A Decade of Action: A Strategic Approach for a Coal Phase-Down in China

Supplementary Information

March 2022

Data

Table S1. Data description

Variable	Dataset	Resolution	Year	URL
Technical attributes and locations of coal power plants	Global Coal Plant Tracker published by Global Energy Monitor (Jan 2021)[1] and authors' own data collection	Plant level	2020	https://endcoal.org/global-coal-plant-tracker/
Air pollutant emissions of SO2, NOx, and PM	Tang L et al., 2020[2]; Tang L et al., 2019[3]; Li J, et al. 2020[4]	Plant level	2020	https://www.nature.com/articles/s41597-020-00665-1
Overall water risk	Aqueduct Water Risk Global Maps 2.1 Data[5]	Polygons	2010	https://www.wri.org/resources/data-sets/aqueduct-global-maps-21-data
Electricity price	China Electricity Council (CEC), 2021.	Provincial level	2020	China Electricity Council (CEC). China Power Industry Annual Development Report 2019.
Operating hours	China Electricity Council (CEC), 2019.	Provincial level	2018	China Electricity Council (CEC). China Power Industry Annual Development Report 2019.
Coal price	China Coal Transportation and Distribution Association (CCTD), 2014-2019	Provincial level	2019	https://www.cctd.com.cn/index.php?m=content&c=index&a=lists&catid=520

[1] Global Coal Plant Tracker, Global Energy Monitor, Jan (2021).
[2] Tang, L., Xue, X., Qu, J. et al. Air pollution emissions from Chinese power plants based on the continuous emission monitoring systems network. Sci Data 7, 325 (2020). https://doi.org/10.1038/s41597-020-00665-1
[3] Tang, L., Qu, J., Mi, Z. et al. Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards. Nat Energy 4, 929–938 (2019). https://doi.org/10.1038/s41560-019-0468-1
[4] Li J, Cai W, Li H, et al. Incorporating health cobenefits in decision-making for the decommissioning of coal-fired power plants in China. Environ. Sci. Technol. 54, 13935–13943 (2020).
[5] Gassert, F., M. Luck, M. Landis, P. Reig, and T. Shiao. (2014). Aqueduct Global Maps 2.1: Constructing Decision-Relevant Global Water Risk Indicators. Working Paper. Washington, DC: World Resources Institute. Available online at http://www.wri.org/publication/aqueduct-globalmaps-21-indicators

Identification of LHF plants

Policy criteria

We conducted a plant–by-plant assessment of the coal retirement potential during China's 14th and 15th FYP. Based on the existing policies on plant closure, retrofitting, and new builds, and additional policy measures on national carbon emissions trading scheme, clean air action plan and water conservation targets, we developed a list of detailed near-term policy criteria to identify the low-hanging fruit (LHF) coal plants for rapid retirement through 2030.

Plant closure, retrofitting, and new builds

Existing policies require an immediate retirement of 1) non-CHP pure condensing units that are smaller than 100 MW, 2) units that are between 100 to 300 MW and exceed 30 years' lifetime, 3) small CHP units within a 15km radius of large CHP units (>=300MW) in the key regions for air pollution control, 4) units that have not completed low emission upgrading or do not meet the emission standard.

To implement the criteria from the existing policies on plant closure, retrofitting and new builds, we used the coal power plant data of vintage year, unit size, and geographic location from the coal power plant data from GCPT Jan 2021. We identified the CHP, and self-used coal plants based on the plants' full names, and cross validated using other data sources, e.g., coal plants in China's aluminum sector[6]. The key regions for air pollution control used in the criteria include the Beijing-Tianjin-Hebei (BTH) region (the "2 + 26" region), the Yangtze River Delta (YRD) and Fenwei Plain.

We identified 318 units, a total of 44 GW which meet the first two criteria for rapid closure through 2030, accounting for 4.3% of existing capacity. The third policy criteria from the three-year action plan for cleaner air identified 10 units, a total of 1.5 GW. Based on our data collection of coal power plants with efficiency retrofit and lifetime extension, up to 2021, 96 units, a total of 32 GW have completed flexibility retrofits and 28 units, about 8.3 GW have extended their lifetime for another 10 to 15 years.

National carbon emissions trading scheme

We assessed additional policy measures from the national carbon emissions trading scheme (ETS). To understand how the national ETS may affect individual coal plants through 2030, we calculate the gross profit of each plant under a range of carbon prices. Gross profit is estimated by the difference between the annual revenue and annual cost of the coal-fired power plants.

$$Net\,profit = Revenue - Cost \qquad \text{Equation 1}$$

[6] https://ember-climate.org/commentary/2021/02/07/china-aluminium-2020-emissions/

The annual revenue is estimated by electricity price and amount of electricity generated by the coal-fired power plants.

$$Revenue = P_{elecoal} * Q_{elecoal}$$ Equation 2

Where, $P_{eleccoal}$ is the electricity (sourced from coal) price by province, RMB/MWh. We used the 2019 province-level electricity price data from Beijixing website[7]. $Q_{eleccoal}$ is the electricity generated by coal power plants, MWh. $Q_{eleccoal}$ is estimated by the product of coal plant capacity (MW) and operating hours (hr). Plant-level capacity is derived from Global Coal Plant Tracker (Jan 2021), and operating hours are from China Electricity Council (CEC) for the year of 2018.[8] For Combined Heat and Power (CHP) plants, heat revenue is estimated to be 50% of the plant's electricity revenue.

The annual costs of coal-fired power plants are the sum of delivered fuel cost (*coalcost*), variable Operating and Maintenance (O&M) cost (*varOM*), fixed O&M costs (*fixOM*), and additional costs, including environmental costs and tax (*add*), as follows:

$$Cost = coalcost + carboncost + varOM + fixOM + add$$ Equation 3

Coal is the main fuel to support the operation for coal-fired power plants. It is calculated in Equation 3.

$$coalcost = coalcost_u / \alpha * H$$ Equation 4

coalcost is measured in the price of delivered coal, in which costs of purchasing and transportation are included. Unitary delivered coal price ($coalcost_u$) by province is from China Coal Transportation and Distribution Association (CCTD) in the year of 2020, in RMB/t.[9] α is standard coal consumption rate, referring to lower heating value (LHV), 27,778.62 Btu/t. H represents the heat rate, which is dependent on the technology, age, and size of the coal power plants, in Btu/kWh.[10]

$$H = H_{base} * \theta$$ Equation 5

Where, H_{base} denotes the base heat rate, dependent on the technology (Global Coal Plant Tracker) . θ is the adjustment multiplier, based on the size and age of the coal power plants, ranging from 1-1.45. The capacity-adjusted multipliers increase when capacity decreases. We assume the multiplier for plants with capacity ≥ 1000MW as 1, 600MW ≤ capacity < 1000MW as 1.05, 300MW ≤ capacity < 600MW as 1.1, and capacity <300MW as 1.15. Age effects on the

[7] https://m.solarbe.com/21-2670-320043-1.html

[8] China Electricity Council (CEC). China Power Industry Annual Development Report 2019.

[9] https://www.cctd.com.cn/show-46-199445-1.html

[10] Tong, D., Zhang, Q., Davis, S. J., Liu, F., Zheng, B., Geng, G., ... & Streets, D. G. (2018). Targeted emission reductions from global super-polluting power plant units. Nature Sustainability, 1(1), 59.

heat rate is linear on top of the capacity-adjusted heat rate, which is calculated by $H_{cap} + (age/100 - 0.15)$.[11]

$$carboncost = P_{carbon} * a * Annual\ CO_2 \quad \text{Equation 6}$$

$carboncost$ is the carbon cost of the coal plants, which includes the CO2 emission permits under ETS that the coal plants need to pay if their CO_2 emissions exceed the allocated amount. a is the auction rate. Specifically, for 2025, we assume a carbon price of 80 RMB/tCO2 and that 50% permits will be auctioned; and for 2030, we assume a carbon price of 100 RMB/tCO2 and that 75% permits will be auctioned.

The carbon prices are based on a market participants' expectation survey conducted by China Carbon Forum,[12] and the auction rates are based on a recent study on the national carbon pricing scheme in China.[13]

To assess the uncertainty of the carbon prices and auction rates, we conducted a sensitivity test across different carbon prices and auction rate levels. Between a carbon price of 80 RMB/tCO2e to 120 RMB/tCO2e with an auction rate of 50% to 75%, we find 1-153 GW of installed capacity, accounting for 0.1%-14.7% of the existing, will become financially vulnerable to the carbon price risk.

$Annual\ CO_2$ is estimated as CO2 emission rate at unit-level. CO2 emission rate refers to the amount of CO2 emitted per unit of electricity generation. The annual CO2 emissions are calculated as follows:

$$Annual\ CO_2 = elecgen * \gamma * H * E * c \quad \text{Equation 7}$$

$$elegen = Capacity * T \quad \text{Equation 8}$$

Where, $Annual\ CO_2$is the annual CO2 emissions, in Mt; $elecgen$ is the electricity generation, calculated by plant-level capacity (Capacity) and operating hours (T), in kWh/yr; γ is the conversion coefficient, 1.06×10^{-9} TJ/Btu; H represents the heat rate in Btu/kWh; E is the carbon content of coal in China, in tC/TJ . Carbon content is dependent on coal type, we used Aden et al. (2008) study to fill the missing data in the Global Coal Plant Tracker database. c is constant, which is equal to $12/44\times10^{-9}$.

The Operation and Maintenance (O&M) costs include the variable O&M cost (*varOM*) and fixed O&M (*fixOM*) cost. Variable O&M cost refers to long run marginal cost that measures the cost to produce a unit of electric energy, 2.76 $/MWh in this study; while fixed O&M cost captures the

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[11] International Energy Agency (IEA). (2012). Technology Roadmaps: High-efficiency, low-emissions coal-fired power generation. p.17.
[12] China Carbon. Survey of Carbon Prices in China (中国碳价调查). http://www.chinacarbon.info/wp-content/uploads/2020/12/2020-CCPS-CN.pdf (2020).
[13] Mo, J. et al. The role of national carbon pricing in phasing out China's coal power. iScience 24, 102655 (2021).

recurring annual cost that occurs regardless of the size or architecture of the power system, 11.03 \$/kW/yr.[14]

$$varOM = varOM_u * Q_{elecoal} \quad \text{Equation 9}$$

$$fixOM = fixOM_u * Capacity \quad \text{Equation 10}$$

Additional costs (add) mainly include environmental costs and tax. Environmental cost is 0.006 RMB/kWh.[15]

By quantifying the gross profit which includes the cost of generating electricity and carbon costs, we identified four plants (1.3 GW) in 2025 and 179 plants (61.8 GW) in 2030 which may not be able to cover the operation costs with their revenues.

Clean air action plan

We identified super polluting plants as candidates for near-term retirements as the LHF plants. By using multiple sources of plant level air pollutants emissions data,[16,17] and Global Coal Plant Tracker (GCPT) coal power plant database, we developed a plant level dataset of air pollutant emissions. Three main air pollutants are considered in this analysis, namely sulfur dioxide (SO2), nitrous oxide (NOx) and fine particulate matter (PM2.5). Using this dataset, we identified the plants with the top 10% and 20% highest emission intensities for each pollutant, in terms of kilogram per MWh power generated, as super polluters to be phased out by 2025 and 2030 respectively (Figure S1). The total is 85.8 GW for retirement in 2025, and 31 GW in 2030.

[14] Miao, B. (2015). Outlook of Power Generation Technology Cost in China. Norwgian School of Economics, Bergen.

[15] Yuan, J., Hu, Z., Zhang, W. (2016). National Development and Reform Commission (NDRC, 2014). The 2005 National GHG Inventory of China.

[16] Li, J. *et al.* Incorporating Health Cobenefits in Decision-Making for the Decommissioning of Coal-Fired Power Plants in China. *Environ. Sci. Technol.* **54**, 13935–13943 (2020).

[17] Tang, L. *et al.* Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards. *Nat Energy* **4**, 929–938 (2019).

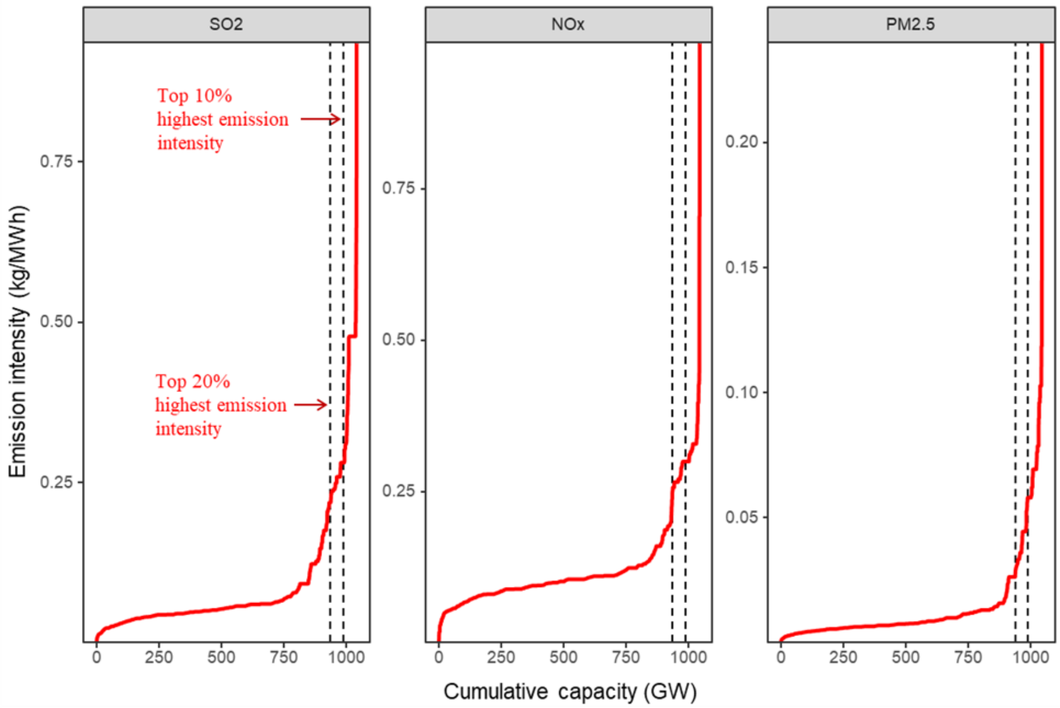

Figure S1 Unit level air pollutant emission intensities of SO2, NOx and PM2.5

Water conservation targets

First, we identify the cooling technology of each coal plant. Air cooling information at the plant level before 2012 are from Zhang et al. (2014) and we assume air cooling technology will be fully deployed in Gansu, Shanxi, Shaanxi, Inner Mongolia, Ningxia after 2009 and in Xinjiang after 2013, based on the provincial-level policy. For all other plants, we assume water cooling technology will be deployed. Second, we identify the water-stressed regions using the water stress index developed by Aqueduct. We mark regions with a water stress index above 4.0 as high water stress and above 4.2 as extremely high water stress. With this information, we find plants located in water-stressed regions but equipped with water-intensive cooling technologies. We use the water stress index above 4.2, an extremely high standard, as the cutoff for 2025 retirement; and above 4.0, a high standard, as the cutoff for 2030 retirement.

Low-hanging fruit (LHF) plants

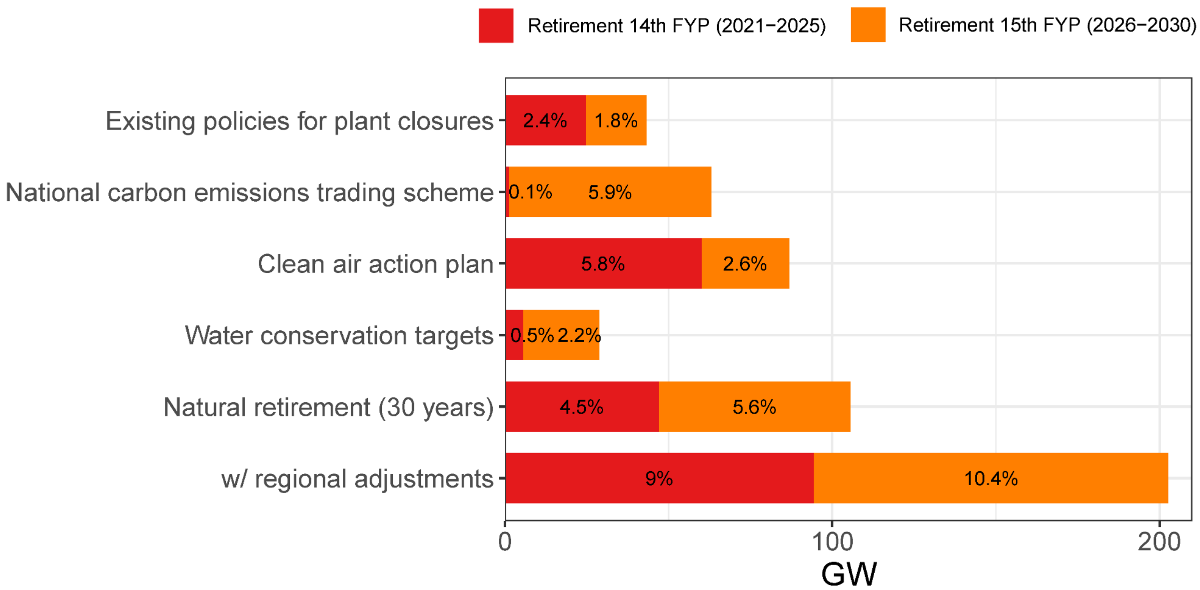

Figure S2. LHF plants identified for closure during China's 14th and 15th Five-Year Plan by each policy measure.

Combining multiple policy measures from the national carbon emissions trading scheme, clean air action plan, water conservation targets, and plant age, 1,040 (34,8%) coal power generation units with a total of 203 (19.4%) GW installed capacity are identified as LHF plants for near-term retirement by in China's 14th and 15th FYP period (Figure S2). 9% of existing capacity (95 GW, 577 units) is scheduled to retire during the 14th FYP, mostly driven by the implementation of clean air action plans. The other 10.4% of existing capacity (108 GW, 463 units) is scheduled to retire during the 15th FYP, mostly driven by the implementation of the national ETS and water conservation targets.

Using only the policy measure from the national carbon emissions trading scheme, a total of 86.9 GW (6.0%) are required to retire rapidly by 2030. Under the air quality measure, the numbers are 183 plants (17%) and 63 GW (6%). Identified by the water risk criteria, 92 plants (8.5%), 28.9 GW (2.8%) need to retire by 2030. Additionally, 227 plants (21%) with a total capacity of 106 GW (10%) will reach their 30-yr designed lifetime by 2030 and are identified as LHF plants.

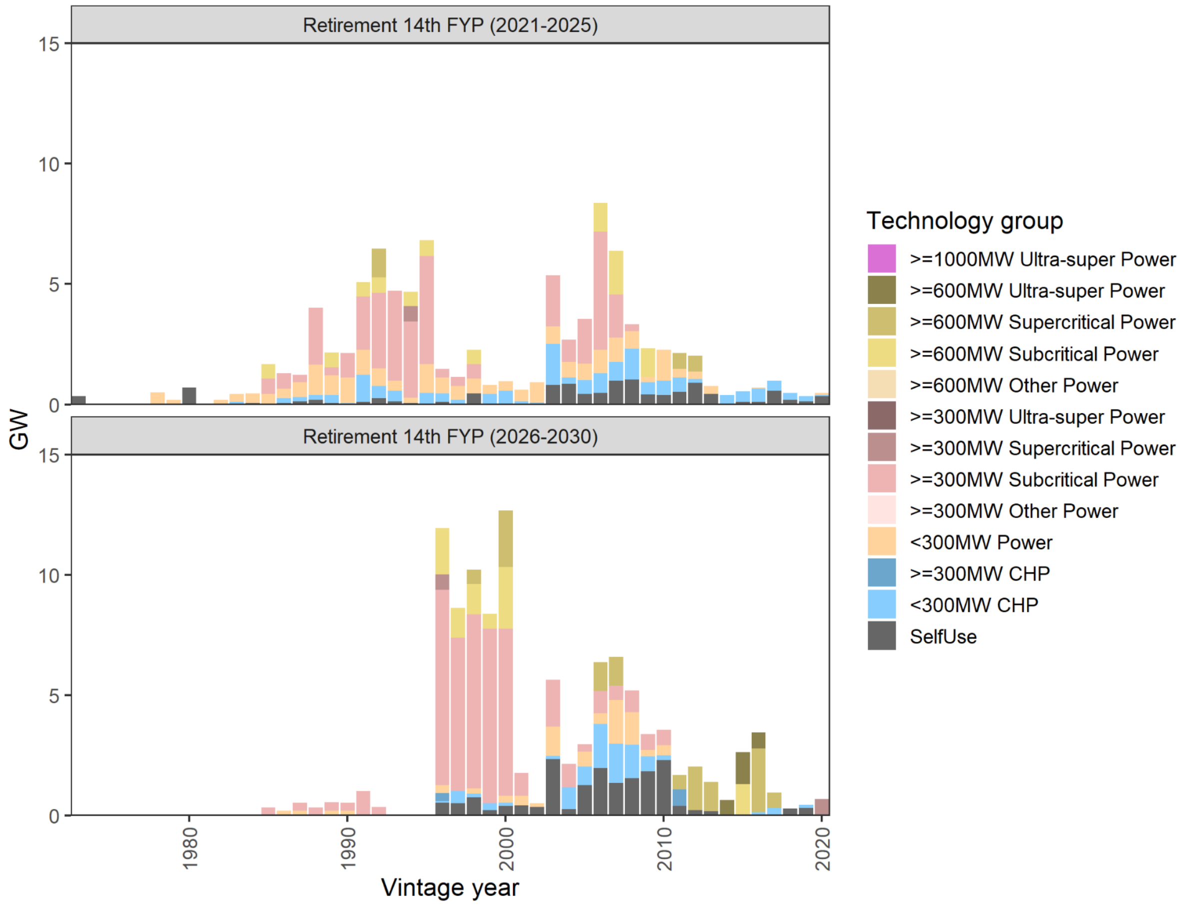

Figure S3. Technology groups of the LHF plants

The identified LHF plants are generally smaller, older, and less efficient, compared to the remaining coal fleet (Figure S3). Over half (52%) of the LHF plants have capacity smaller than 300MW, about 92% are smaller than 600MW, and none are 1000MW or larger. By retiring these plants, the remaining coal fleet is left with only 14% of the capacity smaller than 300MW. Moreover, about 63% of the LHF plants capacity has been operating more than 15 years as of 2021, and will be aged at least 20 years by the time of retirement. This ratio for the remaining non-LHF plants capacity is less than 7%. The vast majority (about 90%) of the LHF plants' capacity is equipped with less efficient subcritical combustion technology. This ratio decreases to 36% in the remaining non-LHF plants. Lastly, LHF plants capacity includes 14% for self-use plants, 13% for combined heat and power (CHP) plants, and the remaining for power generation plants.

Quantification of benefits and risks of LHF plant retirement

Carbon emissions reduction

Carbon emissions reduction from retiring the LHF units is calculated as the sum of carbon emissions of each of the LHF units (Equation 11). CO2 emissions for each unit are calculated based on Equation 7.

$$Annual\ CO_2\ reduction = \sum_i Annual\ CO_2^{\,i} \qquad \text{Equation 11}$$

where $Annual\ CO_2\ reduction$ is the annual CO2 emissions reduction from retiring the LHF units; $Annual\ CO_2^{\,i}$ is the annual CO2 emissions for unit *i*.

Air pollutant emissions reduction

By using multiple sources of plant level air pollutants emissions data[18][19], and Global Coal Plant Tracker (GCPT) coal power plant database, we developed a plant level dataset of air pollutant emissions. Three main air pollutants are considered in this analysis, namely sulfur dioxide (SO2), nitrous oxide (NOx) and fine particulate matter (PM2.5).

We estimate air pollutants emission reduction from retiring LHF plants by adding up reduced emissions from each of the retired units. These metrics can measure the benefits in air quality improvement for each province, especially in air quality control key areas.

Water savings

Following the national standard for water withdrawals in coal power plants released by the Ministry of Water Resources (see Table S2), we calculate annual water consumption for retiring LHF plants to measure water savings from retiring coal power plants at provincial level and evaluate the impact of water savings at high water stress areas. First, we estimate annual water withdrawals for each coal power plant based on multiple factors, including generating technology, annual generation, cooling technology, national standard for water withdrawals in coal power plants. Second, we estimate annual water savings by adding up reduced water withdrawals from retired coal power plants.

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[18] Tang, L. *et al.* Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards. *Nat Energy* **4**, 929–938 (2019).
[19] Li, J. *et al.* Incorporating Health Cobenefits in Decision-Making for the Decommissioning of Coal-Fired Power Plants in China. *Environ. Sci. Technol.* **54**, 13935–13943 (2020).

Table S2. Standards for water withdrawal per kW electricity generation by cooling technology, unit size for coal power plants.

Cooling Technology	Cooling Type	Size	Advance (m3/kW)	High (m3/kW)	Standard (m3/kW)
Circulating Water Cooling	Water	<300MW	1.73	1.85	3.2
Circulating Water Cooling	Water	300MW	1.6	1.7	2.7
Circulating Water Cooling	Water	600MW	1.54	1.65	2.35
Circulating Water Cooling	Water	1000MW	1.52	1.6	2.35
Once-through Water Cooling	-	<300MW	0.25	0.3	0.72
Once-through Water Cooling	-	300MW	0.22	0.28	0.49
Once-through Water Cooling	-	600MW	0.2	0.24	0.42
Once-through Water Cooling	-	1000MW	0.19	0.22	0.57
Air Cooling	Air	<300MW	0.3	0.32	0.8
Air Cooling	Air	300MW	0.23	0.3	0.57
Air Cooling	Air	600MW	0.22	0.27	0.49
Air Cooling	Air	1000MW	0.21	0.24	0.42

Stranded assets

We measure stranded value for each coal power plant using the remaining value of premature retired plants. A straight-line depreciation method to calculate remaining value of premature retired plants assuming 30 yr designed economic lifetime.

$$stranded\ assets\ value_r = \sum_{1}^{N} \left(OCC \times K \times \frac{(L-R)}{L}\right)_{i,r} \qquad \text{Equation 12}$$

Where OCC indicates overnight capital cost of the power plant, K indicates capacity, L indicates expected lifetime, and R indicates retirement age of each plant. Where i indicates each individual technology in BRI region r, and N means the total number of technologies.

Table S3. Overnight capital cost of coal power plant by combustion technology

Combustion	Overnight capital cost (yuan/kW)
Subcritical	4443

Supercritical	3900
Ultra-super	3540
Unknown	4443
CFB	4800
IGCC	8900

Using this information , we quantify the stranded value of each early retired coal power plant (both absolute and relative value) and therefore evaluate the economic impact of premature retirement at company and provincial level.

Employment

Here we quantify the total numbers of job losses and the affected groups, and their locations caused by shutting down LFH plants. In this report, we mainly focus on the operation and maintenance (O&M) jobs in the coal-fired power plants which are the most directly impacted when shutting down these plants. We calculate the O&M employment of coal power plants as the production of capacity in MW and job coefficient per MW.

The job coefficients are obtained from the Job Impact Model for China Power System (JIMC) model[20]. The JIMC model classifies coal power plants into five categories based on their installation sizes, namely <100MW, 100-300 MW, 300-600 MW, 600-1000 MW and ≥1000 MW, and collects China-specific job coefficients for each category. Given the fact that labor productivity differs substantially in small and large coal power plants, specific job coefficients for each category of plants, rather than one unified average job factor, could better reflect the current status of coal power plant employment in China. The adoption of the China-specific job coefficients also enables a more detailed plant-by-plant estimation especially for the existing coal fleet in China.

$$Employment_i^{OM} = \sum_t CC_i \cdot EF_{i,t}^{OM} \quad \text{Equation 13}$$

where $Employment_i^{OM}$ is the operation and maintenance employment in coal fired power unit *i*; CC_i indicates the installed capacity of unit *i* of technology *t*; Here we classify coal power technology into five categories based on their installation size: <100MW, 100-300 MW, 300-600 MW, 600-1000 MW and ≥1000 MW. $EF_{i,t}^{OM}$ is the job coefficients for unit *i* of technology category *t*.

[20] Zhang X, Cui X, Li B, et al. Immediate actions on coal phaseout enable a just low-carbon transition in China's power sector. Applied Energy, 308: 118401 (2022).