportionately small
152 fraction of power-generating capacity. Figure 3 shows the contribution of different-sized
153 generating units to total operating capacity, CO₂, SO₂, NO_x, and PM_{2.5} emissions, with
154 separate panels for each fuel type (coal, gas, and oil) and region (China, India, US, Europe
155 and world). In each case, the absolute magnitudes are also shown at the top of each bar.
156 Across all regions, small coal-fired units (for example, <100 MW) represent a small share of
157 total generating capacity, but a larger share of air pollutant emissions (SO₂, NO_x, and PM_{2.5}).
158 For example, small coal-fired units represent 9% of generating capacity in China, 14% in
159 India, 6% in the US, and 10% in Europe but produce 24%, 25%, 12%, and 33% of PM_{2.5}
160 emissions in those regions, respectively (Fig. 3, pink, purple and blue bars in left column). In
161 contrast, gas-fired generators are seldom equipped with control measures for SO₂ and PM_{2.5},
162 so that the proportion of overall capacity and SO₂/PM_{2.5} emissions is more consistent across
163 different-sized units, varying only due to combustion and operating efficiencies. However,
164 gas- and oil-fired units may be equipped with denitration measures to reduce NO_x emissions,
165 which is especially common on larger generators in developed countries. These controls may
166 result in a lower share of NO_x emissions from large gas- and oil-fired units (≥300 MW, orange
167 and red bars in middle column) relative to their total capacity (see, for example, Europe in
168 Fig. 3).

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

175 **Super-polluting power-generating units**

176 Figure 4 shows the relationship between generating capacity and annual emissions of
177 different air pollutants from coal-fired units in China, India, Europe and the US, and
178 highlights “super-polluters” in each region, which we define as those units whose emission
179 intensity (tonnes per MW) is more than two standard (2σ) deviations greater than the
180 region’s mean. Globally, 14.2%, 12.6% and 28.3% of global primary $PM_{2.5}$, SO_2 , and NO_x
181 emissions from coal-fired units in GPED were respectively produced by 0.8%, 1.6%, and
182 11.2% of the total capacity. 26.8% of global super-polluters were super-polluting units for
183 multiple pollutants, further emphasizing the importance of mitigating emissions from those
184 units.

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

195 The importance of super-polluting units is particularly striking in some regions. For
196 example, 0.8% (333 units) and 1.8% (66 units) of coal-fired capacity in China and India,
197 respectively, produced 16.0% and 13.2% of $PM_{2.5}$ emissions from all coal-fired units in 2010
198 (Figs. 4a,b). Perhaps surprisingly, super-polluting units are not confined to developing

199 regions; 0.1% and 1.2% ((34 and 59 units) of coal-fired capacity in Europe and the US,
200 respectively, produced 14.6% and 11.8% of PM_{2.5} emissions from all the coal plants in those
201 regions (Figs. 4c,d).

202 **Targeted opportunities to mitigate air pollutant emissions**

203 We estimate the potential reductions of air pollutants (PM_{2.5}, SO₂, and NO_x) if super-
204 polluting coal-fired units in different regions were updated with control measures, improved
205 fuel quality or replaced by large units that brought their emissions down to the regional
206 mean intensity, as shown in Fig. 5 (for PM_{2.5}) and Supplementary Figs. 5 and 6 (for SO₂ and
207 NO_x). Globally, installing current emissions control technologies on super-polluting units or
208 retiring them could reduce PM_{2.5}, SO₂, and NO_x emissions by 7.7-14.2%, 4.6-12.6%, and 5.2-
209 28.3%, respectively. Applying current pollution control technologies to the super-polluting
210 coal-fired units (that is, light red; corresponding to dark gray area in Fig. 4) could reduce
211 larger fractions of PM_{2.5} and SO₂ emissions than NO_x in each region, and these controls have
212 a larger effect than changes in coal quality or unit efficiency (darker shades of red) in most
213 regions. Perhaps more surprisingly, the proportion of PM_{2.5} emissions that could be avoided
214 if all coal-fired units achieved the mean intensity for their respective region (cumulative
215 emissions shown by the darkest blue, red, orange and green bars in Fig. 5a) are substantially
216 greater in Europe than any other region (56% as compared to 41% in China, 44% in all other
217 regions, and 26% in India and 25% in the US). This is explained by the inclusion of both a
218 relatively large number of high-emitting units in areas of eastern Europe and a similarly large
219 number of very low-emitting units in western Europe, which acts to establish a low mean
220 intensity with a large range (see spread of points in Fig. 4).

221 **Discussion**

222 Our study constructed a unit-based global plant emission dataset and explored the
223 mitigation opportunity from a small sub-group of the most polluting units. In the future, our
224 database of global power plant emissions, GPED, can help prioritize cost-effective actions for
225 further emission reductions and thereby regional and global impacts of outdoor air pollution
226 on human health^{27,42,43}. The potential impacts on the climate are also deserving of further
227 study; power plants emit a range of CO₂ and other precursor gases simultaneously^{28,44}. Our

228 database can be used to support model analyses on potential air quality and climate co-
229 benefits of global power plants.

230 Regional and international efforts to reduce both air pollution and CO₂ emissions are
231 increasing. For instance, China has implemented strict emission standard since 2015⁴⁵ and
232 plans to increase the share of non-fossil power to 31% by 2020⁴⁶ to tackle the severe air
233 pollution problem, and the Clean Power Plan in the US aims to reduce CO₂ emissions by 32%
234 in 2030 compared with 2005. Such efforts can contribute to international agreements on
235 climate change. Our results can be applied not only to prioritize retrofits but to prioritize
236 retirement and replacement of super-polluting power-generating units with non-emitting
237 energy sources. In developing countries such as China, excess emissions were always a
238 problem due to a lack of effective regulation enforcement^{23,47}. Strengthened supervision
239 systems should be developed and operated to avoid such undesirable emissions. In addition,
240 there are still substantial disparities between the mean emission intensities in developed
241 and developing countries (Supplementary Table 2), underscoring the potential of efforts to
242 strengthen international collaboration and technology transfer to decrease the global
243 impacts of air pollution^{48,49} and accelerate the transition to ‘clean’ and/or non-fossil sources
244 of power in developing countries. In turn, such progress could avoid further ‘lock-in’ of fossil
245 energy technologies in both developing and developed economies^{50,51}.

246 The GPED is subject to uncertainties and limitations. A detailed description of
247 uncertainties is presented in the Supplementary Information. In summary, the average
248 uncertainties of global emissions are estimated to be –14% to 15% for CO₂, –20% to 21% for
249 SO₂, –26% to 27% for NO_x, and –21% to 32% for PM_{2.5}. Uncertainties of unit-level emissions
250 vary among units and regions, with larger uncertainties for smaller units and developing
251 regions due to incomplete information. GPED might be still incomplete because the World
252 Electric Power Plant (WEPP) database may have omitted some small units⁶. More regional
253 databases should be collected and incorporated in the future. The accuracy of GPED may
254 vary regionally due to integration of regional datasets of differing data quality. Inter-
255 comparison initiatives among different regions could help to narrow the gap. At present,
256 GPED is only available for 2010 given that collecting underlying data is a challenging task.
257 Building transparent data reporting systems in developing countries and continuous efforts

258 under international collaboration frameworks could help to deliver more complete and
259 reliable data. Our database will be updated and improved in the future as more and better
260 data become available.

261

262 **Author information.** Correspondence and requests for materials should be addressed to Q. Zhang
263 (qiangzhang@tsinghua.edu.cn) or S. J. Davis (sjdavis@uci.edu).

264

265 **Acknowledgements.** This work was supported by the National Science Foundation of China
266 (41625020), China's National Basic Research Program (2014CB441301), and the National Key R&D
267 program (2016YFC0201506). Q.Z. and K.H. are supported by the Collaborative Innovation Center for
268 Regional Environmental Quality. D.G. acknowledges support from the National Science Foundation of
269 China (41629051). The India component of the work was funded by the Office of Biological and
270 Environmental Research in the US Department of Energy, Office of Science, for which Z.L. and D.G.S.
271 are grateful to Ashley Williamson and Bob Vallario.

272

273 **Author contributions.** Q. Z. designed the research. D.T., F.L., B.Z., G.G., T.X., M.L., and C.H. performed
274 the research. Z.L. and D.G.S. provided data for Indian power plants. D.T., S.J.D., and Q.Z. interpreted
275 data. D.T., S.J.D., and Q.Z. wrote the paper with inputs from all coauthors.

276 **Methods**

277 **Global Power Emissions database.**

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

282 There are a few databases of global power plants available for CO₂ emissions (for
283 example, the Carbon Monitoring for Action (CARMA) database⁸ and an improved version of
284 Fossil Fuel Data Assimilation System (FFDAS) database³¹). CARMA has been widely used in
285 bottom-up emission inventories to allocate power plants emissions⁶, which estimated plant-
286 level CO₂ emissions for 2004, 2009, and the “future” by using the commercially available
287 Platt’s WEPP database³⁶. A regression model was used in CARMA for predicting the capacity
288 factor, heat rate, and CO₂ emission factor of each power plant, and then calculating CO₂
289 emissions based on these inputs⁸. As an update of FFDAS utilize an updated and improved
290 global power plant emission data product that includes improved location information and
291 individual power plant uncertainties³¹, which uses data from both the public disclosure data
292 and the WEPP database.

293 Here, we developed a new global power plant emission database including both CO₂ and
294 air pollutant emissions (SO₂, NO_x, and primary PM_{2.5}). When constructing GPED, we chose
295 2010 as the base year for the database, because it was the latest year for which detailed
296 data were publicly available in the national databases we used. We began by using the WEPP
297 database to compile unit-based information of generators in service as of 2010 (for example,
298 unit capacity, start year of operation, physical address, fuel type) as well as technologies in
299 place for desulfurization, denitration and dust removal. Next, we cross-checked and where
300 necessary overwrote unit-based information and emissions for units operating in the US,
301 China and India using what we think are the more comprehensive and reliable data
302 contained in the national databases: The Emissions and Generation Resource Integrated
303 Database (eGRID)³⁵, the China Coal-Fired Power Plant Emissions Database (CPED)⁶ and the
304 India Coal-Fired Power Plant Database (ICPD)^{9,10}. CPED considers the unit-level fuel qualities
305 (for example sulfur and ash content) and removal efficiency of control measures, which
306 significantly improve the accuracy of emission data⁶. ICPD also applies unit- or plant-level
307 information (for example, specific coal consumption and boiler type)^{9,10}. eGRID is based on
308 available plant-specific data for all US power plants that provide power to the electric grid
309 and report data to the US government³⁵. The eGRID data include both unit- and plant-level

310 emission data (CO₂, SO₂ and NO_x) for 2010. CPED includes unit-specific activity data and net
311 emissions factors for CO₂, SO₂, NO_x and PM_{2.5} for the period of 1990-2010 for Chinese coal-
312 fired generators. ICPD includes generator-level SO₂ emissions during 2005-2012 and NO_x
313 emissions from 1996 to 2010. Note that the CPED includes only coal-fired units and that the
314 ICPD excludes both privately owned generators and smaller (<20 MW) publicly owned coal-
315 fired units. Thus, where WEPP includes data not in the above regional databases, we retain
316 that information such that our GPED represents an integration of the best available data.

317 Because geographical locations (exact latitudes and longitudes) are not included in the
318 WEPP database, we obtained the locations of 19,105 generating units (25.4% of the total
319 75,223 units) from the eGRID, CPED and ICPD. We then geolocated one-by-one all remaining
320 units at plants with a total capacity ≥10 MW using either data from the Global Energy
321 Observatory (<http://globalenergyobservatory.org/>) or Google Earth, which represent
322 locations for an additional 19,001 units (25.3%). For the remaining, smaller units, we obtain
323 locations by using Google Maps to map the physical address provided in the WEPP database.
324 Further details of this analysis and a summary of units and their total installed capacities are
325 shown in Supplementary Table 1.

326 **Unit-based CO₂, SO₂, NO_x and PM_{2.5} emission estimation**

327 As described above, where available, we adopt unit-based estimates of CO₂, SO₂, NO_x
328 and PM_{2.5} emissions for 2010 from existing databases. For example, CO₂, SO₂, NO_x emissions
329 of American units from eGRID; CO₂, SO₂, NO_x and PM_{2.5} emissions of Chinese coal-fired units
330 from CPED; and SO₂, NO_x emissions of Indian coal-fired power plants from ICPD. For units
331 not included in those databases, we estimate emissions of CO₂ and air pollutants ($E_{s,i}$) using
332 the following equation:

$$333 \quad E_{s,i} = A_{i,j} \times EF_{s,k} \times (1 - \eta_{s,m}) \times 10^{-3} \quad (1)$$

334 where s , k , i , j , and m represent emission species, country, generating unit, fuel type and
335 emission control technology, respectively. E represents unit-based emissions (kg),
336 A represents specific fuel consumption for each unit (kg for solid- or liquid-fired units and m³
337 for gas-fired units); EF represents the unabated emissions factors (g/kg for solid- or liquid-
338 fired units and g/m³ for gas-fired units); and η represents the removal efficiency of control
339 technology, $\eta > 0$ when the control equipment is present, otherwise $\eta = 0$.

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

343 Unit-level fuel consumption is a function of installed capacity, annual operating hours
 344 and fuel consumption per unit power generation⁶, but of these, only installed capacity data
 345 are readily available. We therefore make the simplifying assumption that annual average
 346 operating hours of generating units burning the same fuel (65 fuel types) are consistent at
 347 the country level. Although this assumption may bias our findings at the country and unit
 348 levels, the assumption does not apply to the largest emitting countries (for which we have
 349 unit-level data). A detailed description and evaluation of results is presented in the
 350 Supplementary Information. Fuel consumption per unit power generated is inversely related
 351 to electric efficiency. Electric efficiencies in different utilities range from 25–45% for coal-
 352 fired power plants, 35–50% for oil-fired power plants, and 35–60% for natural-gas-fired
 353 power plants⁵², corresponding to different technology and operating conditions. Instead, we
 354 estimate electric efficiency using a function we built based on data in eGRID, CPED and ICPD,
 355 as well as measurements collected from various electric reports or companies' websites. Our
 356 function reflects an obvious nonlinear relationship between installed capacity and electric
 357 efficiency in coal-, gas-, oil- and biomass-fired units, respectively, as illustrated in
 358 Supplementary Fig. 7.

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

$$361 \quad A_{i,j} = A_{k,j} \times \frac{\frac{C_i}{e_i}}{\sum \frac{C_{k,j}}{e_{k,j}}} \quad (2)$$

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

368 Supplementary Fig. 7 shows further details of electric efficiency across units burning
 369 different fuel types. In general, electric efficiency increases with unit capacity, but the
 370 marginal rate of efficiency gains declines as units become larger, and efficiency gains
 371 eventually disappear. Using these samples, we build functions to estimate coal-, gas-, oil-,
 372 biomass-fired generating units' electric efficiencies where local information is not available
 373 (Supplementary Fig. 7a–d). Although most units burn coal, gas, oil or biomass, there are
 374 some other generating units fueled by less common and/or mixtures of fuels (for example,
 375 waste, peat and coke oven gas) where we lack sufficient samples to build functions. We
 376 categorize these fuel types as solids, liquids or gaseous fuels and constructed piecewise

377 constant functions to estimate their electric efficiencies and differentiate the fuel
378 consumptions per kWh supplied on the different range of unit capacity. The detailed values
379 for each fuel type are also shown in Supplementary Table 4. In this way, we derive electric
380 efficiencies of all units, which in turn allowed us to calculate unit-level fuel consumptions by
381 equation (2).

382 *CO₂ emissions.* The CO₂ emissions factors were estimated by calculating the carbon
383 content of the consumed fuel⁵³. The following equation was used to calculate CO₂ emissions
384 factors according to guidelines from the Intergovernmental Panel on Climate Change
385 (IPCC)⁵⁴:

$$386 \quad EF_{CO_2,j,k} = CA \times O \times 44/12 \times H_{j,k} \quad (3)$$

387 where j, k represent fuel type, and the country, respectively; EF_{CO_2} represents the CO₂
388 emissions factor in g/kg for solid and liquid fuels, kg/m³ for gaseous fuels; CA represents
389 the carbon content in kg of carbon per GJ (kg-C/GJ), O represents carbon oxidation factor;
390 $44/12$ is the molecular weight ratio of CO₂ to carbon; H is the heating value in kJ/g for
391 solid and liquid fuels, MJ/m³ for gaseous fuels. In this study, the carbon oxidation factor
392 assumed to be 1, the carbon contents were obtained from the IPCC guidelines⁵⁴. The heating
393 value data for each fuel type and country are from IEA^{1,2}.

394 *SO₂ emissions.* In the absence of desulfurization technology, emissions of SO₂ are
395 directly related to the sulfur content of the fuel. Therefore, we estimate the unabated SO₂
396 emissions factors as follows:

$$397 \quad EF_{SO_2,j,k} = 2 \times S_{j,k} \times (1 - SR_{j,k}) \times 10 \quad (4)$$

398 where j, k represent sub fuel type (for example, anthracite, bituminous, subbituminous or
399 lignite), and the country, respectively; EF_{SO_2} represents the unabated SO₂ emissions factor;
400 S represents the sulfur content of fuel; and SR represents the sulfur retention in ash.

401 For coal-fired units, because unit-level data on fuel sulfur content is not available, we
402 reflect differences in coal quality by assuming the national average sulfur content of
403 different types of coal obtained from the United States Geological Survey (USGS). Where a
404 national average sulfur content is not available, we instead use an average of all the
405 countries in the same region for which sulfur content data was available. Using the default
406 values derived from USEPA AP-42⁵⁵ and other previous works^{56,57}, SR was assumed to be 5%
407 for bituminous-fired units, 12.5% for sub-bituminous-fired ones, 2.5% for anthracite-fired
408 units, 25% for lignite-fired units and 15% for other coal-fired unit without specific sub type⁵⁵.
409 The effects of combustion technology and boiler age on SR were not taken into account
410 because we lack sufficient data about their effects on SO₂ emissions⁶. For oil-fired units, the
411 SR ratios were also taken from USEPA AP-42⁵⁵ for different fuel sub-types and country-level

412 estimates of the sulfur contents of oil are derived from previous literature⁵⁷⁻⁶⁰. For gas-fired
413 units, we neglect these differences between countries/regions and apply a global average
414 emissions factor from AP-42⁵⁵ due to low SO₂ emissions from gas-fired units and insufficient
415 data. The SO₂ emissions factors of biomass and other fuel combustion were based on the
416 measurements from AP-42⁵⁵ and previous works^{60,61}.

417 The net emissions factor of SO₂ is also strongly dependent on the removal efficiency of
418 desulfurization devices¹⁰. At present, flue gas desulfurization (FGD) technologies are most
419 common and widely used desulfurization devices. From GPED, we can see desulfurization
420 devices were widely used in coal- and oil-fired units. Moreover, we differentiate 55 specific
421 desulphurization technologies from GPED (Supplementary Table 5). For each technology,
422 removal efficiencies were derived from USEPA AP-42⁵⁵ and others' works^{62,63} and applied to
423 each country depending on emission standards and economic development because of the
424 lack of unit-specific data. Higher removal efficiency for the same control technology was
425 applied in developed countries. In this study, we assumed that the removal efficiency of SO₂
426 for wet scrubbers is 20%⁶.

427 *NO_x emissions.* NO_x emissions factors of power-generating units vary primarily by type of
428 fuel and combustion, and NO_x control technology^{6,9}. In this study, we used the same size
429 classification in CPED and ICPD to differentiate the NO_x emissions factors between boiler
430 sizes^{6,9}. National measurement data have been gradually reported in literatures^{64,65}.
431 However, due to the absence of country-specific measurement data for all the fuel types
432 and countries, default NO_x emissions factors by fuel type were obtained from AP-42⁵⁵,
433 EMEP⁶⁶ and various literatures^{56,61,67} and then applied to all countries without specific
434 measurements. In this study, boiler-size-specific and fuel-type-specific emissions factors
435 were applied to units without taking boiler type into consideration.

436 NO_x emissions were regulated in some developed countries in 2010, such as the US,
437 Japan and western Europe. Some developing countries, like China and India, also regulated
438 NO_x emissions and began to control NO_x emissions according to local emission standards but
439 with much lower penetration rates for NO_x-emission-control technologies. Most developing
440 countries, like some in Africa, are not regulated NO_x emissions in 2010. There are two types
441 of NO_x-emission controls: combustion controls (e.g., low-NO_x burners for coal-fired units, dry
442 low-NO_x combustors for gas-fired units, and wet controls using water or steam injection to
443 reduce combustion temperatures) and post-combustion controls (e.g., selective catalytic
444 reduction and selective non-catalytic reduction)^{62,68}. In total, we differentiate 34 types of
445 NO_x-control technologies from GPED (Supplementary Table 6). Removal efficiencies for NO_x-
446 emission-control technologies were derived from USEPA AP-42⁵⁵.

447 *PM_{2.5} emissions*. PM emission levels are a complex function of boiler firing configuration,
448 boiler operation, pollution control equipment, and fuel properties⁵¹. Because PM_{2.5}
449 emissions are mainly from coal-fired generating units (due to the much larger proportion of
450 non-combustible components in the fuel relative to other fuel types), we estimate unabated
451 emissions factors of PM_{2.5} for coal-fired units as per previous analyses⁶⁹:

$$452 \quad EF_{PM_{2.5},k} = AC_{k,j} \times (1 - ar_{k,j}) \times f \quad (5)$$

453 where *k* and *j* stand for the country and coal sub-type; *AC* represents the ash content of coal,
454 *ar* represents the mass fraction of retention ash, *f* represents the PM_{2.5} mass fraction to
455 the total particulate matter in fly ash. Given the sparse number of country-level samples
456 counted from USGS, excluding some countries with sufficient samples, we use the
457 corresponding regional average ash content for each coal sub-type. The PM_{2.5} mass fraction
458 *f*, was obtained from the Greenhouse Gas and Air Pollution Interactions and Synergies
459 (GAINS) database^{70,71}. In addition, the mass fractions of retention ash of anthracite,
460 bituminous, lignite and subbituminous were also derived from the GAINS^{70,71}. Combining
461 these parameters, we calculate the unabated emissions factors of coal-fired units. For the
462 relatively small proportion of PM_{2.5} produced by units burning other fuels, a global average
463 emissions factor for each fuel type from AP-42⁵⁵ was applied due to small national
464 differences and scarce data.

465 Dust-removal technologies were installed in nearly all the coal-fired generating units
466 worldwide with different options such as mechanical collectors, wet scrubbers, electrostatic
467 precipitators, wet electrostatic precipitators, fabric filters and combined precipitators. GPED
468 differentiates 15 different control technologies (Supplementary Table 7). The removal
469 efficiencies of each technology were obtained from previous studies considering operation
470 differences between countries^{6,55,70}. Note that particulate matter can also be removed via
471 wet FGD as a co-benefit of SO₂ removal⁶. In this study, we assume the same PM_{2.5} removal
472 efficiency for wet FGD equipment as we have previously^{6,65}.

473 Dust removal technology data was relatively complete in the WEPP database for large
474 coal-fired units (≥100 MW) but not for small units (<100 MW). In this study, we therefore
475 assume all coal-fired units are equipped with some type of dust-removal technology. Where
476 data are missing from WEPP, we assume country-specific average removal efficiency of dust
477 from coal-fired units according to existing coal-fired units with installed capacity less than
478 100 MW. This assumption may underestimate the emission contribution of super-polluting
479 units if some coal-fired units are not equipped with dust-removal equipment. Because oil-
480 fired units produce much less PM emissions than comparably sized coal-fired units, many oil-
481 fired units do not use PM_{2.5} control measures. Similarly, PM emissions from gas-fired units

482 are typically low because of the gaseous nature of the fuel. For units that burn biomass or
483 waste, PM_{2.5} can be significant but emission standards are often lacking. In these cases,
484 unless we have specific data of control technologies in GPED, we assume zero removal
485 efficiency.

486 Emissions factors for SO₂, NO_x and PM_{2.5} can be substantially reduced by the installation
487 and operation of control technologies, which are in turn determined by environmental
488 policy. Most countries have their own emissions standards for air pollution (for example, the
489 US, China, Japan and Europe), with limits on SO₂, NO_x and PM_{2.5} emissions varying by country
490 and fuel type. However, unit-specific data on installed control technologies are incomplete;
491 we therefore make estimates regarding the different pollutants and different units as
492 described above.

493 **Potential mitigation of coal-fired units emissions estimated**

494 We defined super-polluting coal-fired units as those with air pollutant emission
495 intensities (that is, emissions per unit of generating capacity) that are two standard
496 deviations greater than the mean in their respective region (here, the regions are China,
497 India, Europe, the US and 'all other regions'; Supplementary Fig. 1). We then evaluated the
498 potential reductions in air pollutant emissions from these units as well as the corresponding
499 effect of such mitigation on generating capacity. Based on equations (2), (4) and (5), the
500 main levers for reducing unit-based PM_{2.5} and SO₂ emissions are: (i) improving coal quality,
501 (ii) installing advanced emission control measures, (iii) replacement with fossil-fuel-burning
502 units of comparable capacity but higher electric efficiency, or (iv) retirement with no fossil
503 fuel replacement. The main levers for reducing unit-based NO_x emissions are (ii)–(iv). Based
504 on related parameters and emissions in GPED, we evaluate the relative potential emission
505 reduction related to each of these main levers for units in each region by assuming the ash
506 content or sulfur content of coal is equal to the best level in the country acquired from the
507 USGS database; assuming installation of SO₂, NO_x and PM_{2.5} removal efficiency equivalent to
508 the best available technology in 2010 in each region from GPED; assuming electric
509 efficiencies equal to the mean level in the country. Residual emissions after all these
510 measures are taken, we assume can be mitigated by retirement of the unit without
511 replacement.

512 **Characteristics of power-generating units**

513 The GPED database includes 11,484 coal-fired units, 23,865
514 natural-gas-fired units, 30,357 oil-fired units, 3,070 biomass-fired units and 6,447 other-fuel-
515 fired units, with total capacities of 1,658 GW (47% of total), 1,284 GW (36%), and 440 GW
516 (12%), 43 GW (1%), and 145 GW (4%), respectively. Worldwide, coal-fired units have the
517 largest mean capacity, 144 MW, and gas- and oil-fired plants are considerably smaller: 54
518 and 15 MW, respectively.

519 Different fuel types and unit sizes are dominant in different regions. Here, we focus our
520 analyses on four regions: China, India, the US and Europe (Fig. 1b–e). Our GPED database is
521 global in its scope, but these four regions account for 64% of global generating capacity
522 (2,284 GW) and also reveal the full extent of variation in power sector infrastructure and
523 emissions. For instance, Fig. 1c,e shows the dominance of mid-sized coal-fired plants in India
524 and China, with mean nameplate capacities of 112 and 117 MW, representing 78% and 93%
525 of total generating capacity in those countries, respectively. In contrast, Fig. 1b shows the
526 joint reliance on gas and coal power in the US, which represent 52% and 40% of US capacity,
527 respectively. Europe has the greatest variation in fuel types, with capacity made up of 40%
528 coal, 35% gas, 14% oil, 9% other and 3% biomass-fired units (Fig. 1d; the other category here
529 reflects less-common types of fossil fuels such as waste, peat and coke oven gas). Such
530 differences in the fuel mix of regional power sectors are primarily determined by resource
531 structure, public policy and economic structure. Regional energy policies and availabilities to
532 renewable energy resources can also affect the penetrations of renewable and nuclear
533 power plants, which in turn lead to the regional differences in power generation mix.

534 **Data availability**

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

537 **References**

- 538 1. Energy Statistics and Balances of OECD Countries, *1990–2010* (International Energy Agency,
539 Paris, 2012).
- 540 2. Energy Statistics and Balances of Non-OECD Countries, *1990–2010* (International Energy

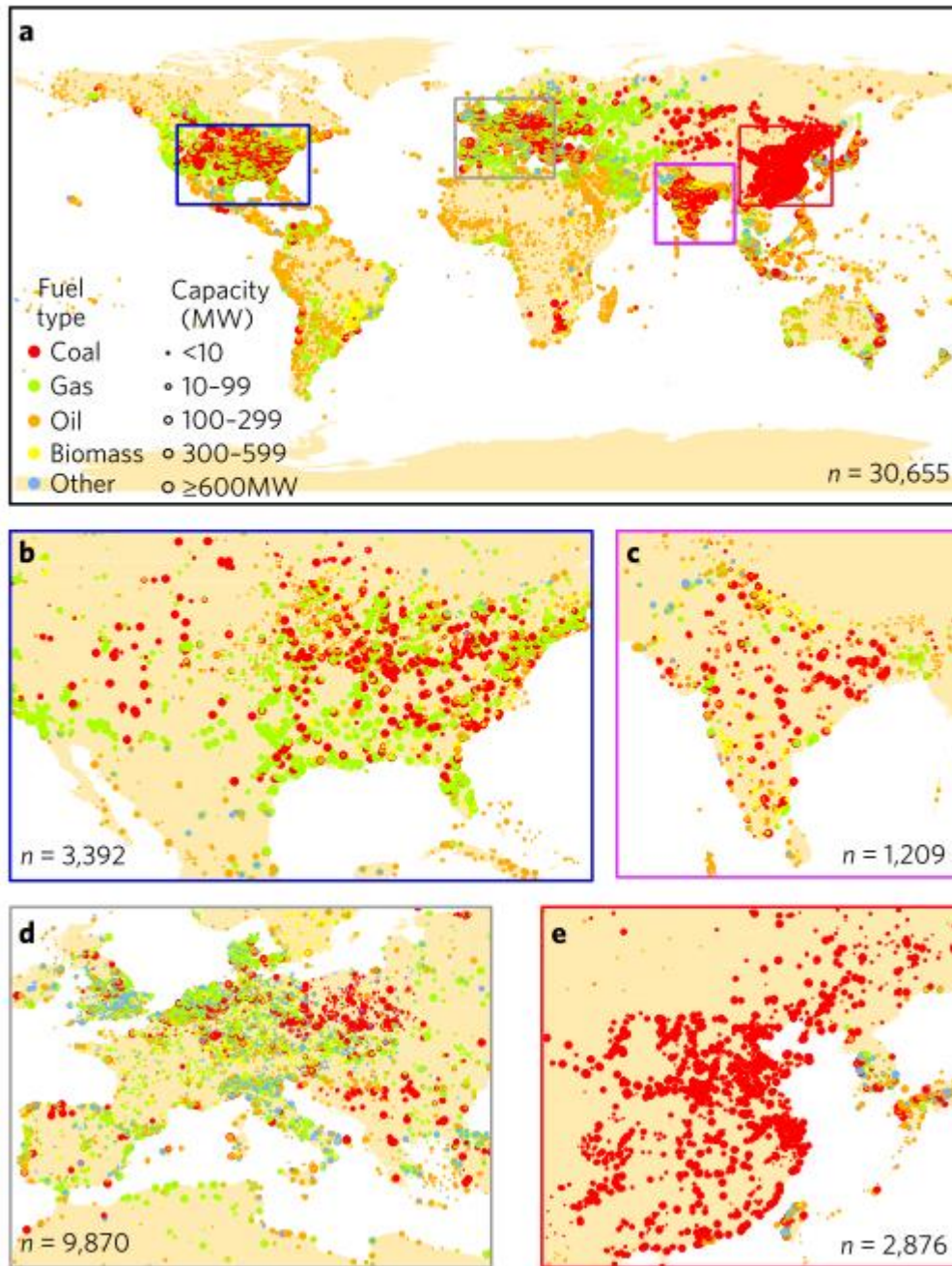
-
- 541 Agency, Paris, 2012).
- 542 3. Chen, S. T., Kuo, H. I. & Chen, C. C. The relationship between GDP and electricity consumption
543 in 10 Asian countries. *Energy Policy* **35**, 2611–2621 (2007).
- 544 4. Chan, C. K. & Yao, X. Air pollution in mega cities in China. *Atmos. Environ.* **42**, 1–42 (2008).
- 545 5. Yoo, S. H. & Lee, J. S. Electricity consumption and economic growth: a cross-country analysis.
546 *Energy Policy* **38**, 622–625 (2010).
- 547 6. Liu, F. et al. High-resolution inventory of technologies, activities, and emissions of coal-fired
548 power plants in China from 1990 to 2010. *Atmos. Chem. Phys.* **15**, 13299–13317 (2015).
- 549 7. Zhao, Y. et al. Primary air pollutant emissions of coal-fired power plants in China: current status
550 and future prediction. *Atmos. Environ.* **42**, 8442–8452 (2008).
- 551 8. Ummel, K. *CARMA Revisited: an Updated Database of Carbon Dioxide Emissions From Power*
552 *Plants Worldwide* Center for Global Development Working Paper 304 (2012).
- 553 9. Lu, Z. & Streets, D. G. Increase in NO_x emissions from Indian thermal power plants during
554 1996–2010: unit-based inventories and multisatellite observations. *Environ. Sci. Technol.* **46**,
555 7463–7470 (2012).
- 556 10. Lu, Z., Streets, D. G., de Foy, B. & Krotkov, N. A. Ozone monitoring instrument observations of
557 interannual increases in SO₂ emissions from Indian coal-fired power plants during 2005–2012.
558 *Environ. Sci. Technol.* **47**, 13993–14000 (2013).
- 559 11. *Emission Database for Global Atmospheric Research* (EDGAR) v. 4.3.1 (EC-JRC/PBL, European
560 Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency
561 (PBL), accessed on 19 August 2017); <http://edgar.jrc.ec.europa.eu/overview.php?v=431>
- 562 12. Crippa, M. et al. Forty years of improvements in European air quality: regional policy-industry
563 interactions with global impacts. *Atmos. Chem. Phys.* **16**, 3825–3841 (2016).
- 564 13. Klimont, Z. et al. Global anthropogenic emissions of particulate matter including black carbon.
565 *Atmos. Chem. Phys.* **17**, 8681–8723 (2017).
- 566 14. Unger, N., Shindell, D. T. & Wang, J. S. Climate forcing by the on-road transportation and power
567 generation sectors. *Atmos. Environ.* **43**, 3077–3085 (2009).
- 568 15. Zhang, Q., He, K. & Huo, H. Cleaning China's air. *Nature* **484**, 161–162 (2012).
- 569 16. Burnett, R. T. et al. An integrated risk function for estimating the global burden of disease
570 attributable to ambient fine particulate matter exposure. *Environ. Health Persp.* **122**, 397–403

-
- 571 (2014).
- 572 17. Markandya, A. & Wilkinson, P. Electricity generation and health. *Lancet* **370**, 979–990 (2007).
- 573 18. Davis, S. J. & Socolow, R. H. Commitment accounting of CO₂ emissions. *Environ. Res. Lett.* **9**,
- 574 084018 (2014).
- 575 19. Kurokawa, J. et al. Emissions of air pollutants and greenhouse gases over Asian regions during
- 576 2000–2008: Regional Emission inventory in ASia (REAS) version 2. *Atmos. Chem. Phys.* **13**,
- 577 11019–11058 (2013).
- 578 20. EMEP/CEIP 2014 Present State of Emission Data (European Monitoring and Evaluation
- 579 Programme (EMEP), accessed on 15 December 2015); <http://www.emep.int/>
- 580 21. Air Pollution Emissions Trends Data (Environmental Protection Agency (EPA), accessed on 15
- 581 December 2015); [https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-](https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data)
- 582 [trends-data](https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data)
- 583 22. The National Pollutant Release Inventory (NPRI) (Environment Canada, accessed on 15
- 584 December 2015); <https://www.ec.gc.ca/>
- 585 23. Zhang, J. J. & Samet, J. M. Chinese haze versus Western smog: lessons learned. *J. orac. Dis.* **7**,
- 586 3-13 (2015).
- 587 24. Verstraeten, W. W. et al. Rapid increases in tropospheric ozone production and export from
- 588 China. *Nat. Geosci.* **8**, 690–695 (2015).
- 589 25. Williams, J. H. et al. e technology path to deep greenhouse gas emissions cuts by 2050: the
- 590 pivotal role of electricity. *Science* **335**, 53–59 (2012).
- 591 26. Frost, G. J. D. et al. Eects of changing power plant NO_x emissions on ozone in the eastern United
- 592 States: Proof of concept. *J. Geophys. Res. Atmos.* **111**, D12306 (2006).
- 593 27. Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D. & Pozzer, A. The contribution of outdoor air
- 594 pollution sources to premature mortality on a global scale. *Nature* **525**, 367–371 (2015).
- 595 28. Shindell, D. & Faluvegi, G. The net climate impact of coal--red power plant emissions. *Atmos.*
- 596 *Chem. Phys.* **10**, 3247–3260 (2010).
- 597 29. Pétron, G., Tans, P., Frost, G., Chao, D. & Trainer, M. Highresolution emissions of CO₂ from
- 598 power generation in the USA. *J. Geophys. Res.* **113**, G04008 (2008).
- 599 30. Gurney, K. R. et al. High resolution fossil fuel combustion CO₂ emission fluxes for the United
- 600 States. *Environ. Sci. Technol.* **43**, 5535–5541 (2009).

-
- 601 31. Asefi-Najafabady, S. et al. A multiyear, global gridded fossil fuel CO₂ emission data product:
602 evaluation and analysis of results. *J. Geophys. Res.* **119**, 10213-10231 (2014).
- 603 32. Freudenburg, W. R. Privileged access, privileged accounts: toward a socially structured theory
604 of resources and discourses. *Soc. Forces* **84**, 89–114 (2005).
- 605 33. Grant, D., Jorgenson, A. & Longhofer, W. Targeting electricity's extreme polluters to reduce
606 energy-related CO₂ emissions. *J. Environ. Stud. Sci.* **3**, 376–380 (2013).
- 607 34. Jorgenson, A., Longhofer, W. & Grant, D. Disproportionality in power plants' carbon emissions:
608 a cross-national study. *Sci. Rep.* **6**, 28661 (2016).
- 609 35. *The Emissions & Generation Resource Integrated Database (eGRID)* (US Environmental
610 Protection Agency (USEPA), accessed on 15 December 2015);
611 <https://www.epa.gov/energy/egrid>
- 612 36. *World Electric Power Plant Database (WEPP)* (Platts, 2014).
- 613 37. Davis, S. J., Caldeira, K. & Matthews, H. D. Future CO₂ emissions and climate change from
614 existing energy infrastructure. *Science* **329**, 1330–1333 (2010).
- 615 38. Quadrelli, R. & Peterson, S. The energy–climate challenge: recent trends in CO₂ emissions from
616 fuel combustion. *Energy Policy* **35**, 5938–5952 (2007).
- 617 39. Haszeldine, R. S. Carbon capture and storage: how green can black be? *Science* **325**, 1647–
618 1652 (2009).
- 619 40. Power Plant Carbon Dioxide Capture and Storage Projects (accessed on 15 August 2017);
620 http://sequestration.mit.edu/tools/projects/index_capture.html
- 621 41. Smith, S. J. et al. Anthropogenic sulfur dioxide emissions: 1850–2005. *Atmos. Chem. Phys.* **11**,
622 1101–1116 (2011).
- 623 42. Buonocore, J. J. et al. Health and climate benefits of different energy-efficiency and renewable
624 energy choices. *Nat. Clim. Change* **6**, 100–105 (2016).
- 625 43. Zhang, Q. et al. Transboundary health impacts of transported global air pollution and
626 international trade. *Nature* **543**, 705–709 (2017).
- 627 44. Unger, N. et al. Attribution of climate forcing to economic sectors. *Proc. Natl Acad. Sci. USA*
628 **107**, 3382–3387 (2010).
- 629 45. Work Plan of Fully Implementing Ultra-low Emissions and Energy Savings by Coal-fired Power
630 Plants (in Chinese) (China's Ministry of Environmental Protection, 2016);

-
- 631 http://www.zhb.gov.cn/gkml/hbb/bwj/201512/t20151215_319170.htm
- 632 46. The Power Sector Development during the 13th Five-Year-Plan (in Chinese) (National Energy
633 Administration, 2016); http://www.gov.cn/xinwen/2016-11/07/content_5129638.htm
- 634 47. Wang, S. et al. Satellite measurements oversee China's sulfur dioxide emission reductions from
635 coal-fired power plants. *Environ. Res. Lett.* **10**, 114015 (2015).
- 636 48. Liu, H. & Liang, D. A review of clean energy innovation and technology transfer in China. *Renew.*
637 *Sust. Energ. Rev.* **18**, 486–498 (2013).
- 638 49. Liu, Z. et al. A low-carbon road map for China. *Nature* **500**, 143–145 (2013).
- 639 50. Seto, K. C. et al. Carbon lock-in: types, causes, and policy implications. *Annu. Rev. Environ.*
640 *Resour.* **41**, 425–452 (2016).
- 641 51. Ha-Duong, M., Grubb, M. J. & Hourcade, J. C. Influence of socioeconomic inertia and
642 uncertainty on optimal CO₂ emission abatement. *Nature* **390**, 270–273 (1997).
- 643 52. Maruyama, N. & Eckelman, M. J. Long-term trends of electric efficiencies in electricity
644 generation in developing countries. *Energy Policy* **37**, 1678–1686 (2009).
- 645 53. Liu, Z. et al. Reduced carbon emission estimates from fossil fuel combustion and cement
646 production in China. *Nature* **524**, 335–338 (2015).
- 647 54. 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006).
- 648 55. USEPA: Compilation of Air Pollutant Emission Factors (AP-42) (US Environmental Protection
649 Agency (USEPA), accessed on 15 December 2015); <http://www.epa.gov/ttn/chief/>
- 650 56. Zhang, Q. et al. Asian emissions in 2006 for the NASA INTEX-B mission. *Atmos. Chem. Phys.* **9**,
651 5131–5153 (2009).
- 652 57. Lu, Z. et al. Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000. *Atmos.*
653 *Chem. Phys.* **10**, 6311–6331 (2010).
- 654 58. Streets, D. G., Wu, Y. & Chin, M. Two-decadal aerosol trends as a likely explanation of the global
655 dimming/brightening transition. *Geophys. Res. Lett.* **33**, L15806 (2006).
- 656 59. Lu, Z., Zhang, Q. & Streets, D. G. Sulfur dioxide and primary carbonaceous aerosol emissions in
657 China and India, 1996–2010. *Atmos. Chem. Phys.* **11**, 9839–9864 (2011).
- 658 60. Streets, D. G. et al. An inventory of gaseous and primary aerosol emissions in Asia in the year
659 2000. *J. Geophys. Res.* **108**, D21 (2003).
- 660 61. Reddy, M. S. & Venkataraman, C. Inventory of aerosol and sulphur dioxide emissions from India.

-
- 661 Part II: biomass combustion. *Atmos. Environ.* **36**, 699–712 (2002).
- 662 62. Graus, W. H. J. & Worrell, E. Effects of SO₂ and NO_x control on energy-efficiency power
663 generation. *Energy Policy* **35**, 3898–3908 (2007).
- 664 63. Yao, W. Experiment on the SO₂ removal efficiency of wet scrubbers. *Environ. Protection* **2**, 11–
665 13 (1989).
- 666 64. Zhu, F., Liu, D. & Wang, S. Overview of NO_x emissions and control measures from thermal
667 power plants. *Environ. Protection* **21**, 40–41 (2009).
- 668 65. Zhao, Y., Wang, S., Nielsen, C. P., Li, X. & Hao, J. Establishment of a database of emissions factors
669 for atmospheric pollutants from Chinese coal-fired power plants. *Atmos. Environ.* **44**, 1515–
670 1523 (2010).
- 671 66. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2013: Technical Guidance to Prepare
672 National Emission Inventories EEA Technical Report 12/2013 (EMEP/EEA, 2013).
- 673 67. Nazari, S. et al. Experimental determination and analysis of CO₂, SO₂ and NO_x emissions factors
674 in Iran's thermal power plants. *Energy* **35**, 2992–2998 (2010).
- 675 68. Srivastava, R. K., Hall, R. E., Khan, S., Culligan, K. & Lani, B. W. Nitrogen oxides emission control
676 options for coal-fired electric utility boilers. *J. Air Waste Manage. Assoc.* **55**, 1367–1388 (2005).
- 677 69. Lei, Y., Zhang, Q., He, K. B. & Streets, D. G. Primary anthropogenic aerosol emission trends for
678 China, 1990–2005. *Atmos. Chem. Phys.* **11**, 931–954 (2011).
- 679 70. Klimont, Z. et al. Modelling Particulate Emissions in Europe: a Framework to Estimate Reduction
680 Potential and Control Costs IIASA interim report (IIASA, 2002).
- 681 71. Amann, M. et al. Cost-effective control of air quality and greenhouse gases in Europe: modeling
682 and policy applications. *Environ. Modell. Softw.* **26**, 1489–1501 (2011).



683

684

685

686

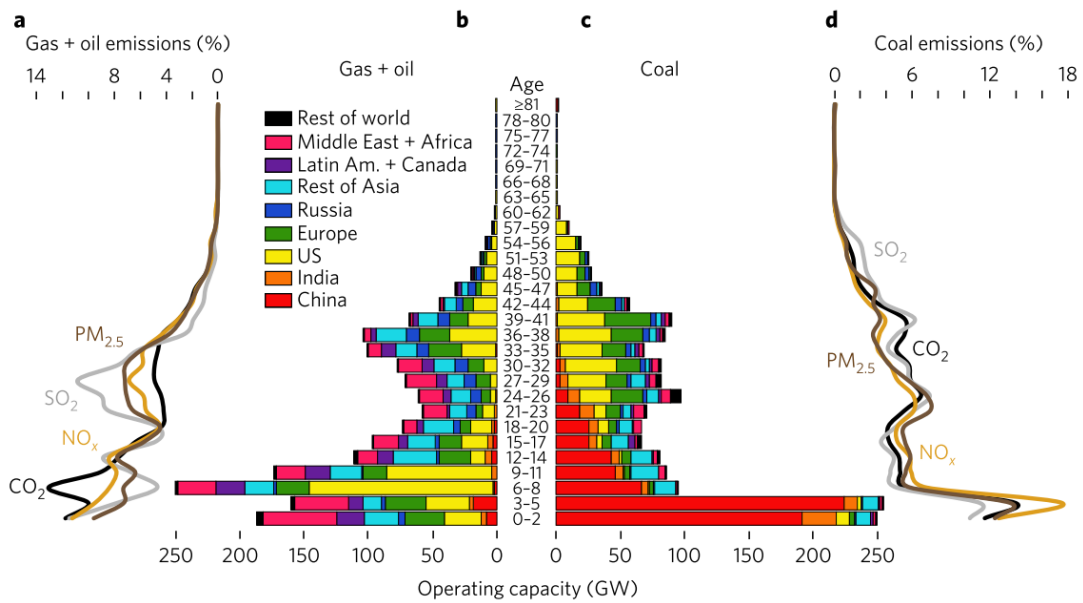
687

688

689

690

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).



691

692

693

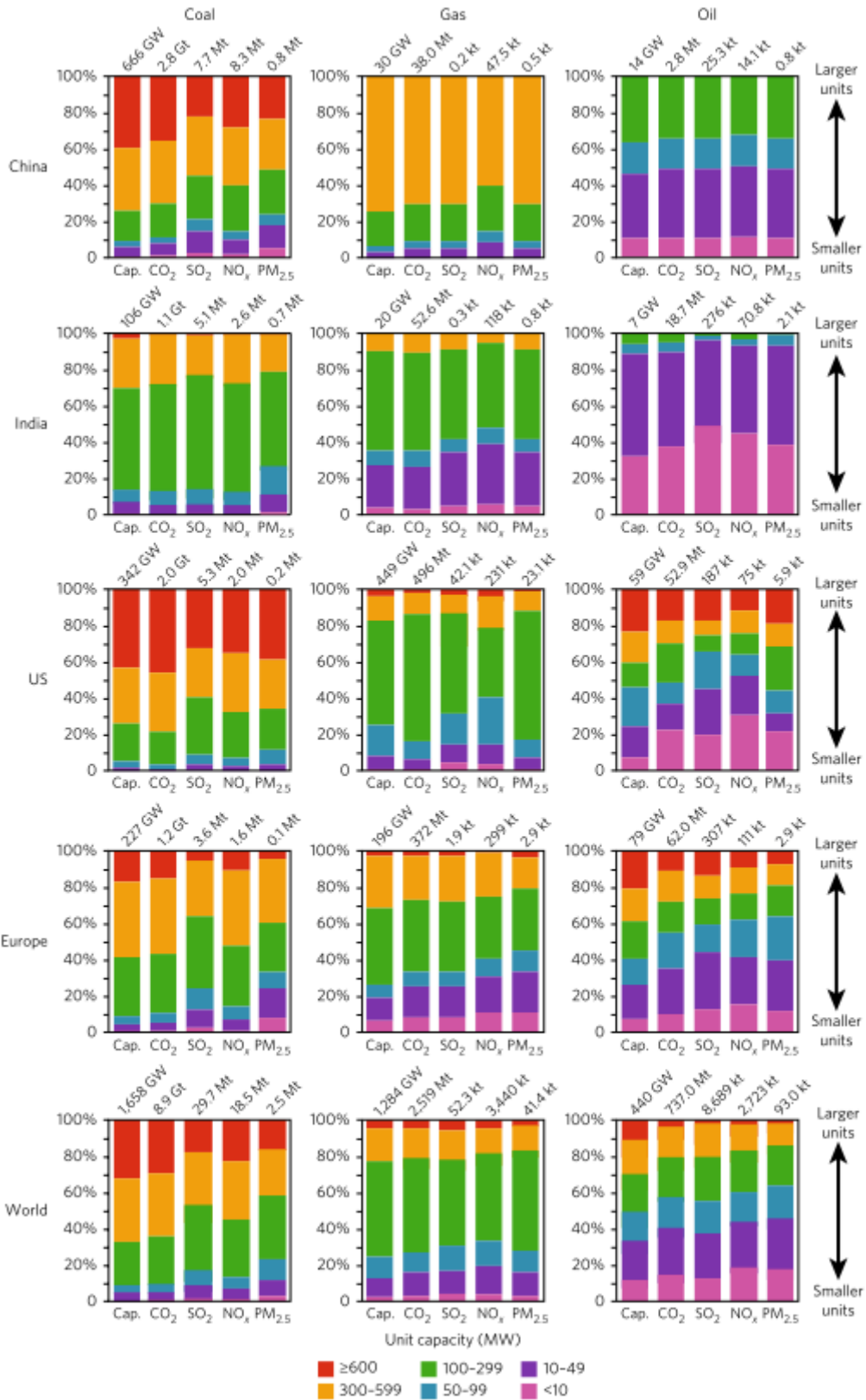
694

695

696

697

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.



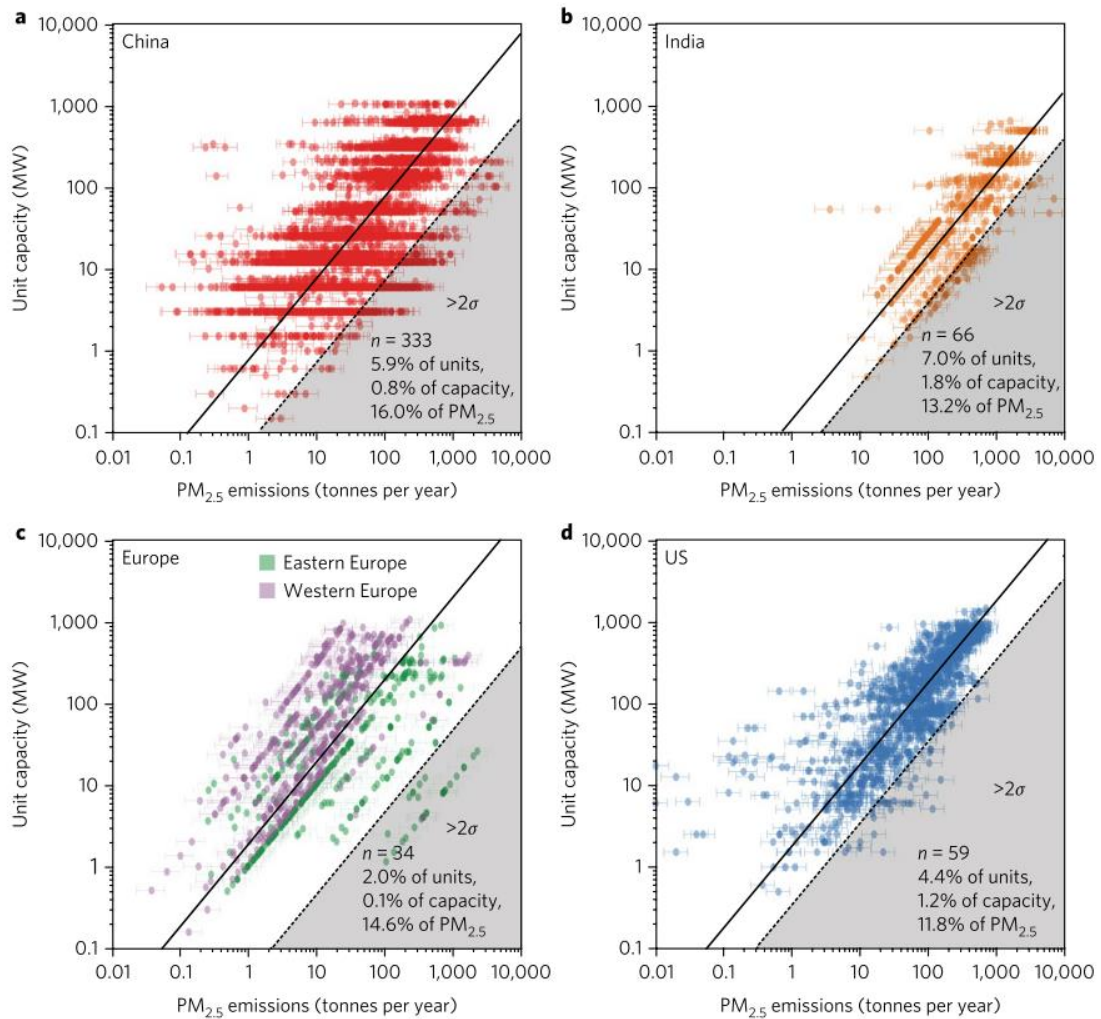
698

699

700

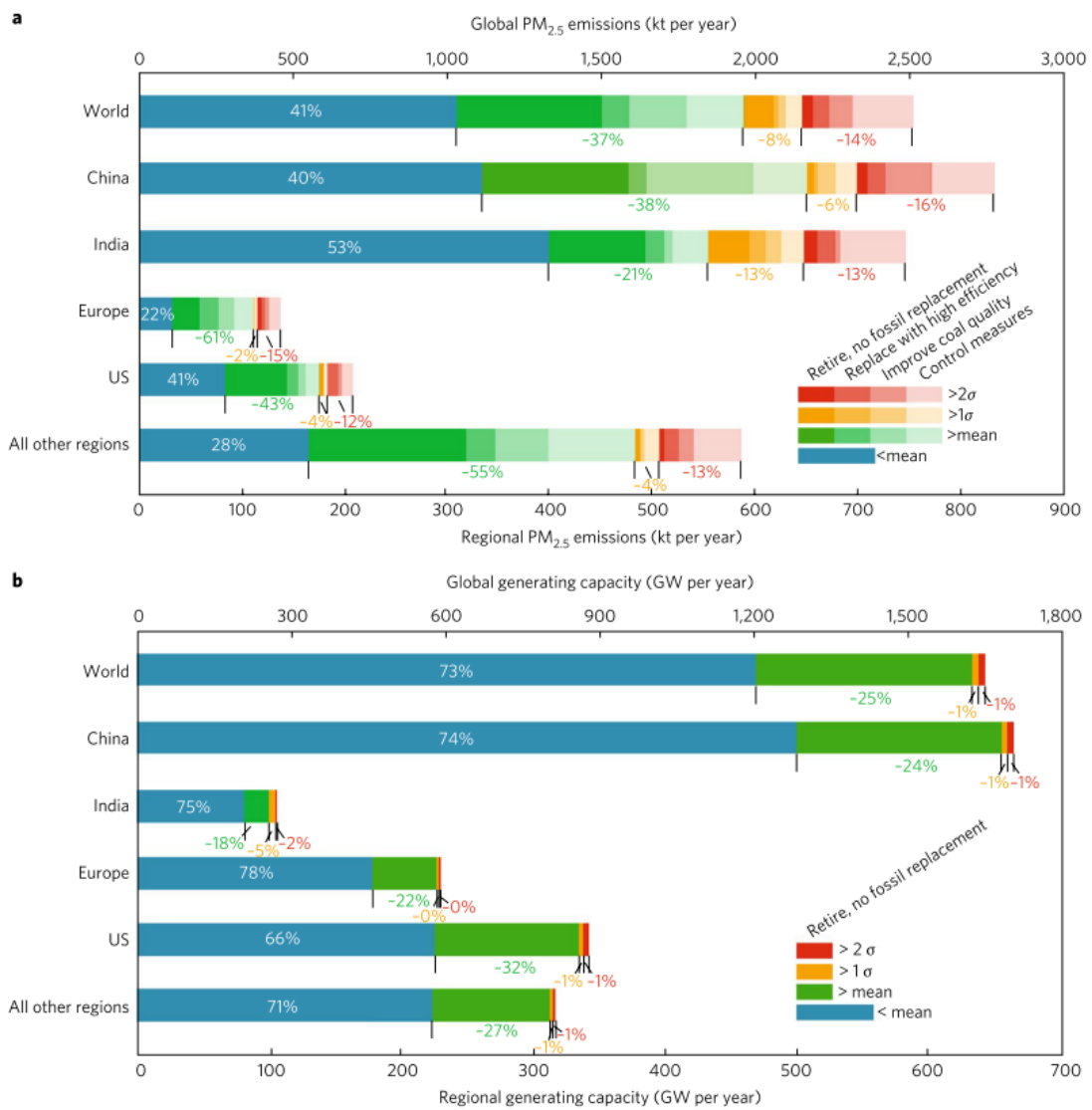
701

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, CO₂, SO₂, 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).



702

703 **Fig. 4 | Super-polluting units.** a–d, The data points represent individual coal-fired units in China (a),
 704 India (b), Europe (c), and the US (d), in each case plotted according to nameplate capacity (y axis) and
 705 annual PM_{2.5} emissions (x axis). Solid diagonal lines indicate the mean emission intensity (tonnes PM_{2.5}
 706 per MW) and shaded triangles indicate units whose emission intensity is 2σ above the mean. As noted
 707 in the panels, these units in each case represent < 7% of all coal-fired units but at least 12% of the
 708 PM_{2.5} emissions from all coal-fired units. Unit-level uncertainty ranges (95% confidence interval) of
 709 emission estimates in this work are also provided. Supplementary Figs. 3 and 4 show analogous plots
 710 for SO₂ and NO_x.



711
712
713
714
715
716
717
718
719
720
721

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).