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Managing China's coal power plants to address multiple environmental objectives

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China needs to manage its coal-dominated power system to curb carbon emissions, as well as to address local environmental priorities such as air pollution and water stress. Here we examine three province-level scenarios for 2030 that represent various electricity demand and low-carbon infrastructure development pathways. For each scenario, we optimize coal power generation strategies to minimize the sum of national total coal power generation cost, inter-regional transmission cost and air pollution and water costs. We consider existing environmental regulations on coal power plants, as well as varying prices for air pollutant emissions and water to monetize the environmental costs. Comparing 2030 to 2015, we find lower CO_2 emissions only in the scenarios with substantial renewable generation or low projected electricity demand. Meanwhile, in all three 2030 scenarios, we observe lower air pollution and water impacts than were recorded in 2015 when current regulations and prices for air pollutant emissions and water are imposed on coal power plants. Increasing the price of air pollutant emissions or water alone can lead to a tradeoff between these two objectives, mainly driven by differences between air pollution-oriented and water-oriented transmission system designs that influence where coal power plants will be built and retired.

Fossil-based electricity generation not only has large carbon emissions, but also has important implications for local air quality (due to emissions of primary and reactive air pollutants) and water stress (due to cooling needs). Power sector strategies are thus central to address climate, air pollution and water issues. For instance, increasing the generation from low-carbon sources, such as wind, solar and nuclear, can mitigate carbon emissions, while simultaneously bringing air quality and health co-benefits by reducing emissions of air pollutants from fossil-based generation[1–4]. Influences on water stress, however, depend on the choice of low-carbon technology because some technologies such as nuclear and bioenergy power plants can be more water-intensive than coal units[5–9].

Furthermore, fossil-based generation can reduce its carbon and environmental impacts by adjusting power plant configurations. Installing end-of-pipe control devices and dry cooling systems can substantially decrease air pollutant emissions and water use from coal units, though these retrofits lower plant efficiency, leading to increases in CO_2 emissions. Post-combustion carbon capture and storage can significantly mitigate CO_2 emissions from coal-fired power plants, at the expense of higher costs, larger cooling water use and lower thermal efficiency (which increases air pollutant emissions per unit electric output)[10]. In addition, since air pollution and water stress levels are often spatially heterogeneous, transmitting electricity into polluted and water-stressed areas changes the location of generation activities, so the impacts of fossil generation can be avoided in regions where reducing air pollution and water stress is most urgent[11,12].

China is a key country to examine power system strategy and the implications on carbon, air pollution and water. It is currently the world's top carbon emitter[13] and also suffers from serious air pollution[14,15] as well as increasingly severe water stress[16]. On the one hand, China is expected to experience major transitions in its electricity system, due to projected rapid growth in electricity demand and low-carbon infrastructure. On the other hand, China has the world's largest existing coal generation fleet, with more than 70% of current electricity generation coming from coal[17]. Since coal power generation contributes to substantial CO_2 emissions, air pollution and water impacts, it is a central challenge for China to manage its existing coal fleet and curb new additions in the future.

We focus on the following questions in this study: how should China manage its coal-dominated electricity system to address CO_2, air pollution and water conservation objectives in the future? More specifically, how would the coal power system respond to more stringent air pollution and/or water policies under various future energy development scenarios?

While the impacts of CO_2 emissions are global, air pollution and water stress are largely local concerns and can vary substantially across regions within a country (Fig. 1). Although most existing studies examine the air pollution or water implications in isolation[1–3,5,7,8], we consider them simultaneously. We focus on the provincial variations in air pollution and water stress levels, and demonstrate how improving air quality in pollution centers may favor different coal generation and transmission configurations than those aimed at reducing water stress in water-scarce areas.

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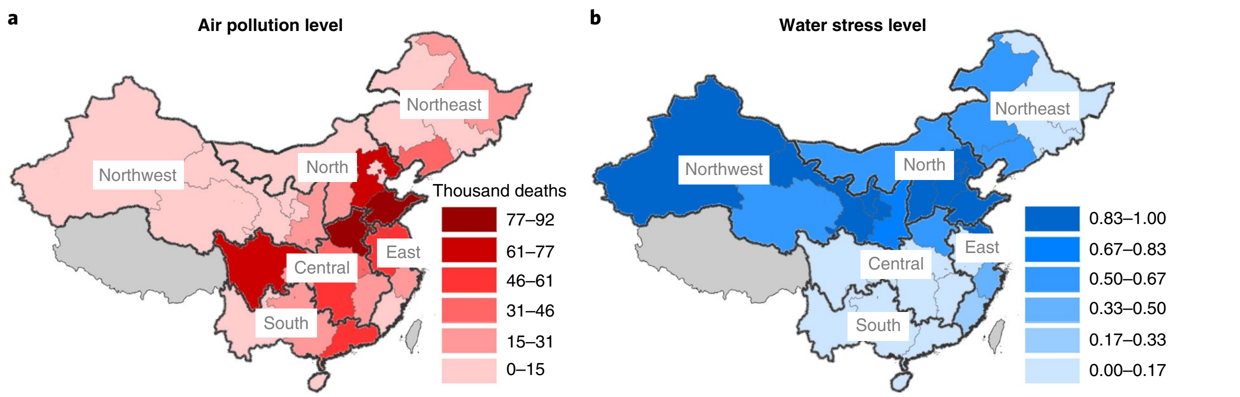

Fig. 1 | Spatial distribution of air pollution and water stress in China. a, Air-pollution-related deaths in 2010 by province (data from ref. [12]). **b**, Present-day water stress index by province (WSI, data from ref. [47]). Water stress is defined as the ratio of annual total consumptive freshwater use to annual average freshwater availability. WSI ranges from 0 (no stress) to 1 (maximum), following a logistic function. The six regional power grids are indicated with bold black lines and include the Northwest Grid, North Grid, Northeast Grid, Central Grid, South Grid, and East Grid. Individual provinces are indicated with lighter grey lines.

Furthermore, many countries, including China, are gradually strengthening their air pollution and water policies due to increasing concerns about the local environment. The relative weight given to these two issues depends on perceived urgency. For example, driven by record-high smog events in eastern urban centres, in recent years China has significantly tightened its air pollution control policies nationwide, with more stringent targets in major metropolitan regions[18,19]. Meanwhile, the policies to tackle water stress, such as water prices, have not changed significantly. Here we examine the effect of strengthening air pollution and water policies individually or simultaneously. We do this by increasing the prices associated with emitting air pollutants and of using water. These increased prices are a proxy for higher marginal cost to achieve greater reductions in air pollutant emissions and water use, essentially increasing the economic evaluation of these impacts. We assess how the interactions between air pollution and water prices would affect coal strategies. Understanding these interactions is important for policymakers to coordinate energy and environmental policies, and to tackle air pollution, water and climate issues simultaneously.

In this study, we first design three province-level scenarios for 2030 to represent plausible electricity demand and infrastructure development pathways. For each scenario, we optimize coal strategies, including plant configurations (for example, end-of-pipe controls and cooling technologies) and the location of generation with the help of transmission (for example, whether coal generation occurs in polluted or water-stressed regions). The objective is to minimize the sum of national total coal power generation cost, inter-regional transmission cost (assuming perfect transmission within an electricity regional grid) and air pollution and water costs. We consider existing environmental regulations, as well as higher prices for air pollutant emissions and water to monetize the environmental costs. We model deployment decisions and impacts at the province level because provincial governments play an important role in approving or closing coal units and in making local air pollution and water policies under national guidelines.

Results

2030 scenarios. We design three province-level scenarios for 2030 based on the reference scenarios developed by the International Energy Agency (IEA)[20], the Chinese Energy Research Institute (ERI)[21] and the US Energy Information Administration[22] (more details in Method and Supplementary Note 1). These scenarios all assume a continuation of current trends and policies, but vary in future energy demand and low-carbon infrastructure development levels. They are called Moderate (IEA projection), High Renewables (ERI projection) and Low Demand (Energy Information Administration projection), respectively, in this study (Fig. 2a). The High Renewables scenario projects 7% less coal power generation in 2030 than 2015, while the Moderate and Low Demand scenarios project a 26 and 4% increase, respectively.

We then use the regional 2030 projections by the ERI and present-day spatial patterns of total generation to estimate the provincial distributions of electricity demand and low-carbon deployment in 2030 (Fig. 2b). Wind and solar generation in 2030 are projected to be more uniformly distributed across China than today. This reflects the recent shift from installing renewable capacity primarily in renewable-abundant but sparsely populated regions to deploying it closer to demand centres where grid integration is easier. Nuclear generation is projected to be concentrated in coastal regions that can use seawater for cooling (for example, 45 and 35% of total generation located in the East and South Grid). Significant public concern about inland nuclear plants has resulted in recent approvals only at coastal locations[23].

To further assess coal deployment strategies, we hold constant the electricity demand and non-coal generation in each scenario, and optimize the plant configuration and location of coal power plants to minimize the sum of annual total coal power generation cost, inter-regional transmission cost, as well as air pollution and water costs. The air pollution cost is quantified by multiplying population density-weighted SO_2 and NO_x emissions with varying prices for air pollutant emissions. We use population density weight to capture the greater health impacts of air pollutant emissions in populous regions. The water cost is quantified by multiplying water stress index- (WSI-)weighted water consumption with varying water prices. We use WSI weight to reflect the greater impacts of water consumption in water-scarce regions. Since water is treated as an economic good valued by its market price, we monetize water consumption, the portion of water that is lost during the cooling process and the operation of wet flue gas desulfurization, rather than water withdrawal, of which a large portion can be returned to the source and be used again. To consider the seasonality of water supply, we also impose a constraint on water withdrawal using the projected 2030 surface water availability[24] both for the annual average and the driest month (see Supplementary Note 5 and Fig. 16). We find that this constraint does not affect our main results.

Comparing 2030 to 2015, we find 15% higher national total CO_2 emissions in the Moderate scenario, but 15 and 5% lower CO_2 emissions in the High Renewables and Low Demand scenarios,

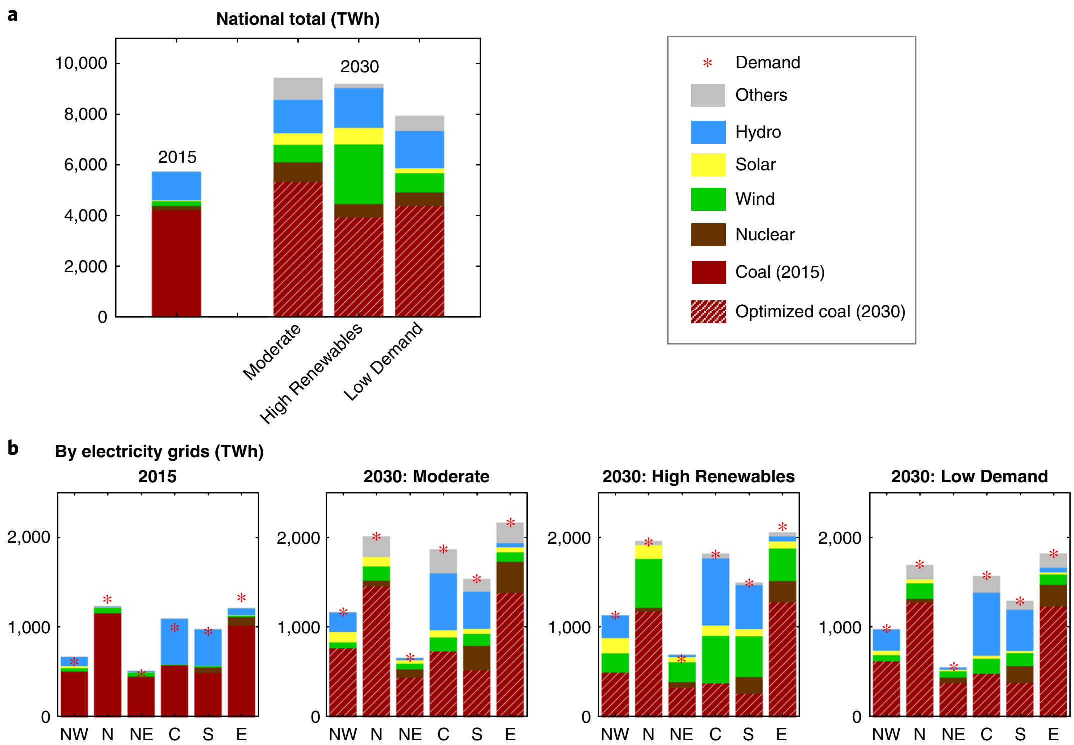

Fig. 2 | National and regional electricity generation mix in 2015 and in 2030 scenarios under existing environmental policies. Existing environmental policies include current air pollution and cooling system regulations, as well as present-day emission charges and water prices. For the Moderate, High Renewables and Low Demand scenarios, the generation from non-coal sources (solid bars), as well as grid-total demand (red stars), are inferred from the 2030 projections by IEA, ERI and EIA, respectively. The optimized coal power generation (hatched dark red bars) and the amount of inter-regional transmission (the difference between the total local generation and demand) are determined by a province-level optimization model that optimizes the location, generation and configuration of coal power plants operational in 2030 with the aim of minimizing the annual total generation, transmission, air pollution and water costs relative to 2015.

respectively (grey bars in Fig. 3). These trends are driven by the changes in the amount of coal power generation and the average efficiency of the coal fleet. On the one hand, national total coal power generation is 7% lower than 2015 in the 2030 High Renewables scenario, but is 26 and 4% higher in the Moderate and Low Demand scenario, respectively. On the other hand, in all three scenarios we observe an increasing share of supercritical and ultra-supercritical units in the 2030 coal fleet, leading to higher average efficiency and lower CO_2 emissions per unit of electricity generated than 2015. Due to a combination of these two factors, the percentage reduction (or increase) in CO_2 emissions is greater (or smaller) than that for coal power generation.

National impacts under existing environmental policies. We consider current regulations and present-day prices as existing environmental policies. We model regulations on pollution controls nationwide[18,19] and dry cooling systems in northern water-stressed regions[25] by setting constraints on plant configuration choices in affected provinces. We also quantify the air pollution and water cost using present-day national-average emission charges (US\$200 per ton for sulfur dioxide, SO_2, and nitrogen oxide, NO_x, emissions from power plants[26]) and water prices for non-residential users (US\$0.50 per m^3 (ref. [27]), see water prices for selected Chinese cities in Supplementary Table 9).

Compared to 2015, we find lower air pollution impacts, measured by population density-weighted SO_2 and NO_x, and reduced water impacts, measured by WSI-weighted water consumption, in all three 2030 scenarios. Among the three scenarios, the lowest air pollution and water impacts are found in the High Renewables scenario, due to a higher share of renewables and thus lower air pollutant emissions and water consumption per unit electricity output (see Supplementary Note 3 and Figs. 8 and 9). The population density-weighted SO_2 and NO_x emissions, are 50, 58 and 56% lower in the Moderate, High Renewables and Low Demand scenarios than in 2015, mainly because nearly all coal units in 2030 are projected to be equipped with control devices under existing air pollution policies. The reduced coal power generation in the High Renewables and Low Demand scenarios further reduces the air pollution impacts compared to 2015. The WSI-weighted water consumption are 45, 58 and 55% lower in the Moderate, High Renewables and Low Demand scenarios than 2015. These reductions in water impacts are achieved by: (1) increased installation of dry cooling systems in the water-stressed regions as required by existing regulations, (2) reduced coal power generation in the High Renewables and Low Demand scenarios and (3) siting nuclear power plants in coastal regions and using seawater for cooling.

Although electricity transmission could allow the displacement of coal power generation in more polluted or water-stressed regions, under existing environmental policies, we observe no inter-regional transmission in the Moderate and Low Demand scenarios, and only a small amount of transmission in the High Renewables scenario. This indicates that current prices of air pollutant emissions and water are too low to justify inter-regional transmission costs (Fig. 2b). Electricity transmission across regions, though critical for renewable integration, does not seem to be a cost-effective strategy to tackle air pollution and water stress issues under current valuations of air pollution and water.

National impacts under strengthened environmental policies. We evaluate the effect of more stringent environmental policy by

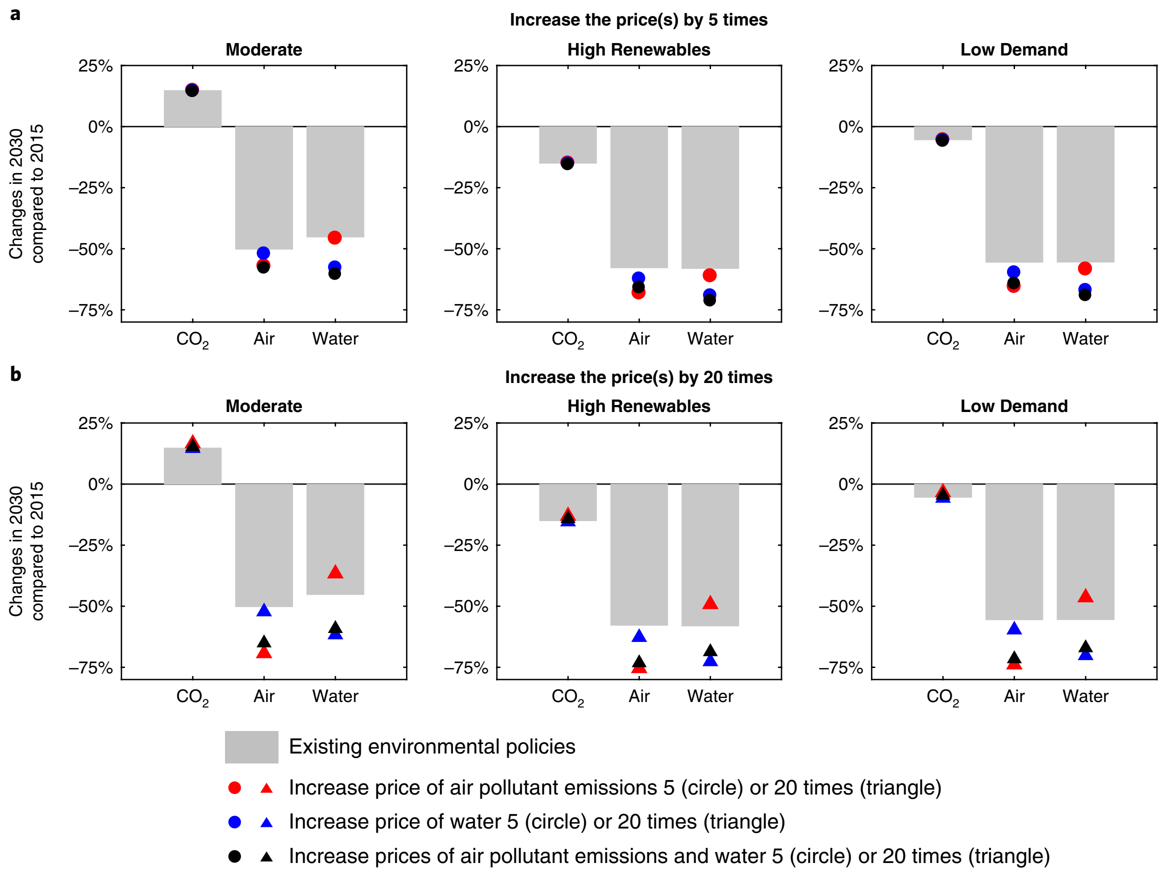

Fig. 3 | Percentage changes in national total CO_2 emissions, air pollution impacts (Air, population density-weighted air pollutant emissions) and water impacts (Water, WSI-weighted water consumption) in the 2030 scenarios compared to 2015. The grey bars indicate the results under existing environmental policies; that is, existing regulations and current prices. **a**,**b**, The circles (**a**) and triangles (**b**) indicate the results with existing regulations combined with higher pricing for air pollution and/or water (that is, 5 and 20 times the present-day levels, respectively).

combining current regulations with increasing prices of air pollutant emissions and/or water use. While the environmental policies in China traditionally rely on command-and-control regulations, market-oriented policy instruments, such as pricing, are becoming increasingly relevant. Here, we increase prices to 5 or 20 times the 2015 levels. A 20-times higher air pollutant emission charge (that is, US\$4,000 per ton) is comparable to the damage costs found in China (see Supplementary Table 10 for a literature review). A 20-times higher water price (that is, US\$10 per m^3) is roughly the same as current water prices in western Europe[27]. These high valuations therefore are still plausible for policymakers to consider.

We find that national total CO_2 emissions are not significantly affected by increasing prices for air pollutant emissions or water. As air pollutant or water prices increase, we find more deployment of large-size, efficient coal units, which increases the average efficiency of the coal fleet (see Supplementary Fig. 5). Meanwhile, a higher price for water encourages more installation of dry cooling systems, leading to an efficiency penalty of 1–2% and hence a small increase in CO_2 emissions. However, these changes in CO_2 emissions in response to higher air pollution/water prices are negligible compared to the total reduction that can be achieved from the three 2030 scenarios relative to 2015.

Nationally, we find reduced air pollution impacts as the price of air pollutant emissions increases. For the Moderate, High Renewables and Low Demand scenario, increasing the price of air pollutant emissions by five (or 20) times leads, respectively, to 14% (or 38%), 24% (or 42%) and 22% (or 42%) more reduction in population density-weighted emissions relative to those under existing environmental policies. These reductions are mainly due to increased electricity transmission into polluted population centres, because displacing coal power generation with imported electricity brings more air pollution and human health benefits from reduced air pollution when occurring in populous regions (for example, East and Central Grid). Similarly, we observe greater reductions in water impacts as the water price increases, mainly attributable to higher penetration rates of water-saving cooling system in water-stressed provinces (see Supplementary Figs. 6 and 7). For instance, compared to existing environmental policies, increasing the water price by five (or 20) times leads to 23% (or 30%), 26% (or 35%) and 26% (or 33%) more reduction in WSI-weighted water consumption in the Moderate, High Renewables and Low Demand scenario, respectively.

However, increasing only the price of air pollutant emissions reduces air pollution impacts more than when current prices are used, but at the expense of less reduction in water impacts (red and blue circles/triangles in Fig. 3). For instance, comparing the Moderate scenario results under 20 times higher air pollution prices to those under existing environmental policies, we find 42% lower air pollution impacts (measured by population density-weighted air pollutant emissions), but 16% greater water impacts (measured by WSI-weighted water consumption). Such results are driven by differences in the choices of coal plant configurations and transmission system designs. First, a higher price of air pollutant emissions and water encourages more installation of air pollution control devices and dry cooling systems on the coal power fleet, respectively. Since these two technology choices are largely independent, a higher price on one does not necessarily facilitate a shift in technology to

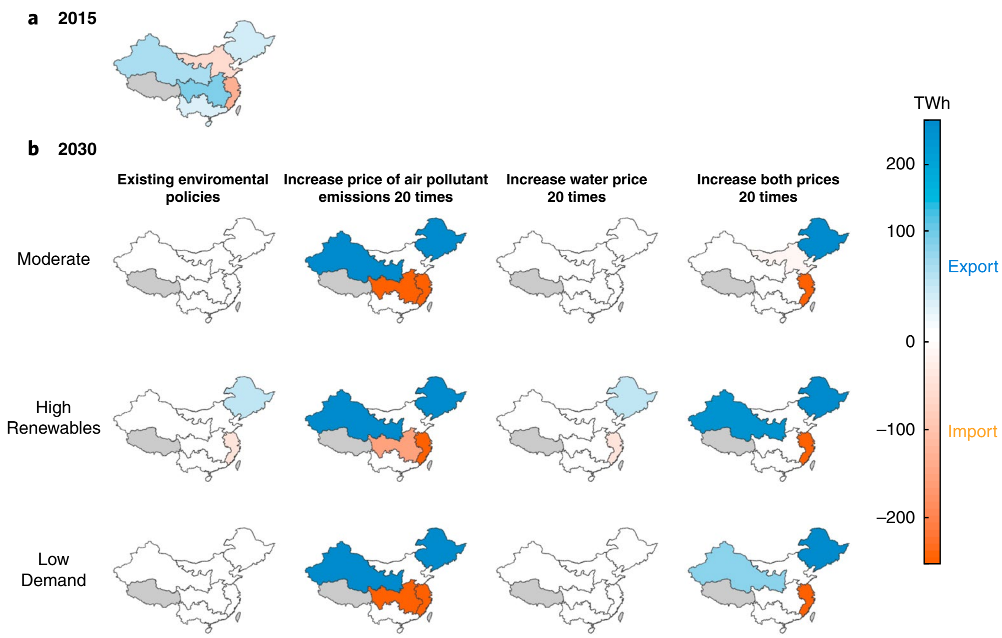

Fig. 4 | Inter-regional electricity transmission pattern. **a**,**b**, The 2015 (**a**) and 2030 (**b**) scenarios with existing environmental policies and 20 times higher prices for air pollutant emissions and/or water consumption. Blue indicates net export and orange indicates net import. The transmission pattern with five times higher prices is presented in Supplementary Fig. 1.

address the other. Second, a higher price on air pollutant emissions encourages more electricity transmission from the Northwest and Northeast Grid into population centres in Central and East China (Fig. 4). Meanwhile, a higher water price up to 20 times the present-day level favours displacing coal power generation in water-stressed but less-polluted regions (for example, Northwest and Northeast Grid), which avoids electricity export from these regions. The trade-offs become more important when the unit transmission cost is lower. With lower transmission costs, the inter-regional transmission decisions are more sensitive to changes in the valuations for air pollution and water, resulting in larger differences between air-pollution-oriented and water-oriented transmission decisions and therefore greater trade-offs between the two goals (Supplementary Note 4 and Figs. 10–13).

With higher prices for both, we observe greater reductions in both air pollution and water impacts than under existing environmental policies. The impacts under increased prices for both are often between the two cases where only one price is increased. However, increasing both prices by five times leads to the greatest reductions in air pollution and water impacts, because it not only encourages more installation of dry cooling systems, but also changes the location of coal power generation within each grid to reduce generation in provinces that are both polluted and water-stressed compared to other provinces in the same grid. Our findings thus underscore the importance of simultaneously strengthening air pollution and water policies to curb both air pollution and water impacts from the electricity system.

Regional distribution of impacts. Since the three scenarios represent different pathways for electricity demand and low-carbon energy development, they project different regional generation mixes in 2030, as well as the changes in regional CO_2 emissions and environmental impacts relative to 2015 (Fig. 5a). Under existing environmental policies, the Moderate scenario projects more coal power generation in 2030 than 2015 in all six grid regions, while the High Renewables and Low Demand scenarios project increases (for example, the East Grid) and decreases in different grid regions (for example, Central and South Grid). Such differences in projected coal power generation lead to different regional patterns of CO_2 emissions across the three scenarios. In comparison, the regional patterns for air pollution and water impacts are more similar because they are affected by technology choices (for example, end-of-pipe controls and cooling system) and coal generation location, more than by the quantity of coal power generation. Under existing environmental policies, all three scenarios reduce air pollution impacts in the East Grid the most, while reducing the water impacts in the North Grid the most.

An increase in the air pollution or water price results in additional distributional considerations across regions: increasing the price of air pollutant emissions mainly benefits the polluted regions (for example, East and Central Grid), while increasing the water price largely benefits the regions that are water-stressed (for example, Northwest, North, East Grid). For example, in the Moderate scenario, compared to the results under existing environmental policies (Fig. 5b), increasing the price of air pollutant emissions by 20 times significantly reduces CO_2 emissions and air pollution impacts in the East Grid (−50 and −46%) as more local coal power generation is replaced by imported electricity, while increasing the CO_2 and air pollution impacts in the Northwest Grid (+16% and +25%) as the electricity export from this region increases. In comparison, increasing the water price by 20 times reduces the water impacts throughout the East, Central, North and Northwest Grid regions.

When the prices of air pollutant emissions and water are simultaneously increased by 20 times, we find lower air pollution impacts in polluted regions, as well as lower water impacts in most water-stressed regions. Therefore, while raising only one price reduces the air pollution or water impacts in some regions at the expense of increasing the impacts in others, raising both prices can largely avoid such trade-offs between regions and address regional equity concerns.

In addition, the geographic patterns of the case that raises both prices are more similar to the case that raises only the water price than the case that raises only air pollution price. Most notably, when the water price is increased alone or together with the air pollution price, the water-stressed Northwest Grid does not export electricity to other regions to avoid generating additional coal power locally.

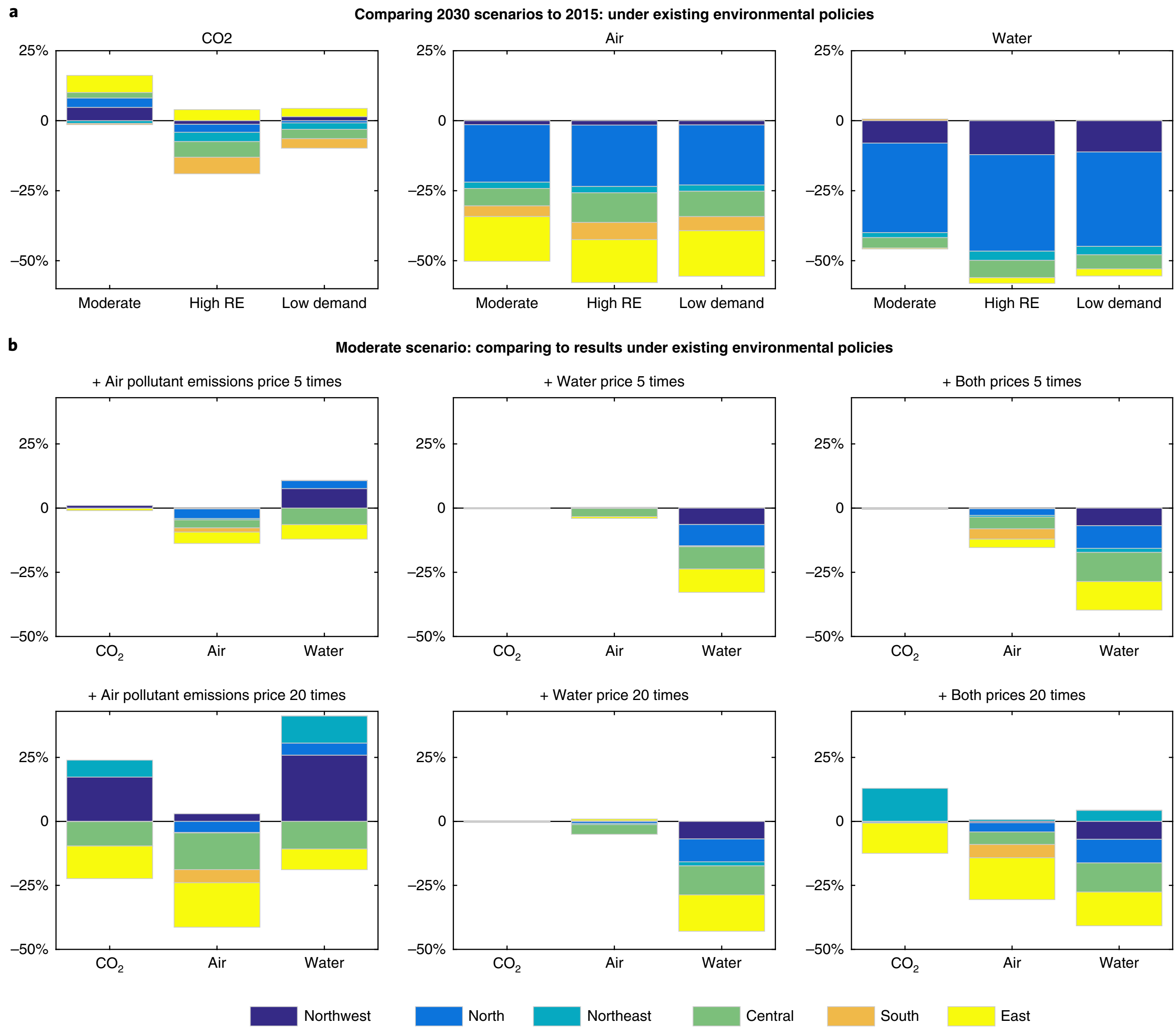

Fig. 5 | Regional distributions of changes in CO_2 emissions, air pollution impacts (Air, population density-weighted air pollutant emissions) and water impacts (Water, WSI-weighted water consumption). a, Comparing 2030 scenarios to 2015: under existing environmental policies. The three scenarios are Moderate, High RE (renewables) and Low Demand. **b**, Moderate scenario: comparing 2030 results under 5 and 20 times higher prices for air pollutant emissions and water consumption with those under existing environmental policies. See the results for other two scenarios in Supplementary Figs 2 and 3.

Such transmission patterns are different from the case that increases the price of air pollutant emissions alone. It hence suggests that with current prices as the benchmark, increasing water price may have a stronger impact on inter-regional transmission than proportionally increasing air pollution pricing (for example, same percentage increase).

Discussion and conclusions

Our analysis indicates that the CO_2 impacts of China's electricity system in 2030 are largely determined by the projected electricity demand level and the share of low-carbon generation in the future power mix. Compared to 2015, we find lower CO_2 emissions for the 2030 scenarios with substantial renewable generation or relatively low projected electricity demand. In comparison, the air pollution and water use implications are affected not only by future demand levels and low-carbon deployments, but also by the stringency of air pollution and water policies that would affect the decisions on coal and transmission system. For all three energy development scenarios, we find substantial reductions in air pollution and water impacts relative to 2015, when existing environmental policies are enforced on coal power plants. However, increasing the price of air pollution or water in isolation may lead to a tradeoff between air quality and water conservation benefits at the national level, as well as winners and losers at the subnational level. This is largely because air pollution and water stress occur in different parts of China, leading to differences in air pollution- and water-oriented designs for the transmission and coal system. Strengthening air pollution and water policies simultaneously by raising the prices for both not only reduces more air pollution and water impacts nationally, but also lessens the trade-offs between regions. Besides coal, a previous study on China's natural gas industry also identified potential trade-offs between multiple environmental objectives[28]. These analyses thus highlight the importance of coordinating air pollution, water and energy policies to tackle local environmental concerns and address regional equity concerns.

Though we focus on China in this analysis, an integrated view is also critical for other countries to align their power sector strategies with their carbon, air pollution and water conservation goals. The air pollution–water tradeoff exists largely due to the regional variations in low-carbon resources, air pollution and water scarcity. India, for example, has high air pollution levels in its northern provinces[15], while more than half of the country faces high to extremely high water stress, particularly in the northwestern regions[29]. Meanwhile, ambitious solar power installation is taking place especially in the western provinces. Depending on the government's priority on air pollution, water and carbon mitigation, the optimal decisions for low-carbon deployment, coal power plants and transmission designs will also vary, leading to potential trade-offs similar to those identified here for China. Therefore, integrating both air quality and water concerns into power system strategies could guide efforts in China and many other countries to better align local environmental objectives with carbon mitigation action.

To fully characterize the complex interactions between power sector decisions and environmental policies there is a need to develop integrated multi-scale, multi-sector models. We suggest four directions for future research. First, while our analysis only considers annual total impacts, higher spatial and temporal resolution could provide additional information on electricity sector designs and environmental impacts. For instance, electricity demand and renewable energy supply have large seasonal and diurnal variations; demand-side measures could change the load curves in real time; the air pollution and water impacts are affected not only by short-term and seasonal variations in meteorology and hydrological availability[11,30–32], but also by cross-boundary transport through wind and river flows. Second, here we explore three different low-carbon deployment scenarios and then focus on the remaining decisions on coal power and transmission system deployment. Future analyses could simultaneously model the decisions on the coal system, transmission system, low-carbon generation and demand-side measures. Optimizing low-carbon generation can be especially important because the total power system costs will largely depend on the future capital and operational costs for low-carbon technologies, as well as the transmission and integration costs for variable renewable sources (see Supplementary Fig. 4 for a summary of power system costs and Supplementary Figs. 10–15 for a sensitivity analysis on lower and higher unit transmission cost). Third, there are other environmental policies that target the electricity sector but are not considered in our analysis, such as standards on surface water temperature variations due to discharged thermal effluents. The effects of these policies will probably interact with future climate change, due to the changes in hydrological cycle, water availability and water temperature[32–34]. Finally, it would be valuable to expand this single-year, static analysis to a long-term, dynamic planning model (examples of capacity expansion models for China include He et al.[35], Blair et al.[36] and Huang et al.[8]). Many factors are likely to evolve over time: the costs of renewable technologies may decrease in the future; the level of water stress may intensify due to climate change and demand growth[37,38]; the political pressures on governments to reduce air pollution, water use or carbon emissions will vary with time. Integrating these environmental objectives may also change the optimal timing and technological choices for power sector investments. A dynamic perspective could guide present-day investment and policy decisions that have long-term implications.

Method

Coal power system configurations in 2015. The provincial total coal power generation is taken from the China Electric Power Statistical Yearbook 2016[39] (more details in Supplementary Table 3). Within each province, we estimate the age distribution and relative share of subcritical and ultra-/supercritical coal units by aggregating the plant-level data compiled by CoalSwarm[40]. The penetration rates of air pollution control devices are based on the province-level data for 2015 in the ECLIPSE dataset[41] (ECLIPSE_v5a_CLE_base), developed by the International Institute for Applied Systems Analysis. The penetration rates of cooling technologies in each province are based on the 2014 data reported in Liao et al. 2016[42].

2030 scenarios. The national total projections for the Moderate, High Renewables and Low Demand scenarios are based on the 2030 projections by International Energy Agency (Current Policy Scenario in the World Energy Outlook 2017[20]), the Chinese Energy Research Institute (Current Policy Scenario in the China Renewable Energy Outlook 2017[21]) and US Energy Information Administration (Reference Case, International Energy Outlook 2017[22]). Among the three scenarios, the Low Demand scenario projects the lowest electricity demand and the High Renewables scenario projects the most rapid increase in wind and solar energy (more details in Supplementary Note 1 and Table 1). These differences in electricity demand and share of low-carbon electricity affect the associated CO_2 emissions, air pollutant emissions and water use.

To estimate the provincial generation of each non-coal source, we first allocate the national total generation to six electricity grids on the basis of the regional patterns projected by the ERI and further allocate the grid-total amount to provinces on the basis of the generation pattern in 2015. The regional projections by the ERI consider socioeconomic drivers (such as population growth, urbanization rate and so on) that determine future demand, as well as resource and technology availability that affect electricity supply technology choices (more details in Supplementary Note 1).

Optimization framework for the coal system. Based on non-linear optimization functions in MATLAB, for each 2030 scenario, we hold electricity demand and non-coal generation constant, and optimize coal power system configurations in each province (that is, plant configuration, quantity of coal power generation), as well as inter-regional electricity transmission (assuming perfect transmission within a grid). The objective is to minimize the sum of the annualized national total coal power generation, inter-regional transmission, air pollution and water costs.

Specifically, let J denote the set of coal plant configurations $j=1,2,\ldots,48$, which include two types of coal-fired power plants (subcritical, ultra-/supercritical), three types of SO_2 control technology (wet flue gas desulfurization, limestone injection and low sulfur coal), one type of NO_x control technology (selective catalytic reduction) and three types of cooling systems (once-through, wet cooling tower and dry cooling systems). We do not consider coal power plants with carbon capture and storage in this study. Let I represent the set of provinces $i=1,2,\ldots,31$ in mainland China that belong to the six regional electricity grids (excluding Tibet; Inner Mongolia is divided into two sub-regions that belong to the North and Northeast Grid, respectively). Let G_k denote the set of provinces in regional grid $k=1, 2, \ldots, 6$.

Objective function. The objective function is $\min_{x_{i,j}}(G+T+A+W)$, where $x_{i,j}$ is the amount of electricity production from coal power plant configuration j in province i (in units of MWh).

Here G is the national total coal power generation costs $\sum_{i\in I}\sum_{j\in J}\mathrm{LCOE}_{i,j}\cdot x_{i,j}$, where $\mathrm{LCOE}_{i,j}$ is the levelized cost of electricity (LCOE) for coal power plant configuration j in province i (excluding water cost, in units of US$ per MWh; more information is given in Supplementary Table 6). We first calculate the levelized cost of electricity for plant configuration without end-of-pipe control devices and with wet cooling towers, based on the projected capital costs and non-fuel operational costs for 2030 in IEA 2017 (ref. [20]) and province-specific coal prices in 2015 (Supplementary Table 7). Then for other coal power plant configurations in the same electricity grid region, we adjust for the efficiency penalty and cost escalation based on the percentage changes calculated using a power plant modelling tool, the Integrated Environmental Control Model (IECM) v9.0.1 (ref. [43]) with region-specific inputs for climate variables and fuel prices (Supplementary Table 8).

T is the national total inter-regional transmission costs $B\cdot\frac{1}{2}\cdot\sum_{k\in K}\mathrm{abs}\left(\sum_{i\in G_k}\sum_{j\in J}x_{i,j}+Y_k-D_k\right)$. Here B is the unit cost of inter-regional transmission ($B=$ US$10 per MWh), based on the magnitude of present-day inter-regional transmission cost values in the literature[44] and government documents[45]. See Supplementary Note 4 and Figs. 10–15 for results using a higher or lower unit cost, US$20 and US$5 per MWh. Y_k and D_k are the total non-coal generation and electricity demand in grid k (in units of MWh), both of which are determined by the scenario.

A is the national total air pollution costs $p_{\mathrm{em}}\cdot\sum_{i\in I}\mathrm{EM}_{\mathrm{PD-weighted},\,i}$, where p_{em} is the unit price of air pollutant emissions (in units of US$ per ton SO_2 or NO_x emissions). The current emission charges for power plants are roughly US$200 per ton SO_2 or NO_x (ref. [27]). $\mathrm{EM}_{\mathrm{PD-weighted},i}$ is the population density-weighted air pollutant emissions in province i, defined as $\sum_{j\in J}(\mathrm{EF}_{\mathrm{SO_2}_{i,j}}\cdot x_{i,j}+\mathrm{EF}_{\mathrm{NOx}_{i,j}}\cdot x_{i,j})\cdot\mathrm{PD\_wt}_i$. $\mathrm{EF}_{\mathrm{SO2}_{i,j}}$ and $\mathrm{EF}_{\mathrm{NOx}_{i,j}}$ represent SO_2 and NO_x emission factors for coal power plant configuration j in province i (in units of kton per MWh, Supplementary Table 4). The air pollutant emission factors per unit electricity output are based on the ECLIPSE dataset and the respective net plant efficiency calculated by IECM. PD_wt_i is the population density weight for province i, calculated as the ratio of the population density in province i and the national average projected for 2030 (Supplementary Table 2).

W is the national total water costs $p_w \cdot \sum_{i \in I} W_{WSI-weighted,\,i}$, where p_w is the unit water price (in units of US$ per m^3). Since water prices vary across provinces and cities (see Supplementary Table 9 for a summary), we estimate the magnitude for current national-average water price for non-residential users to be roughly US$0.5 per m^3. $W_{WSI-weighted,i}$ is the WSI-weighted water consumption in province i, defined as $\left(\sum_{j \in J} WC_{i,j} \cdot x_{i,j}\right) \cdot WSI\_WT_i$. $WC_{i,j}$ represents the water consumption rate for coal power plant configuration j in province i (in units of m^3 per MWh, Supplementary Table 5). The water consumption rates for pulverized power plants with wet cooling tower or dry cooling system are calculated by IECM, with considerations on region-specific climate conditions (relative humidity and temperature) that may affect cooling system operations. For pulverized coal power plants with a once-through system, we use the median estimates for the water consumption rates reported in ref. [46]. WSI_WT_i is the province-specific weight, calculated as the ratio of provincial and national WSI reported in Feng et al. 2014[47], based on present-day demand and historical water availability (Fig. 1b). They follow the definition of WSI in Pfister et al.[48] to use a logistic function to represent water stress level, which is defined as the ratio of annual total consumptive freshwater use to annual average freshwater availability. The mathematical form is presented in Supplementary Equations 1 and 2.

Constraints.

1. Energy balance: for each grid region, the electricity demand should be met by the sum of local generation from coal and non-coal sources, plus net import. We assume 5% of the electricity being transmitted across regions is lost in the transmission process.
2. Range for provincial total coal power generation: for each province, total coal power output in 2030 is no less than the amount generated from existing coal units that were built after 2010.
3. Range for specific coal plant configurations: on the basis of recent regulations[18,19,25], we assume the coal power generation from the following configurations cannot be greater than the 2015 level: (a) subcritical units, (b) plants without SO_2 or NO_x control and (c) coal units that locate in northern water-stressed regions, but do not use the dry cooling system. For other configurations, the province-total output should be no greater than an upper limit calculated as the output from the capacity in 2015 plus cumulative additions from 2015 to 2030 at an annual rate of 718 GW per year (that is, the highest annual provincial addition rate in 2015 found in the Anhui province; data source: *China Electric Power Statistical Yearbook 2016*[39]).
4. Reliability: to avoid grid reliability threats posed by intermittent generation, for each regional grid, the share of annual total wind and solar generation should be no more than 40% of the total generation.
5. Water withdrawal (see sensitivity analysis in Supplementary Note 5 and Supplementary Fig. 16): annual provincial total water withdrawal should be no greater than the projected surface water availability in 2030[24] based on the annual average supply or the supply in the driest month.

Code availability. The MATLAB codes for the optimization model developed are available from the corresponding authors upon request.

Data availability

Data used to perform this study can be found in the Supplementary Information. Any further data that support the findings of this study are available from the corresponding authors upon request.

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Author contributions
W.P., F.W. and D.L.M. designed the study. W.P. performed the research. F.W., M.V.R., H.Z, M.J.S., C.D. and X.Z. contributed data and analysis tools. W.P. and D.L.M wrote the initial manuscript and all authors contributed to subsequent revisions.

Competing interests
The authors declare no competing interests.

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