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A DECADE OF ACTION: A STRATEGIC APPROACH TO COAL PHASE-DOWN FOR CHINA

ENVIRONMENTAL AND SOCIOECONOMIC BENEFITS OF TARGETED COAL RETIREMENTS IN CHINA'S 14TH AND 15TH FIVE-YEAR PLANS

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SUMMARY FOR POLICYMAKERS

A successful transition away from coal to clean energy is the central pillar of China's strategy to achieve carbon neutrality before 2060—and will be critical to keep a global 1.5° Celsius (C) pathway within reach. Yet recent trends are raising uncertainties for the critical period of 2020-2030 and even diverging from what is needed to achieve China's own internal goals embedded in the five-year plans. A feasible and practical strategy to address this can be driven by the existing five year planning processes and policy priorities, to carefully structure an orderly phase-down of coal coupled with feasible levels of accelerating renewable energy, energy efficiency, transmission, and load balancing.

Recent high-level policy statements from China have highlighted its willingness and interest to initiate a transition in its own economy in support of these global and national goals. Framing its overall trajectory are its latest Nationally Determined Contribution (NDC) and Long-Term Strategy (LTS), which signal China's intent to achieve carbon emissions peaking before 2030 and carbon neutrality before 2060. The more detailed action plans in the "1+N" policy framework provide a process for elaborating strategies to implement these goals. In these plans, for example, China has committed to "strictly control" new coal power projects and coal consumption over the 14th Five-Year Plan (2021-2025) (FYP) period, start to phase it down during the 15th FYP (2026-2030), and stop building coal power projects overseas. Notably, new commitments in the U.S.-China Joint Glasgow Declaration (2021) have also opened the opportunity to accelerate the work of reducing coal consumption.

Yet, despite these broad outlines and signals toward an overall gradual peaking and reduction of coal consumption, increasing policy emphasis on energy stability and security—and associated plans to build new coal power generation capacity and support continued coal production—has created high uncertainty in how China's coal power sector may evolve within this critical decade, and how China will deliver the commitment of a near-term coal phasedown. As a result, China's coal fleet and coal consumption have been growing and appear on track to continue to do so: newly-added capacity in China accounted for about three quarters of total global new builds in 2020 and there were over 200 gigawatts (GW) of new projects under development in China as of July 2021.

Coal transition pathways in support of these goals require a decrease in China's coal power generation by 25-30% between 2020 and 2030. However, current trends are not in line with this target. **Through a comprehensive review of existing policies on coal plant closure, retrofitting, and new builds, we estimate that total coal power capacity may grow by about 158 GW through 2030, with 202 GW of new builds and 44 GW of retirements, and reach 1,237 GW during the 15th FYP. If new early-stage coal power plant builds are canceled, China's coal fleet may still grow to 1,139 GW by the end of the 15th FYP.**

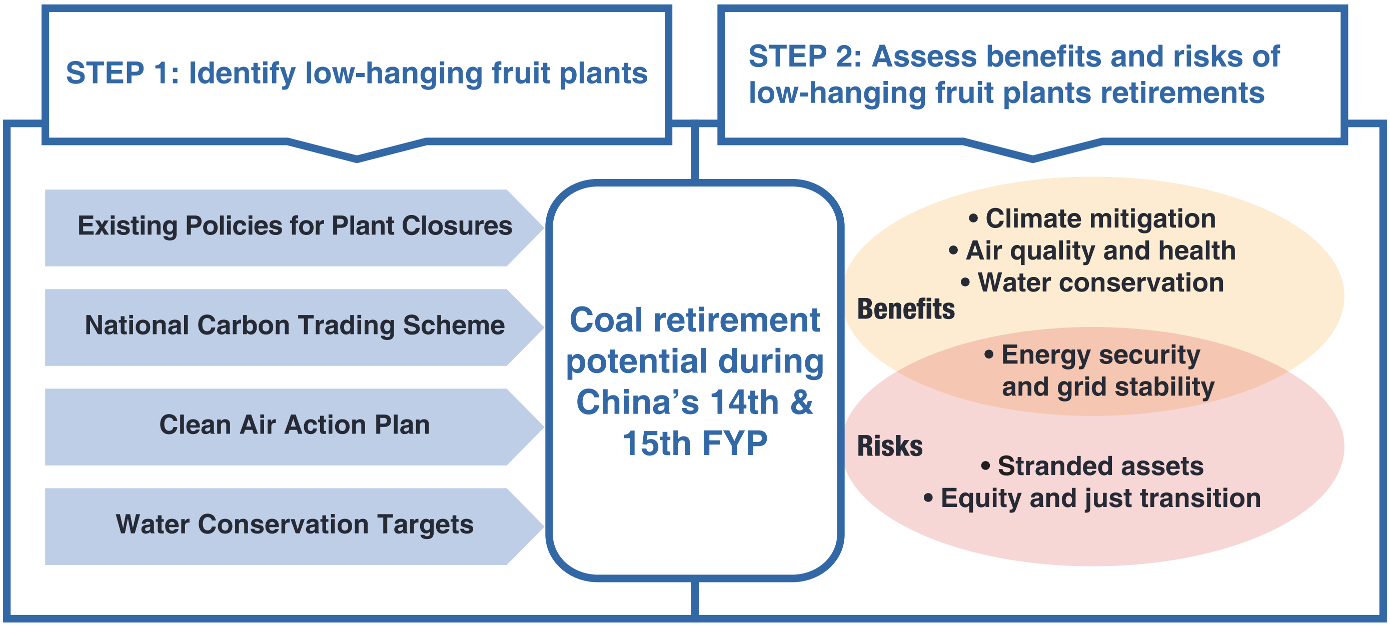
To scale down the coal fleets to be consistent with carbon neutrality and climate goals, it is therefore important to explore the full potential for near-term retirement and assess the broad environmental and socioeconomic outcomes of these retirements. A critical element of a rapid and orderly coal transition strategy is to target a small set of poorly performing, old, small, redundant, or otherwise undesirable plants (what we define as the "low-hanging fruit plants") for rapid retirement in the near term. This strategy not only effectively supports the attainment of other policy goals, but also substantially increases the feasibility and flexibility of the transition plan for the majority of existing coal plants. We ask: ***(1) how much obsolete coal power capacity can be orderly retired through existing policy measures during China's 14th and 15th FYP? and (2) more importantly, what environmental, economic, and social benefits and risks will be brought by the near-term coal retirements through 2030?***

To answer these two questions, we first develop a comprehensive, feasible plan to phase down coal-fired power capacity in China during the 14th and 15th FYP by retiring a small set of low-hanging fruit plants, and then demonstrate the effectiveness and broad social value of this plan by quantifying the large benefits and small risks of the rapid retirements of low-hanging fruit plants through 2030. Combined with rapid renewable deployment, efficiency improvements, and cross-region balancing, the well-structured and targeted near-term coal phasedown can help China achieve a rapid and orderly transformation of the power system in support of the national carbon neutrality goal and the global 1.5˚C goal while maintaining high-quality economic growth with improved human well-being.

Specifically, this near-term coal retirement plan takes into consideration China's existing policies, intersecting policy priorities, and near- and long-term climate commitments. The full retirement potential is explored with additional policy measures— including the National Carbon Emissions Trading Scheme, the Clean Air Action Plan, and the water conservation targets—and other regional priorities and equity concerns (SPM Figure 1). **We find that a total of 203 GW coal power capacity (19.4% of existing capacity) can be targeted for retirements during China's 14th and 15th FYP period (SPM Figure 2 & 3).** Combining the retirements with cancellation of new projects at early development stages, China's total coal power capacity would decrease to 981 GW by 2030. These retirements would bring large reductions in carbon and air pollutant emissions, improvement in average efficiency, large water conservation benefits, low risk in stranded assets, moderate and manageable job losses, and a small impact on the regional grid (SPM Table 1).

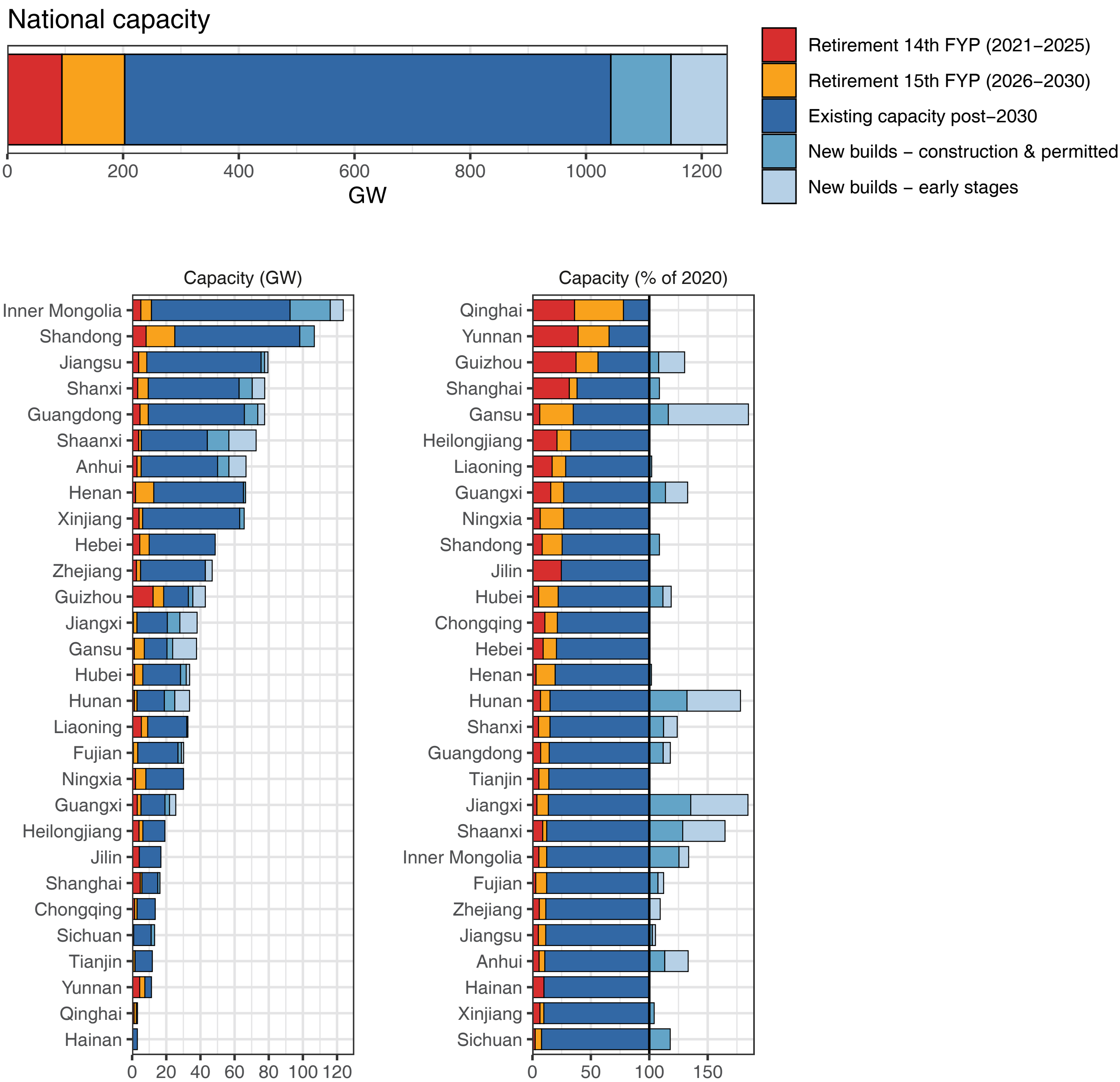
SPM FIGURE 1. Analytical framework of this report.

Identify low-hanging fruit plants for targeted retirements based on 14th & 15th FYP policies, and assess the environmental and socioeconomic benefits and risks of these retirements



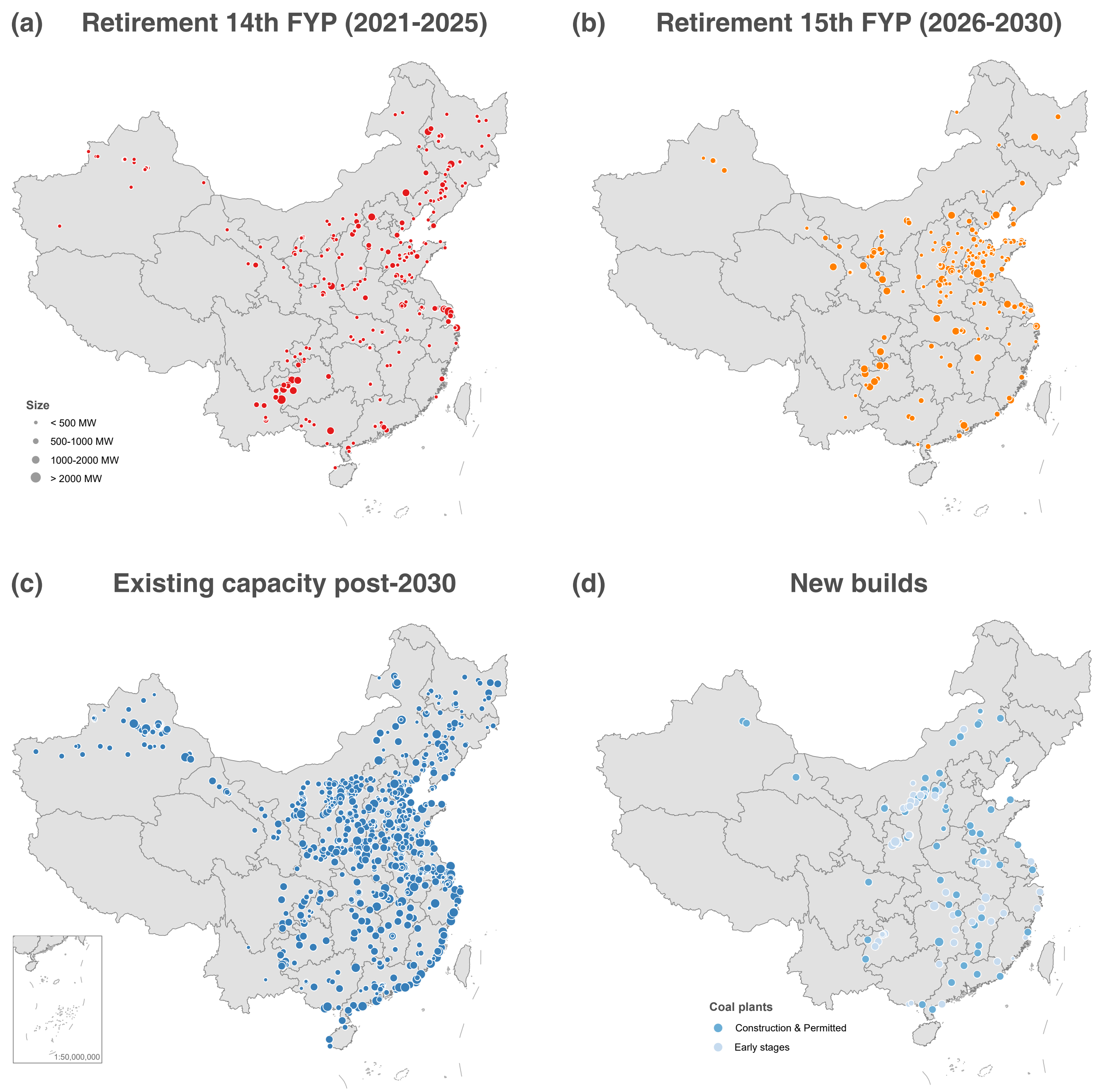
SPM FIGURE 2. **National and provincial coal-fired plant retirements, existing capacity, and new builds during the 14th and 15th FYP.**

The top bar shows national coal power capacity by different categories; the bottom left bars show coal power capacity by category and by province; the bottom right bars show the percentage of coal power capacity relative to 2020 by category and by province.



SPM FIGURE 3. Location of existing and proposed coal-fired power plants in China.

Locations of the low-hanging fruit plants for near-term retirements (a) during the 14th FYP (2021-2025) and (b) during the 15th FYP (2026-2030), (c) locations of the existing coal power plants remaining post-2030, and (d) locations of potential new builds of projects under construction and permitted, or at early development stages. Retirements are relatively evenly spread out over time and space, and the remaining coal plants are evenly distributed geographically.



There are significant benefits and manageable risks to implementing a practical strategy of phasing down low-hanging fruit plants. As shown in Table 1 below, the environmental, social and economic benefits of coal phasedown are substantial. It reduces coal power carbon emissions by 20.6% from 2020, or cumulatively about 1.2% of the remaining global carbon budget for achieving 1.5˚C (400 $GtCO_2$), a significant reduction with major benefits to the climate. It will lead to cleaner air with 36.6% reductions in SO_2, 29.3% reductions in NO_x and 41.2% reductions in $PM_{2.5}$, compared to 2020 levels, which are the primary causes of air pollution and a serious public health challenge. The plan presented in this report saves 2.3 billion cubic meters (m^3) of water annually, or 23% savings from 2020, an important factor given China's water stress and increasing droughts due to climate change. Closing down small, old, inefficient plants leads to 3.3% improvements in average coal power efficiency, outperforming the stated target.

Our analysis demonstrates that through a strategic and integrated planning process, the risks of phasing down coal become manageable and are clearly outweighed by the benefits. Our analysis considers these risks over time and space to address variations and imbalances across the country and geographic disparities. The shut down of these coal plants leads to the loss of only 5.7% of assets, which is comparatively small. It will lead to job losses of 33% of existing power plant workers, primarily medium- and highly-skilled workers who have transferable skills for working in the growing renewable energy sector. With our suggested retirement schedule, coal generation capacity could be replaced through a combination of new non-fossil generation, energy storage, and investment planning. Furthermore, as coal plants gradually shift from base load to peaking generation to help support an increasing share of renewables on the grid, it may not make economic or environmental sense to retrofit the low-hanging fruit plants for improved flexibility to serve this role.

As local and national governments begin to consider coal phase-down, there are tangible benefits to retiring low hanging fruit plants. These benefits are best realized through a strategic planning approach that considers both existing climate and socio-economic policy priorities and renewable energy needs. China's approach to planning provides a policy mechanism to develop these types of plans and integrate multiple policy goals.

A targeted strategy, which takes a long-term, national and subnational perspective as is presented in this report, provides a mechanism to spread coal retirements relatively evenly across the country and over time. This can proactively reduce shocks and risks for local communities, provinces, and regions to ensure that no area is overburdened. At the same time, it supports the necessary additional investments for building sustainable green economies and supporting workers and their families. It also provides time for the appropriate regulatory, fiscal and technical planning, and implementation for a sustainable energy transition.

This report provides a model for a feasible and practical strategy to phase-down coal to be coupled with accelerating renewable energy, energy efficiency and transmission, and load balancing. The report results offer a way forward and provide ample reasons for this work to start within the next five years. In order for a coal phase-down strategy to become reality, additional planning on the parts of the national and subnational governments will be required.

SPM TABLE 1. Total benefits and risks of the coal retirement during the 14th and 15th FYP*

Benefits		
Carbon emissions reduction in 2030 (% of 2020)		925 $MtCO_2$ (20.6%)
Efficiency improvement from 2020 to 2030		3.3%
Air pollutant emissions reduction in 2030 (% of 2020)	SO_2	143.8 kt (36.6%)
	NO_x	160.5 kt (29.3%)
	$PM_{2.5}$	25.1 kt (41.2%)
Savings of water withdrawal in 2030 (% of 2020)		2.3 billion m^3 (23%)

Risks	
Total stranded assets between 2020 and 2030 (% of 2020 coal plants assets value)	US$25 billion (5.7%)
Total job losses between 2020 and 2030 (% of 2020 coal plants jobs)	293,800 workers (33%)
Reduced power generation from low hanging fruit plants (% of 2020 total electricity)	830 TWh** (11%)

* $MtCO_2$: million metric tons of carbon dioxide; kt: metric kiloton; TWh: terawatt-hour; m^3 : cubic meters. SO_2: sulfur dioxide; NO_x: nitrous oxide; $PM_{2.5}$: fine particulate matter 2.5 microns in width.

* * Note: Newly-installed solar and wind generation from 2021 to 2030 is estimated to be 2150 TWh.

Chinese national and subnational governments could begin implementation with the following steps:

1. Drawing on the report results, conduct a plant-level review to identify an early retirement schedule and strategy.
2. Combine this strategy with an analysis of renewable energy, grid, storage and transmission investment and fiscal planning to fund these investments and to replace any lost tax revenues.
3. Building on the estimates provided here, evaluate the job losses and their composition at the county level, and provide dedicated fiscal and capacity-building support for actions such as job training for impacted workers.

Through a strategic approach, the analysis presented here contributes to meeting China's long term policy objectives of reaching carbon neutrality, becoming an ecological civilization, and supporting China's social and economic development. In the short-term, it advances multiple intersecting regional policy goals for water management and air quality with rippling benefits for adaptation to climate risks and public health. Through phasing-down coal, China can meet its goals, be a model to demonstrate a pathway for countries and regions facing similar challenges in their transition, and support global climate efforts.

1 INTRODUCTION

Limiting global warming to 1.5˚Celsius (C) requires phasing out all unabated coal consumption within the next three decades.[1] As about 70% of coal is consumed globally for electricity generation in 2021,[2] rapid retirements of coal-fired power plants not equipped with carbon capture, utilization, and storage (CCUS) can generate substantial low-cost emissions reductions in the near term. The transition from coal to clean power generation is also the central pillar of China's strategy to achieve carbon neutrality before 2060, as over 60% of China's electricity generation comes from coal-fired power plants today.[3]

Recent high-level policy statements from China have highlighted its willingness and interest to initiate a transition in its own economy to keep a global 1.5˚C pathway within reach. Framing its overall trajectory are its latest Nationally Determined Contribution (NDC) and Long-Term Strategy (LTS), which signal China's intent to achieve carbon emissions peaking before 2030 and carbon neutrality before 2060. The more detailed action plans in the "1+N" policy framework provide a process for elaborating strategies to implement these goals. These policies confirm China's strong determination to achieve its climate goals through deep transformation of every aspect of the society and integrated as part of its near- and long-term high quality development strategies.

Reaching net-zero emissions requires decarbonizing China's coal-reliant energy system rapidly. These new policies include specific language on near-term coal commitments both domestically and internationally. For example, China has committed to "strictly control" new coal power projects and coal consumption over the 14th Five-Year Plan (2021-2025) (FYP) period, starting to phase it down during the 15th FYP (2026-2030).[4] Notably, new commitments in the U.S.-China Joint Glasgow Declaration (2021) have also opened the opportunity to accelerate the work of reducing coal consumption.[5] Moreover, China has also committed to stop building international coal power projects.

Although progress has been made in scaling down the expansion of coal-fired power capacity during the 13th Five-Year Plan (2016-2020) and in shutting down small, old, inefficient plants to address overcapacity and local air pollution, with an increasing policy emphasis on energy stability and security, it remains highly uncertain how China's coal power sector may evolve within this critical decade, and how China will deliver the commitment of a near-term coal phasedown. China today owns the world's largest coal fleets and is still building new ones: newly-added capacity in China accounted for about three quarters of total global new builds in 2020[6] and there were over 200 gigawatts (GW) of new projects under development in China as of July 2021.[7]

While these developments are cause for concern, China has also been leading global renewable energy deployment. For example, recent wind and solar deployments were in the range of 100-120 GW per year. These rapid renewable capacity additions, along with similarly feasible efficiency improvements, transmission expansion and grid management, and policy adjustments to reduce short-term, policy-driven supply-demand imbalances, can enable a coal phasedown while fulfilling growing demand within this decade.

Near-term actions are critical, as they will set up the path towards a successful and feasible coal phasedown in China. However, there are several challenges for China to further enhance ambitions on coal retirements in the near term. First, strong demand rebound, driven by COVID recovery, has loosened the curbs on new coal builds during the first half of 2021. As of July 2021, there were 97 GW of new projects already under construction and another 43 GW that had received official approval.[7] These projects are more likely to be implemented than projects at earlier development stages, and would further increase total coal power capacity. Second, the majority of Chinese coal plants were built recently and still have a remaining lifetime of decades. Third, these newer plants are also larger in size, more efficient, and have end-of-pipe air pollutants control technologies installed. Closing these plants may lead to higher stranded assets risks compared to those that have been operating for decades in the Organisation for Economic Co-operation and Development (OECD) regions. Fourth, it is a top priority to ensure a stable supply of electricity to meet growing demand, which will become more challenging with increasing renewable energy in the generation mix. Fifth, closing coal plants will lead to job losses related to not only power plant operations but also along the entire supply chain. If not carefully managed, employment losses may lead to larger social impacts especially in local coal-dependent communities.

On the other hand, non-climate drivers and societal priorities can add strong motivation for taking actions more quickly. Coal retirement in the near-term can bring large benefits in meeting other societal priorities. For example, shutting down the super polluters among coal plants can largely reduce local air pollutant emissions including NO_x, SO_2, and $PM_{2.5}$, and improve air quality and human health. In addition, retiring coal power plants with one-through water cooling technology can reduce water withdrawal and help alleviate stress in water-scarce regions, and reduce thermal pollution for water resources. Retiring old and inefficient coal plants can also help address the overcapacity issue, which increases the economic feasibility and flexibility for the coal power industry to make a smoother transition with newer and more inefficient plants.

To maximize the benefits on air quality, health, and water savings, and minimize the impacts on stranded assets, employment, and grid stability, the near-term coal retirement strategies should target specific plants based on detailed plant-by-plant assessments. An increasing number of literature has conducted plant-level analysis to inform coal transition strategies in China. The implementation of ultra-low emissions standards have largely lowered air pollutants emissions from individual coal plants and contributed significantly to air quality improvement during the 13th FYP period.[8] Therefore, closing coal plants based on their potential health benefits can help achieve both climate and air quality goals simultaneously.[9] Moreover, targeting coal plants with large water withdrawals can help alleviate water stress risk, especially in northern China.[10] For coal plants located in regions with abundant crop residues, deploying the coal-bioenergy gasification system with carbon capture and storage could provide a feasible strategy to help these coal plants decarbonize.[11] Carbon pricing is expected to place a long-term effect on the financial feasibility of coal plants' operations, especially those located in western provinces; and even a low carbon price can, on average, shorten coal plants' lifetimes by over 5 years.[12]

A five-dimensional analytical framework was developed in Cui et al. (2021) to systematically evaluate individual coal plants' technological, economic, and environmental performance, and develop a plant-by-plant retirement schedule for a 1.5˚C-compatible phaseout.[13] One of the three key strategies developed for a high-ambition, well-structured coal phaseout in China is to rapidly retire a small set of plants that perform poorly across all criteria. Shutting down these plants in the near-term not only can help increase the flexibility of the phaseout pathways for the majority of Chinese coal fleets, but also contributes to meeting other societal objectives beyond climate mitigation.

In this research, we extend the analytical framework (see Figure 1) to connect individual performance metrics with concrete policy discussions, including the national carbon emissions trading scheme, clean air action plan, water conservation targets, and efficiency improvement targets of thermal power generation, to advance the assessment of near-term coal retirement potential and outcomes in China. Specifically, we ask two questions: ***(1) how much obsolete coal power capacity can be orderly retired through existing policy measures during China's 14th and 15th FYP? and (2) more importantly, what environmental, economic, and social benefits and risks will be brought by the near-term coal retirements through 2030?***

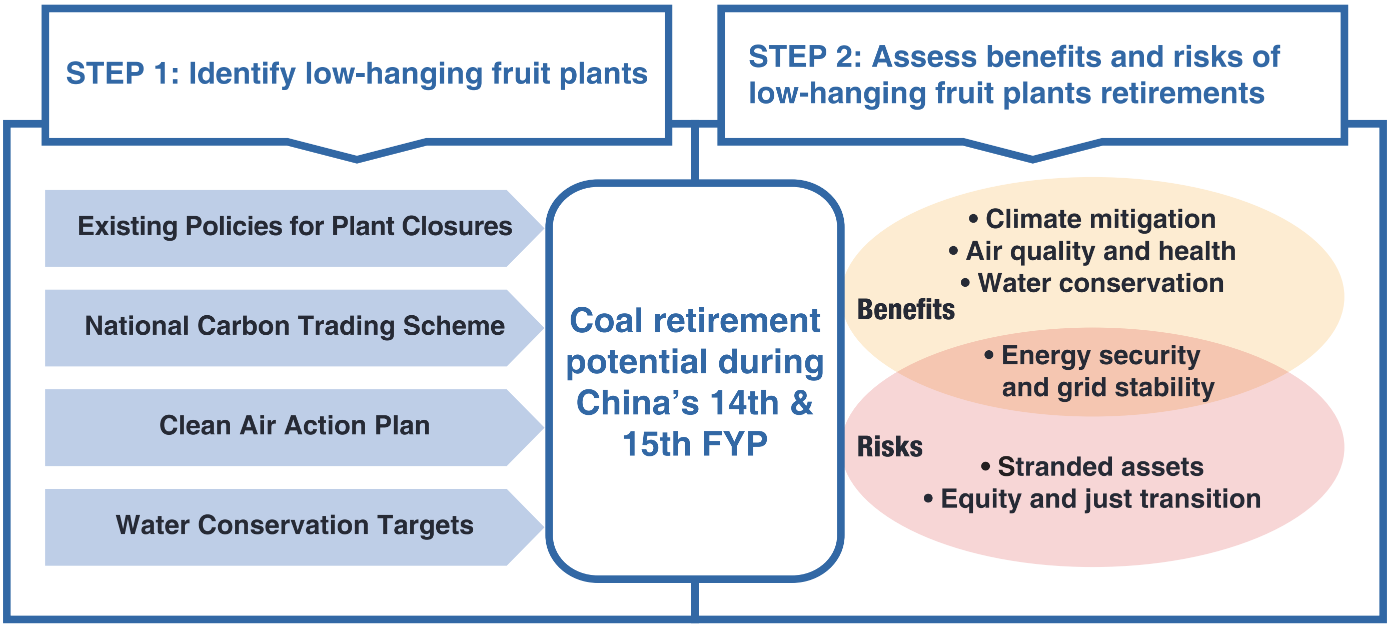
To answer the first question, we start by conducting a comprehensive review of existing policies that specify coal plants' retirement criteria in the near-term. These plants are mostly small, old and polluting, and located in air quality control key regions. By doing this, we glean a better understanding of the ambition gap under announced retirements. We then evaluate three additional policy measures that may indirectly impact the retirement of coal power plants, including the national carbon emissions trading scheme, the clean air action plan, and water conservation targets. Through a plant-by-plant assessment, we identify a list of low-hanging fruit (LHF) plants that can be targeted for rapid retirement through 2030.

To answer the second question, we assess the broader societal outcomes of retiring the identified LHF plants during the 14th and 15th FYP. Quantitative assessments are conducted to measure the gained benefits of climate mitigation, air pollution reduction and water conservation, and the potential costs associated with stranded assets and job losses. We also look at how these benefits and costs are distributed across provinces and regions. In addition, other social benefits, equity, energy security, and grid stability concerns are discussed.

By identifying a list of LHF plants that are suitable for near-term retirements through 2030, our analysis develops a detailed, feasible action plan for China's near-term coal retirement that can generate large benefits and manageable risks. By quantifying the large benefits in air quality, CO_2 emissions reductions, and water savings, and manageable costs in stranded assets and job losses, we demonstrate the effectiveness and value of rapidly shutting a small set of LHF plants to balance multiple societal goals based on China's national policy priorities.

FIGURE 1. Analytical framework of this report.

Identify low-hanging fruit plants for targeted retirements based on 14th & 15th FYP policies, and assess the environmental and socioeconomic benefits and risks of these retirements.



2 RETIREMENT POTENTIAL DURING THE 14TH AND 15TH FIVE-YEAR PLAN

In this section, we focus on the first question to assess the coal retirement potential during China's 14th and 15th FYP. To do so, we conduct a detailed plant-by-plant assessment of how different policy measures may impact individual coal plants, and identify those that will be either directly-targeted for closure or largely impacted by these measures through 2030.

Our plant analysis covers 1,049 GW of operating coal plants as of January 2021 in China,[7] covering 97% of the national total installed capacity in 2020 (1,079 GW) reported by China Electricity Council (CEC).[14] Key policies analyzed here include measures on plant closure, retrofitting, and new builds, national carbon emissions trading scheme, clean air action plan and water conservation targets. We first review existing policies and assess the associated retirement potential in 2021. To fill the ambition gap, we then develop criteria for each policy measure to be implemented in the 14th and 15th FYP, respectively, to explore the retirement potential through 2030.

2.1. EXISTING POLICIES ON PLANT CLOSURE, RETROFITTING, AND NEW BUILDS

We first conduct a comprehensive review of existing policies on coal plant closure, retrofitting, and new builds to assess the number of operating and proposed coal power plants that would be affected. Total coal capacity through 2030 is then estimated without additional measures.

First, several criteria are listed in the policies to identify coal plants for immediate retirement. These plants include non-combined heat and power (CHP) pure condensing units that are smaller than 100 MW; units that are between 100 to 300 MW and exceed 30 years lifetime;[15] small CHP units within a 15 km radius of large CHP units (>=300MW) in the key polluted areas;[16] units that have not completed low emission upgrading or do not meet the emission standard;[17] and illegal self-use plants.[18]

Our plant-level assessment identifies 318 units, a total of 44 GW, that meet the first two criteria for rapid closure through 2030, accounting for 4.3% of today's operating capacity (Table 1). The other criteria are not assessed at the plant level due to data limitations.

TABLE 1. Policies that affect existing coal power plants and the potential impact through 2030.

Policy	Description	Affected coal plants through 2030
Further Eliminating Backward Coal Power Plants[16]	Pure condensing unit capacity<= 100 MW for non-CHP applications;	Retirement: 3.9 GW, 68 units
	Age >=30 years and capacity 100-300 MW but don't meet the condition of lifetime extension	Retirement: 38.8 GW, 240 units
Three-year action plan for cleaner air[15]	Small CHP units within a 15km radius of large CHP units (>=300MW) in the key areas	Retirement: 1.5 GW, 10 units
Flexibility retrofit & Lifetime extension[18]	Enhance the peaking capacity of 300MW coal units; High-efficiency subcritical coal units;	Flexibility retrofit: 31.8 GW, 96 units; Lifetime extension: 8.3 GW, 28 units

Second, existing policies also promote coal plant retrofitting for improved efficiency and flexibility. In November 2021, the National Development and Reform Commission (NDRC) flagged a notice about upgrading and retrofitting existing coal-fired power plants during the 14th FYP, in which they targeted 350 GW efficiency upgrades to lower average coal consumption per unit of electricity generation, and 200 GW flexibility adjustments to allow coal plants to quickly ramp up and down to support increasing renewables penetration in the grid.[18] While efficiency upgrading has made progress since 2005, only a quarter of the 220 GW flexibility retrofits target were completed during the 13th FYP.[14] Due to the lack of proper price incentive mechanisms for coal power to participate in peak-load regulation in most regions, flexibility retrofits are extremely uneconomical. With data limitations on efficiency retrofits, we identified 96 units, a total of 32 GW, that completed flexibility retrofits up to 2021. Moreover, a small set of high-efficiency subcritical coal plants are allowed to extend operation beyond the designed lifetime in several provinces, such as Shandong, Jiangsu, and Hunan. This aims to help control new builds and guarantee the utilization of other existing coal plants. As of July of 2021, 28 units - about 8.3 GW of existing coal plants - have extended their lifetime for another 10 to 15 years.

Third, the latest "1+N" policy framework for carbon peaking and carbon neutrality has emphasized that new builds of coal-fired power projects will be strictly controlled during the 14th FYP. The November notice from NDRC set up criteria that, in principle, restricts new projects to ultra-supercritical plants, and does not allow new water-cooling and air-cooling coal plants to exceed 285 and 300 gram of standard coal consumption per kWh electricity, respectively.[18] As of July 2021, there are 97 GW of new coal power projects under construction, 43 GW received official approvals, and another 120 GW under early development stages.[7] Among these new projects, 58 GW are not ultra-supercritical plants and thus more likely to be halted, leading to 202 GW of potential new builds during the 14th and 15th FYP, or 104 GW of new builds if all proposed projects at early development stages are canceled.

Overall, we estimate that without additional measures, total coal power capacity may grow by about 158 GW through 2030, with 202 GW of new builds and 44 GW of retirements, and reach 1,237 GW during the 15th FYP. If new early-stage coal power plant builds are canceled, China could hold down its coal fleet to 1,139 GW by the end of the 15th FYP. However, pathways in support of the global 1.5˚C goal and the national carbon neutrality target require a decrease in coal power generation by 25-30% between 2020 and 2030.[13] This can be achieved through a combination of plant retirements and reduced utilization. Without additional near-term retirements, coal plant utilization needs to be reduced by over 30% to both offset capacity growth and close the generation reduction gap. Alternatively, further increasing retirements by targeting a limited number of plants can help avoid widespread impacts and make the transition more flexible for the majority of coal plants. It is therefore critical to explore additional retirement opportunities.

2.2. ADDITIONAL POLICY MEASURES AND POTENTIAL IMPLICATIONS ON EXISTING PLANTS

In addition to the measures that directly target coal plants' retirement, other policies can also largely impact certain plants' performance and provide additional motivation for rapid retirement from socioeconomic, and environmental perspectives. Here, we assess three additional policy measures: national carbon emissions trading scheme, clean air action plan, and water conservation targets, and the potential implications of these measures on individual coal plants through 2030.

National Carbon Emissions Trading Scheme (ETS)

The price of carbon can significantly impact the financial viability of coal plants, which will affect the operation of China's coal fleets in real time. After several years of pilot programs in Shenzhen, Beijing, Shanghai, Guangdong, Tianjin, Hubei and Chongqing since 2013, China launched its national carbon trading scheme (ETS) in July 2021. It covers more than 2,000 power companies with coal-fired generators, most of which are operating coal generation units.

Under the ETS, coal plants will have to buy additional permits if their CO_2 emissions exceed the allocated amount. That is, coal plants will face higher generation costs and end up with reduced cash flow and profits. By October 2021, the carbon price of the national market was between 41- 61 RMB/tCO_2e (around US$6.4-9.6)[20] and carbon emission permits were allocated to the entities by free allocation. As the carbon price is expected to grow steadily, those inefficient plants with higher CO_2 emission rates are likely to be affected the most, making it harder for them to continue operation and therefore more likely to retire early.

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 (see Supplementary Information for calculation method and Table S1 for data and source). Gross profit, defined as revenue minus production costs, can measure a plant's ability to cover the production costs and thereby help identify the plants that face challenges to cover production costs and maintain business due to carbon prices. Revenues are estimated based on regional electricity and coal prices and plant operation data. The production cost includes the cost of generating electricity and carbon costs. Specifically, for 2025, we assume a carbon price of 80 RMB/tCO_2 and that 50% permits will be auctioned; and for 2030, we assume a carbon price of 100 RMB/tCO_2 and that 75% permits will be auctioned. The carbon prices are based on a market participants' expectation survey conducted by China Carbon Forum,[21] and the auction rates are based on a recent study on the national carbon pricing scheme in China.[12]

Under these carbon prices, we find that four plants (1.3 GW) in 2025 and 179 plants (61.8 GW) in 2030 may not be able to cover the operation costs with their revenues. Our analysis applies constant electricity and coal prices for different provinces, where changing prices impact the plants' economic performance.

Clean Air Action Plan

Air quality improvement has been the main driver for coal phasedown in China. Specifically, China introduced an ultra-low emissions (ULE) standards policy in 2014 to limit particulate matter (PM), SO_2, and NO_x emission concentrations to 10, 35, and 50 milligrams per cubic meter (mg/m^3), respectively, through plant upgrades. These strict standards for coal-fired units set by the ULE policy are equivalent to the performance of natural-gas-fired units. At the same time, China identified 28 northern cities in the Beijing-Tianjin-Hebei region (also referred to as "2+26 cities"), Yangtze River Delta region and Fenwei Plain as key areas for combating air pollution. Subject to stricter emission standards on air pollutants, these regions set targets to reduce SO_2 and NO_x emissions by 15% and PM 2.5 concentrations by 18%, and highlight closing small and inefficient coal plants as one of the key measures to reduce air pollution.

Remarkable air pollution reductions in the coal power sector have been achieved through these strict regulations. In 2017, thermal power plants, consisting mainly of coal plants, emit only 15.7%, 19.1% and 5.0% of China's SO_2, NO_x and anthropogenic PM, respectively.[22] Over 950 GW of coal-fired units, equivalent to nearly 90% of the existing coal fleet, have completed ULE retrofits by 2020. The coal power sector is no longer the single largest source of air pollutant emissions in China. However, the benefits of end-of-pipe control measures are mostly exhausted, and complying with the World Health Organization (WHO) air quality guidelines will likely require energy system changes toward non-emitting technologies.[23,24]

This research identifies super polluting plants as candidates for near-term retirements as the LHF plants, since retiring those plants are likely to bring significant environmental and health benefits. By combining and complementing multiple sources of plant level air pollutants emissions data,[8,9,22] and mapping with the Global Coal Plant Tracker (GCPT) coal power plant database, we develop a dataset with detailed plant level emissions and location information (see Supplementary Information for calculation method and Table S1 for data and source). Using this dataset, we identify 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. We identify a total of 85.8 GW for retirement as LHF plants in 2025, and a total of 31 GW in 2030 (see Figure S1). We then evaluate the consequential emissions reduction impacts of shutting down these plants in 2025 and 2030, especially in air quality control key areas.

Water Conservation Targets

Retiring coal power plants can bring co-benefits on alleviating water-stress in certain areas and protecting water resources. As one of the water-intensive industries, the water usage of the coal power generation sector can impose pressure on water resources[25] and will be impacted by the future dynamics of water resources in China and elsewhere. Due to the unbalanced distribution of water supply and demand, water withdrawal for coal power generation has raised issues such as water scarcity and thermal pollution in some certain areas of China.

In response, China has implemented a series of policies on water conservation and water resources management measures covering many sectors, among which the "dual-control" of total water consumption and water intensity in the power sector is one of the key areas. At the national level, China sets standards of water withdrawals for coal power generation and provides clear guidance on water usage for plants with different sizes and cooling technologies.[26] At the provincial level, some water-stressed regions, such as Ningxia, Shanxi, Inner Mongolia, Xinjiang, Shaanxi, have enacted policies to strictly control new coal power generation projects without air-cooling technology.

To link coal plants' retirement with existing water conservation policy, we identify the plants located in water-stressed regions but equipped with water-intensive cooling technologies. These plants have greater water savings potential and thus targeting these plants can bring larger co-benefits on achieving water consumption and the water intensity targets compared to other coal plants. Specifically, we develop a database with data of coal plant cooling technology,[1,27] plant locations, and the water stress index of the plant location (see Supplementary Information for method).[28] Using this data, we find all plants that are not equipped with air cooling technology and located in areas with high water stress. We use the water stress index developed by Aqueduct to measure the level of water stress for different regions. According to the water stress index from Aqueduct, a water stress index of 4.0 and above indicates extremely high water risk. Therefore, 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. By doing this, we identify 15 plants, representing a total of 5.6 GW as LHF plants in 2025, and 77 plants, representing a total of 23.3 GW, as LHF plants in 2030.

2.3. OTHER POLICY PRIORITIES IN REGIONAL CONTEXT AND EQUITY CONCERNS

In addition to the policy criteria described above, we also implemented additional adjustments to reflect policy priorities and equity concerns in provincial or regional context for identifying the LHF plants (see Figure 2). Under several conditions, some identified LHF plants are excluded from rapid retirement to avoid undermining grid stability and energy supply in key regions, and in other cases, the retirement schedule and criteria are adjusted considering the cost-effectiveness of early retirement.

First, many CHP plants in northern provinces provide critical residential heating services. Rapidly closing these coal plants may raise energy security concerns for residential heating, while alternative technologies, such as natural gas or heat pumps, may substantially increase the energy costs for consumers in the near term, and create social challenges. Specifically, there are 13 northern provinces, including Xinjiang, Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Hebei, Shandong, Beijing, Tianjin, Liaoning, Jilin, and Heilongjiang, where CHP coal plants play an important role in centralized heating supply. In these provinces, we identified 26.6 GW of CHP plants as the LHF. To avoid large social impacts, we excluded 7.6 GW (24 units) that are solely based on the water saving criteria from the near-term retirement.

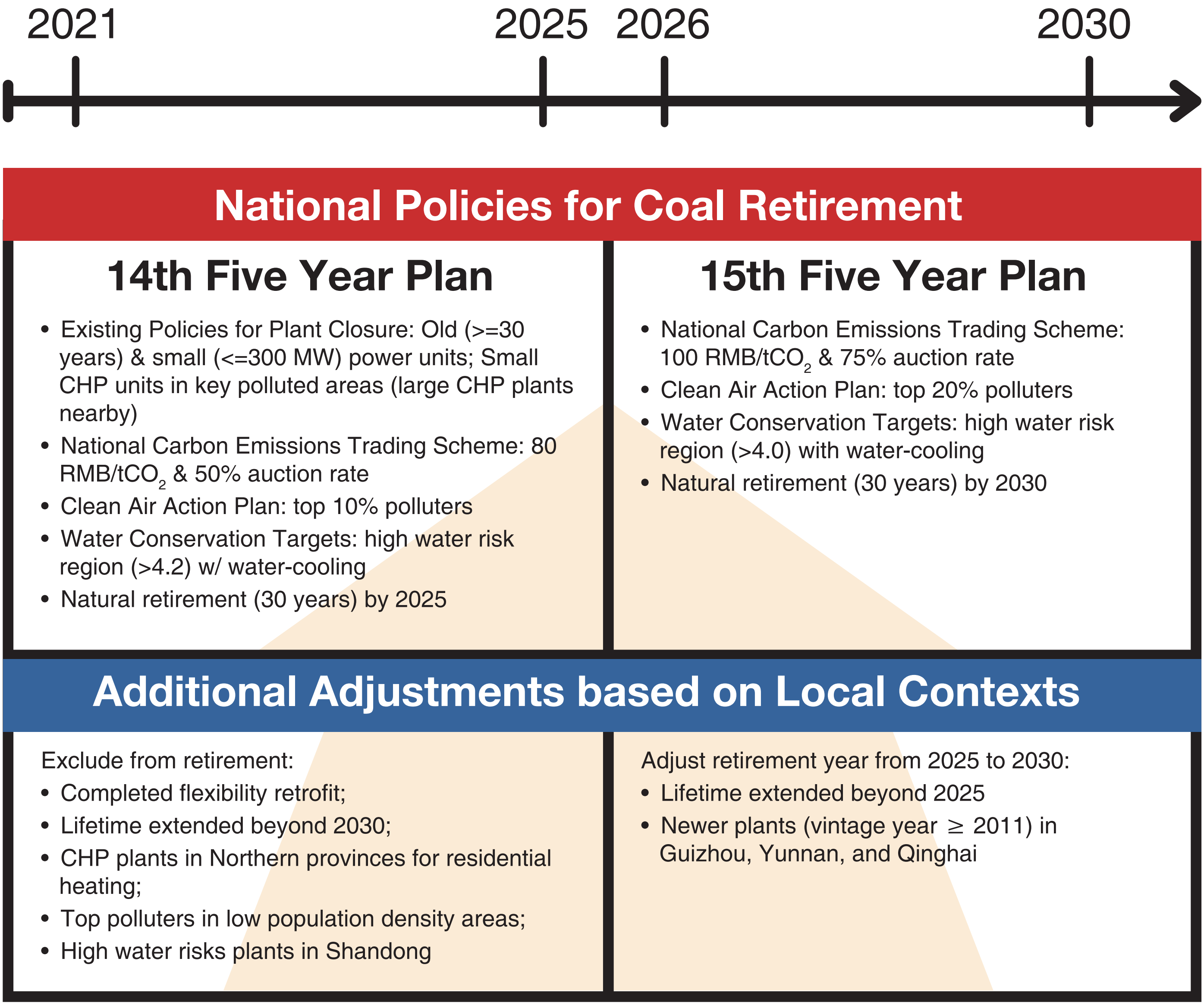
Second, our analysis has excluded all the coal plants (96 units, 31.8 GW) that have completed a flexibility retrofit from the near-term retirement through 2030. These plants are suitable for later retirement not only because of the additional investments made for the upgrades, but also because they can quickly ramp up and down the generation to support the increasing share of renewables in the power system. Moreover, a small set of high-efficiency subcritical coal plants (28 units, 8.3 GW) are allowed to extend operation beyond the designed lifetime in a few provinces to help control new builds. We adjusted the retirement schedule for these plants accordingly.

Third, the top air pollutant emitting plants account for a large share of total coal capacity in several provinces, especially in Guizhou and Yunnan (93% and 84%, respectively). Rapidly shutting down all of the top air polluters may create grid stability concerns in these regions. Therefore, we further prioritize the retirement of those located in populated areas to maximize the public health impacts, while allowing a small set of the 20% top polluters that are located in areas with a population density less than 200 people/km2 and not subject to other policy criteria to continue operating beyond 2030. This adjustment reduces the retirement in Guizhou and Yunnan to 66% and 56% of total existing coal generation capacity, respectively.

Fourth, according to the Aqueduct data, Shandong is one of the provinces that has high water risk. Under the water conservation policy criteria, 42% of coal capacity in Shandong is identified as the LHF (181 units, 41.2 GW). Due to limited data of plant-level cooling technologies, we excluded the coal plants that are not subject to other policy criteria from the near-term retirement to avoid a potential overestimate of the water conservation benefit of closing these plants. This adjustment lowers Shandong's share of LHF retirement from 59% to 25% of total existing coal generation capacity.

Lastly, with all the adjustments above, three provinces, Guizhou, Yunnan, and Qinghai, have over 50% of existing coal capacity identified as potential retirement during the 14th FYP, and thus will face dramatic changes in the first five years. To achieve a smoother transition without risking regional electricity supply, grid stability, and socioeconomic security, we adjust the retirement of a subset of LHF plants (81 units, 28.4 GW) in these provinces from the 14th to the 15th FYP period. They include plants that are implemented after 2011 and subject to only one dimension of the policy criteria. This adjustment lowers the share of retirement to about 40% of existing capacity between 2021 and 2025 in these provinces.

FIGURE 2. Policy criteria to identify low-hanging fruit plants that can be targeted for closure during China's 14th and 15th Five-Year Plan.



2.4. RETIREMENT POTENTIAL THROUGH LOW-HANGING FRUIT PLANTS

Through the detailed plant-by-plant assessment, we identified 1,040 coal power generation units as the low-hanging fruit plants with a total of 203 GW installed capacity. These plants account for 19.4% of existing coal power capacity or 34.8% of operating units and can potentially be targeted for near-term retirement in China's 14th and 15th FYP period. More retirements are expected in the 15th FYP than the 14th FYP (see Figure 3). Specifically, 9.1% 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 10.3% 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.

The identified LHF plants are generally smaller, older, and less efficient, compared to the remaining coal fleet (see Figure S2). 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. The non-LHF plants have a similar distribution across different types of plants, indicating that the near-term retirements are not concentrated on and thus less likely to disrupt particular services.

The identified LHF plants are generally evenly-distributed across provinces in the central east, northeast, and southwest of China (see Figure 4), with the largest capacity retirement in Shandong, Guizhou, Henan, Inner Mongolia, and Hebei provinces. For Jilin, Hainan, Shanghai, Shaanxi, and Guizhou provinces, the majority of the LHF plants are scheduled to retire during the 14th FYP. Thus, near-term retirements are not concentrated and thus less likely to disrupt particular public services.

While most provinces have a small share of identified LHF capacity, Qinghai, Yunnan, and Guizhou provinces have a LHF share that exceeds 50% (see Figure 3). A total of 28.3 GW is expected to retire in the three provinces cumulatively by 2030, accounting for 78%, 66%, and 56% of the province's existing capacity, respectively. Despite a high share of coal retirement, limited impacts to the grid are expected due to the less important role of coal power generation in the electricity system and large renewable energy potentials in these regions. There are only five operating coal plants in Qinghai, which contributes to less than 12% of its total electricity generation, in contrast to 88% coming from renewables.[29] With abundant solar and wind resources, Qinghai is one of the pioneer provinces to phase out coal and transition to clean energy. Similarly, coal power only contributes to 9% of total electricity generation in Yunnan, compared to 82% comes from hydropower.[29] With abundant hydropower resources, rapid coal retirement is also feasible in Yunnan. Guizhou, which currently has a high share of coal power generation, also has great hydropower and wind power potential. Also, Guizhou is a part of the southern power grid which has been fed with abundant renewable energy sources. With the advancement of regional power trade, the improved regional integration will give Guizhou access to renewable energy sources to replace the local coal power generation. Within the identified LHF plants, those with good operating conditions can also be reserved as backup units, rather than be demolished.

FIGURE 3. National and provincial coal-fired plant retirements, existing capacity, and new builds during the 14th and 15th FYP.

The top bar shows national coal power capacity by different categories; the bottom left bars show coal power capacity by category and by province; the bottom right bars show the percentage of coal power capacity relative to 2020 by category and by province.

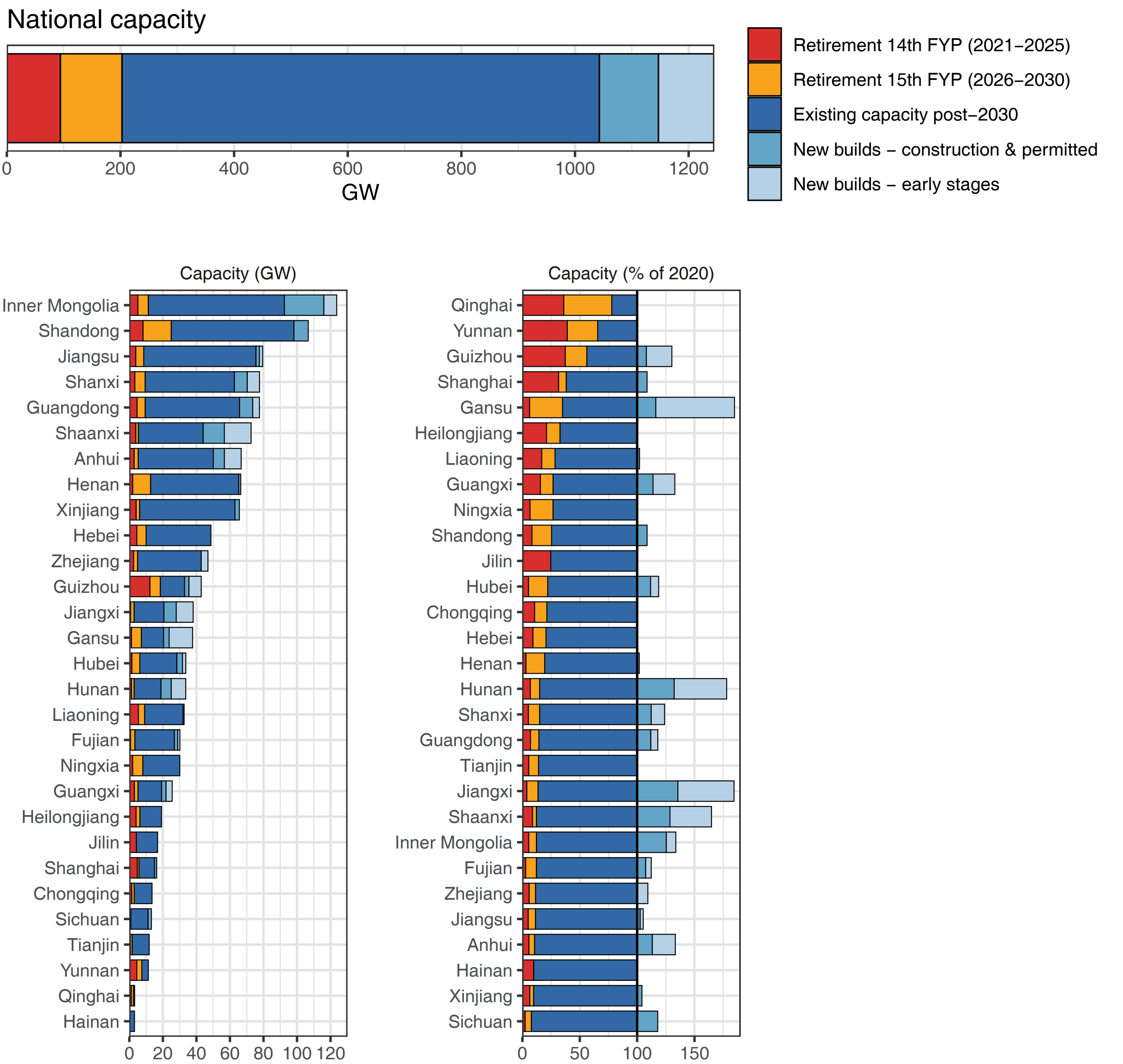
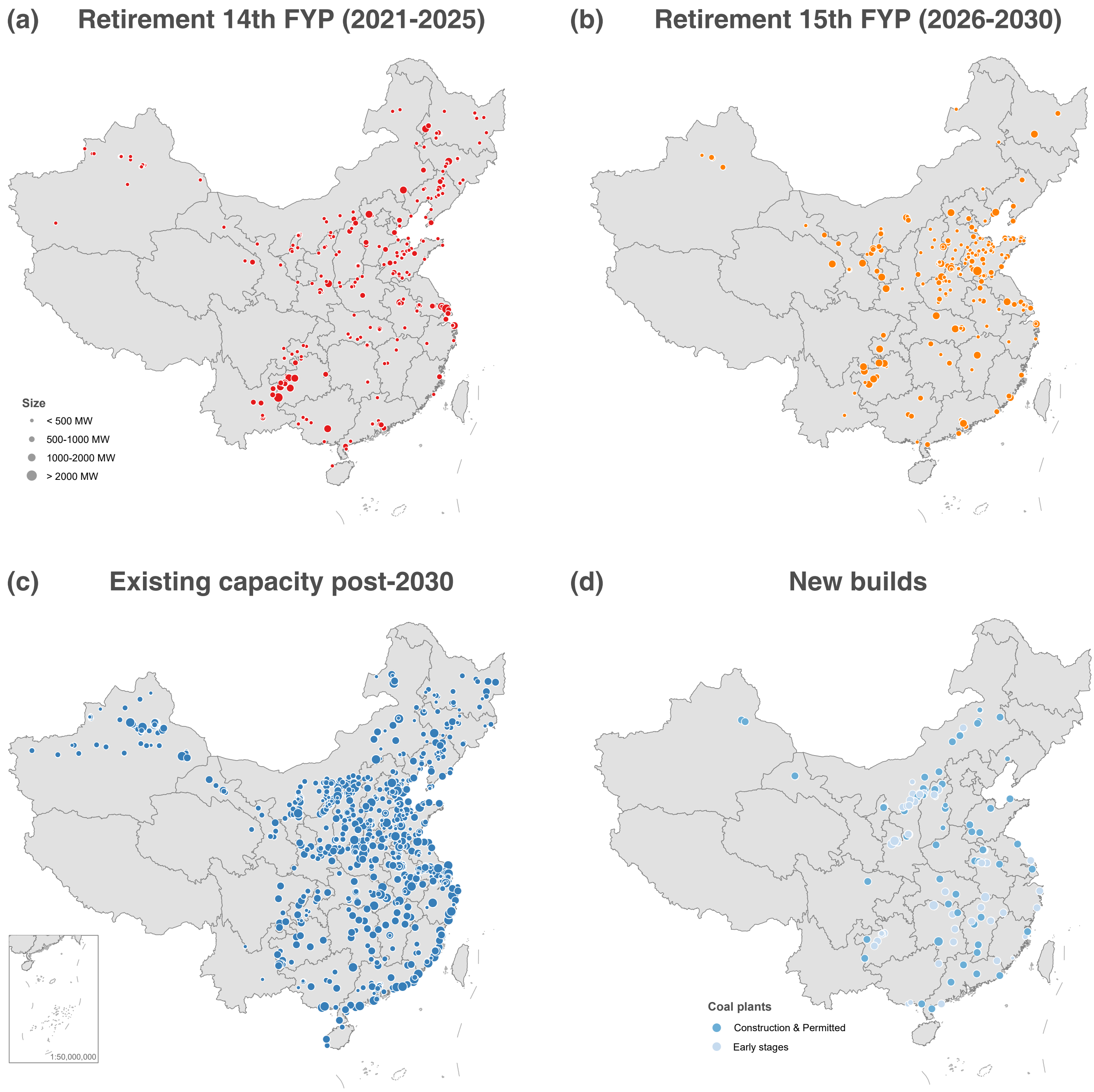


FIGURE 4. Location of existing and proposed coal-fired power plants in China.

Locations of the low-hanging fruit plants for near-term retirements (a) during the 14th FYP (2021-2025) and (b) during the 15th FYP (2026-2030), (c) locations of the existing coal power plants remaining post-2030, and (d) locations of potential new builds of projects under construction and permitted, or at early development stages. Retirements are relatively evenly spread out over time and space, and the remaining coal plants are evenly distributed geographically.



3 BENEFITS AND RISKS OF RETIRING LOW-HANGING FRUIT PLANTS THROUGH 2030

This section focuses on the second question to evaluate the potential environmental, economic, and social benefits and risks brought by rapidly retiring the LHF plants identified in the previous section through 2030. Here, a main contribution of our analysis is the quantification of some of the benefits and risks based on plant-level results, and our results demonstrate that targeting the LHF plants in the near-term can generate significant benefits but relatively minor to moderate risks across different dimensions. Other benefits and risks are discussed qualitatively. All benefits and risks are evaluated compared to the 2020 baseline unless otherwise specified.

Benefits of LHF plants' retirements include climate mitigation, air quality and public health improvements, and water conservation. Here, we quantify the contribution to climate change with CO_2 emissions reduction and average efficiency improvement, and discuss how LHF plants' retirement would help structure China's long-term coal phaseout strategy towards the 2060 carbon neutrality goal. We also quantify air pollutant emissions reduction and water withdrawals reduction from LHF plants' closures and how these reductions would be distributed across provinces and key areas. These reductions will further contribute to air quality and public health improvements.

Risks of LHF plants' retirements include stranded assets, job losses, equity and just transition, grid stability, and energy security. Here, we quantify potential stranded assets from LHF plants retirement and the percentage of today's assets value. Distribution of stranded assets are assessed across provinces and power companies. We also quantify the job losses from LHF plants' closures by position and skill levels. Hotspots with a large number of job losses and/or high unemployment rate are identified at the country level. Job losses will lead to equity issues, and it is critical to ensure a just transition with the near-term plant closures. Moreover, maintaining a stable grid and a secure energy supply is one of China's top priorities, which might face certain risks with LHF plants retirement in the near-term, under existing infrastructure, technology, market structure, and regulations.

3.1. BENEFITS IN CARBON MITIGATION

Retiring the LHF plants during the 14th and 15th FYP can reduce CO_2 emissions and contribute to accelerating China's carbon emissions peaking. Specifically, a total of 925 $MtCO_2$ of carbon emissions could be reduced in 2030 (see Supplementary Information for calculation method). Cumulatively between 2022 and 2030, total CO_2 emissions reduction can reach 4.6 Gt, about 1.2% of the remaining global carbon budget for achieving 1.5˚C (400 $GtCO_2$). [1] Shutting down the 19.4% existing coal capacity can lead to a 20.6% CO_2 reduction from 2020.

Because the identified LHF plants are older, smaller, and less efficient, the average efficiency of coal power generation will increase with these retirements. Specifically, average coal consumption per unit of power generation could decrease by 3.3% between 2020 and 2030. This can contribute significantly to the 1.8% efficiency improvement target set for the 14th FYP.[15]

Moreover, shutting down the LHF plants can help set forth a successful path towards a high-ambition coal power phasedown in China, which is one of the most critical elements for achieving carbon neutrality before 2060. Shutting down a small portion of LHF plants can help reduce overcapacity within the coal power industry and improve the flexibility of how to transition the remaining majority coal plants in China. For example, it can create room for the remaining plants to operate through a minimum lifetime with gradually lower utilization, which helps avoid drastic change over a short period of time.[13]

3.2. BENEFITS IN AIR QUALITY AND PUBLIC HEALTH

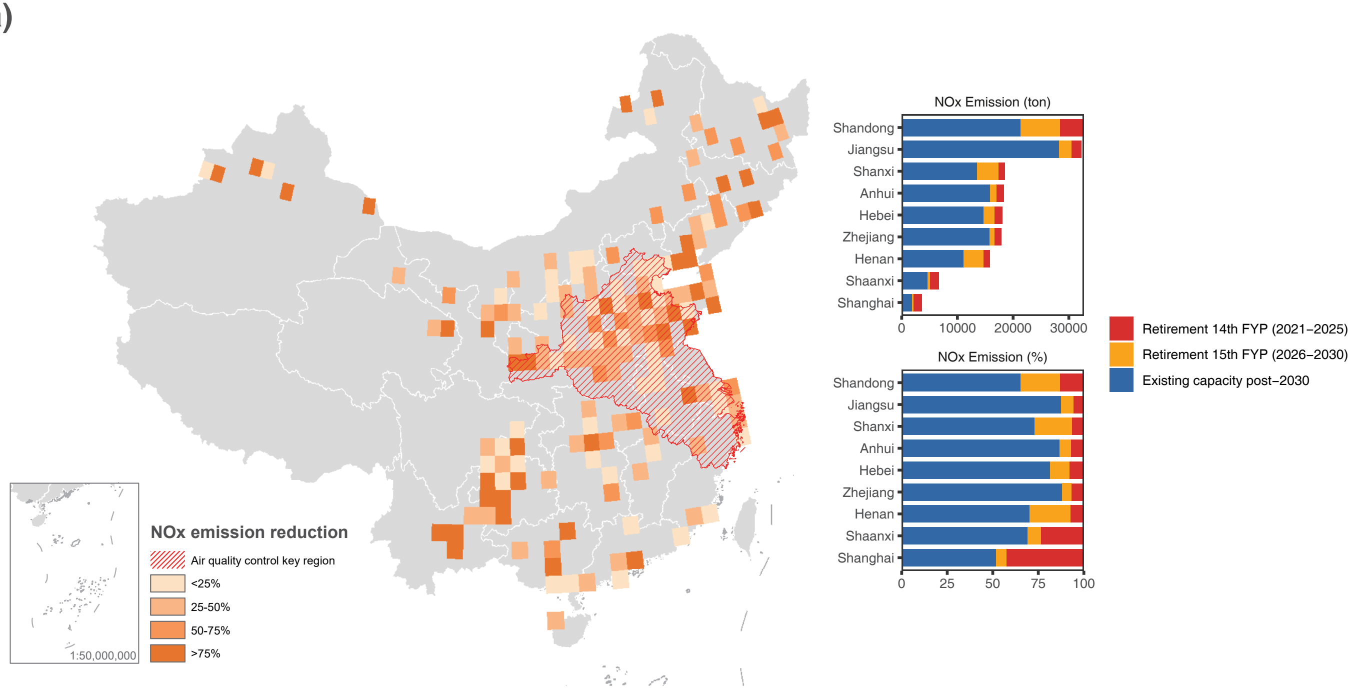
Retiring LHF plants can reduce local air pollutant emissions and improve air quality and public health.[30] Here, we quantify the impacts of retiring the identified LHF plants on local air quality, especially in the highly-polluted and policy-focused regions (see Supplementary Information for calculation method). The LHF plants are mostly old, small, less efficient coal power plants with high air pollution emissions per capacity.

Our results indicate that shutting down these LHF plants can reduce air pollutant emissions by 36.6%, 29.3% and 41.2% for SO_2, NO_x and PM, respectively, at the national level by 2030. Reduction of local air pollution emissions from retiring LHF plants ranges from 25% to 75% across provinces (see Figure 5).

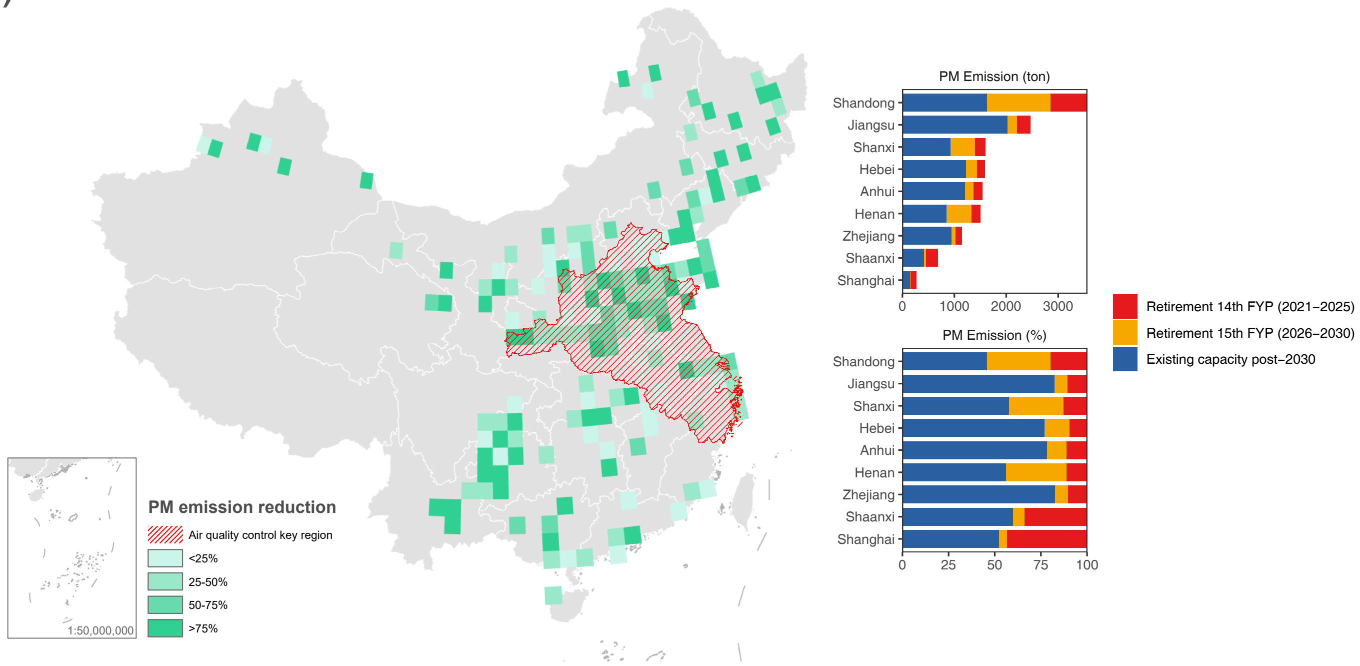
In the air quality control key areas, including Beijing-Tianjin-Hebei region, Yangtze River Delta and Fenwei Plain, we identified 59.8 GW (5.7% of coal power capacity), 132 LHF plants (12.2% of coal power plants). Retirement of these LHF plants can reduce air pollutant emissions in the air quality control key regions, NO_x emissions by 37.0 kt (22.6%), PM emission by 5.0 kt (35.0%), and SO_2 emission by 25.5 kt (26.8%) by 2030, respectively. The emission reductions achieved by the shut-down of the LHF plants in the near-term far exceeds the air quality targets in the key regions, especially in provinces like Shandong, Shaanxi, and Hebei (see Figure 5). Moreover, reduced emissions would meanwhile lead to air quality improvement and human health benefits, especially in densely populated areas, although not quantified in this study.

FIGURE 5. Air pollutant emission reductions from retiring low-hanging fruit plants before 2030 at grid-level and for provinces in the air quality control key areas.
(a) NO_x emission reduction, (b) PM, and (c) SO_2. The grid cell is 10° x10°.

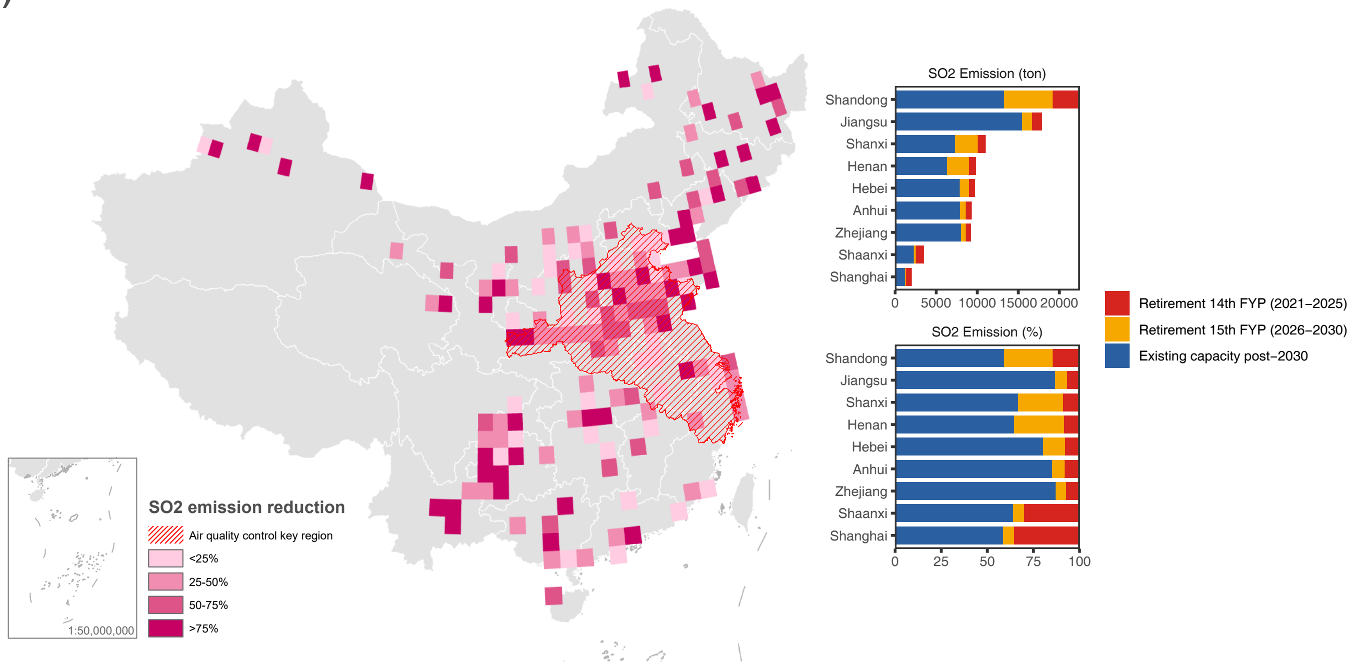
(a)



(b)



(c)



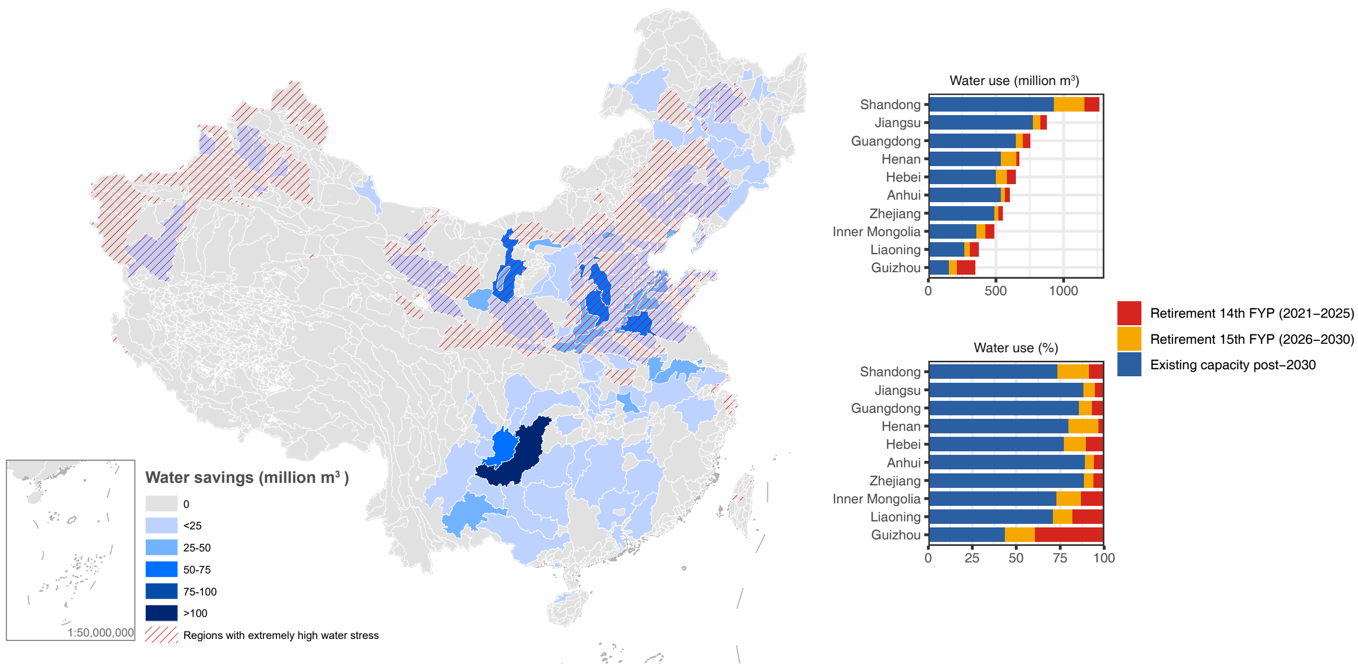
The reduced air pollutant emissions from shutting down LHF plants would also lead to decreasing population-weighted $PM_{2.5}$ concentrations and human health improvements nationwide, although these are not quantitatively assessed in this study. Studies estimate that 77,200 $PM_{2.5}$-related deaths could be avoided in 2030 strategic power plant retirements in line with the 1.5˚C carbon neutrality target in China.[30] As the potential for further reductions from end-of-pipe control measures are rapidly exhausted, complying with the World Health Organization (WHO) air quality guidelines (annual average concentrations of $PM_{2.5} < 5\mu g/m^3$) and minimizing human health impacts depends inevitably upon carbon mitigation. Retiring inefficient and highly-polluting LHF plants could be a critical starting point to achieve the health co-benefits of climate actions.

3.3. BENEFITS IN WATER CONSERVATION

Retiring LHF plants, especially those equipped with water cooling technology, will reduce annual water withdrawals. This study first identified plants equipped with water cooling technology. Based on this, we estimated the annual water withdrawals following China's water consumption guidelines for coal power generation for each coal power plant (see Supplementary Information for calculation method).

The results show that retiring LHF plants will save annual water withdrawals nationwide by 2.3 billion m^3 by 2030, equivalent to 60% of annual freshwater withdrawals in Beijing. It is worth noting that this is a conservative estimate of water saving, because the actual water consumption of most existing coal power plants is larger than the water consumption standard recommended in the policy. In some water-stressed regions such as the North China Plain area and Northwest China, the water savings is above 1200 million m^3 (see Figure 6). Saving water can improve water security in water-stressed regions. Moreover, retirement of LHF plants can bring additional benefits that are not quantified here, such as water quality improvement due to reduced thermal pollution from coal power plants.[31]

FIGURE 6. Water savings from retiring low-hanging fruit plants before 2030 by province (million m^3).



3.4. ECONOMIC RISKS IN STRANDED ASSETS

Although accelerated retirement of LHF plants will result in stranded assets, we find that the impact is relatively small. Here, we define stranded assets as the remaining book value of premature retired coal power plant assets, which is widely used in the existing literature,[32] while profits foregone due to premature retirement are not considered. Using a linear depreciation method,[32] we calculate the stranded assets by retiring LHF plants through 2030 (see Supplementary Information for calculation method). The results show that among all remaining plants today, US$23 billion or 5.7% of the total assets value will be stranded between 2021 and 2030. However, continuing to build new coal plants can be troublesome, because it will lead to large stranded assets in the sector, which will not only greatly exacerbate the financial strain within the coal sector itself, but also be detrimental to China's broader economic and development goals.

Across provinces, the magnitude of stranded assets varies but remains low for most provinces (see Figure 7). Retiring LHF plants will lead to relatively high stranded asset value in Inner Mongolia, Xinjiang, Shandong, Guizhou and Ningxia; and the highest share of stranded asset value in Qinghai. However, for most provinces, the share of stranded asset value is small. On average, 8.1% of total remaining value today will be stranded through 2030 at the provincial level.

Across power companies, stranded assets are mainly concentrated among the top five companies with the largest coal power plant assets (see Figure 8), namely National Energy Investment Group, China Huaneng, China Datang, China Huadian, and State Power Investment Corporation. The estimated stranded assets are similar across the top-five companies but vary in terms of the share proportionate to their current assets value. Among most major companies, the share of stranded asset value remains low within a range of 1% to 9% of total remaining value today stranded through 2030. However, some small local power companies in Shandong, Xinjiang and Shaanxi have over 90% of stranded assets, because the coal plants owned by these companies are small, inefficient, and identified as LHF.

FIGURE 7. Total stranded value of coal power plants from retiring low-hanging fruit plants before 2030 vs. total value of coal power plants in 2020 by province (in billion US$).

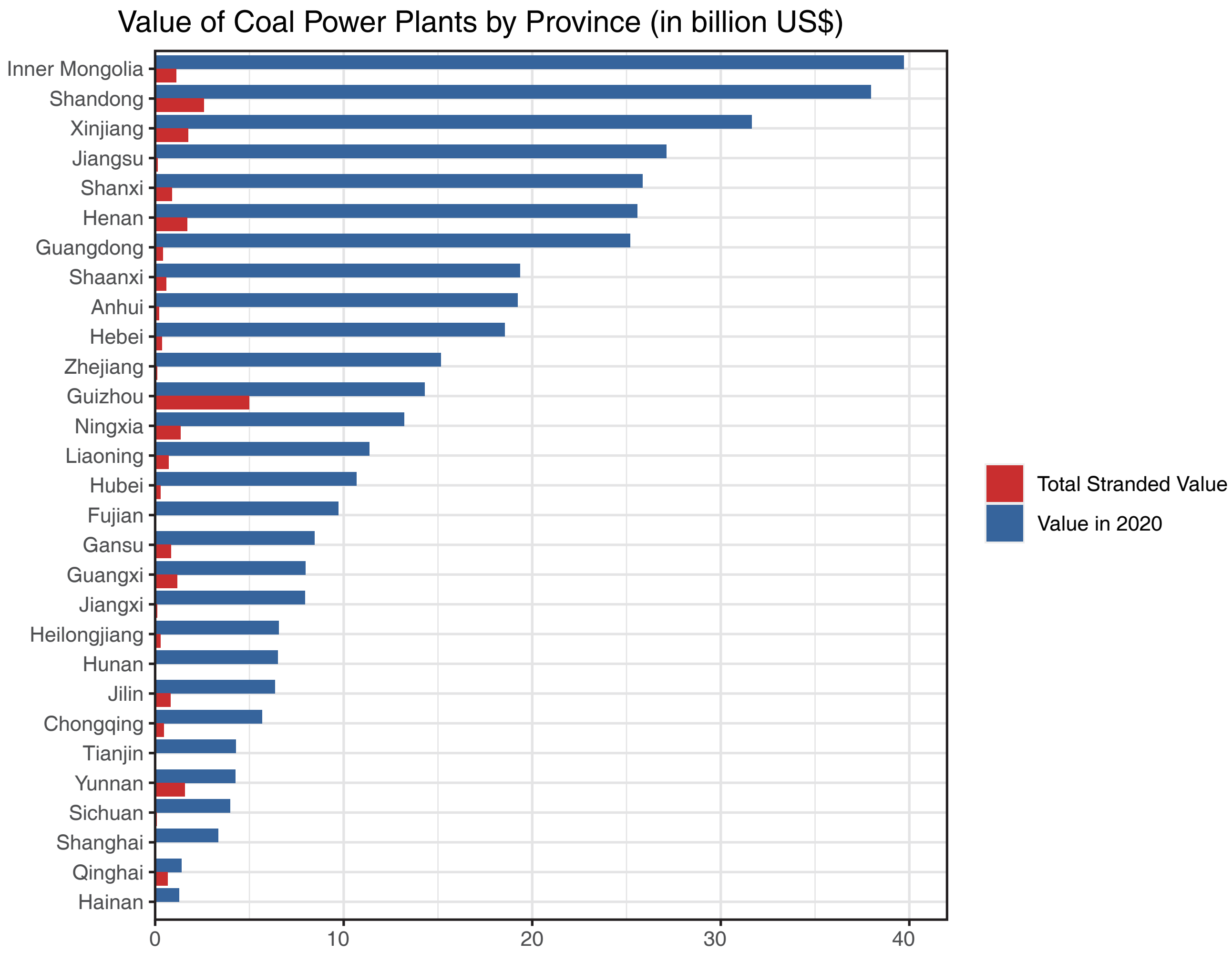
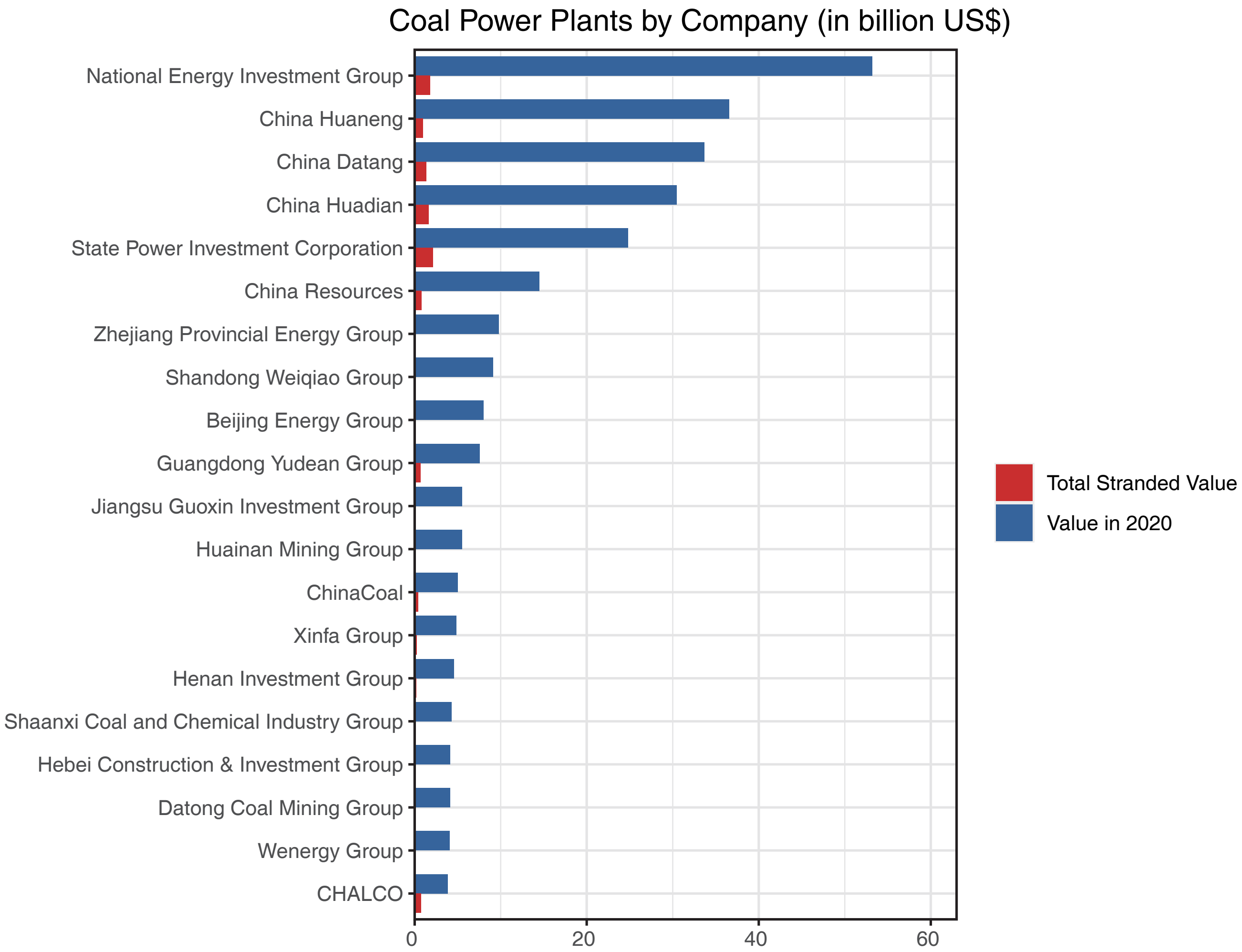


FIGURE 8. Total stranded value of coal power plants from retiring low-hanging fruit plants before 2030 vs. total value of coal power plants in 2020 by major power companies (in billion US$).



3.5. EQUITY AND JUST TRANSITION

The phasing out of coal fired power plants will have economic and social benefits and risks. Through applying the concept of a "just transition," this section focuses on understanding the distribution of benefits and burden of mitigating risks with the recognition that these are not shared equally across populations, time, and geographies. A just transition has become an increasingly important component in the shift away from coal use. Through highlighting the various inherent and unequal risks, there are policy options that can address socioeconomic inequalities and make the transition more sustainable.

There are often several concerns relating to energy transition job losses. First, the challenge of developing new jobs to replace those that are lost. Secondly, the rapid timing of job losses can have rippling impacts on families and the wider local economy. Third, these losses are usually concentrated geographically, impacting some regions much more than others. Our analysis calculates and then addresses all three of these concerns.

To better understand the equity and the employment impacts, we first calculate the total number of job losses caused by retiring the LHF plants. Then, we identify groups and counties that are most vulnerable during the transition. Finally, we provide suggestions to enable a smoother transition for affected workers during the coal transition in China.

Total coal job losses at national level

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. According to our estimation, retiring the 19.7% of existing coal capacity would lead to 293,800 job losses nationwide by 2030, accounting for around 33% of the total coal power sector direct employment today (see Supplementary Information for calculation method). The high proportion of job losses relative to capacity of LHF plant closures are because the majority of the identified LHF plants are small and old plants that are less productive and more labor intensive than modern plants. Figure 9 shows that laid-off workers mainly come from small coal plants under 300MW, and total job losses distribute roughly evenly during the 14th and 15th FYP.

Previous studies have found that renewable energy sectors are more labor intensive than that in fossil fuel sectors.[33] Given the rich renewable resources in China, especially wind and solar power, new green jobs will be created rapidly with the development of renewable power. According to the estimation by the International Renewable Energy Agency,[34] renewables could create between 11.6 and 13.8 million jobs in China by 2050. With the large expansion in renewable energy sectors and appropriate policy support for workforce retraining, job losses due to retiring LHF plants will most likely be offset.

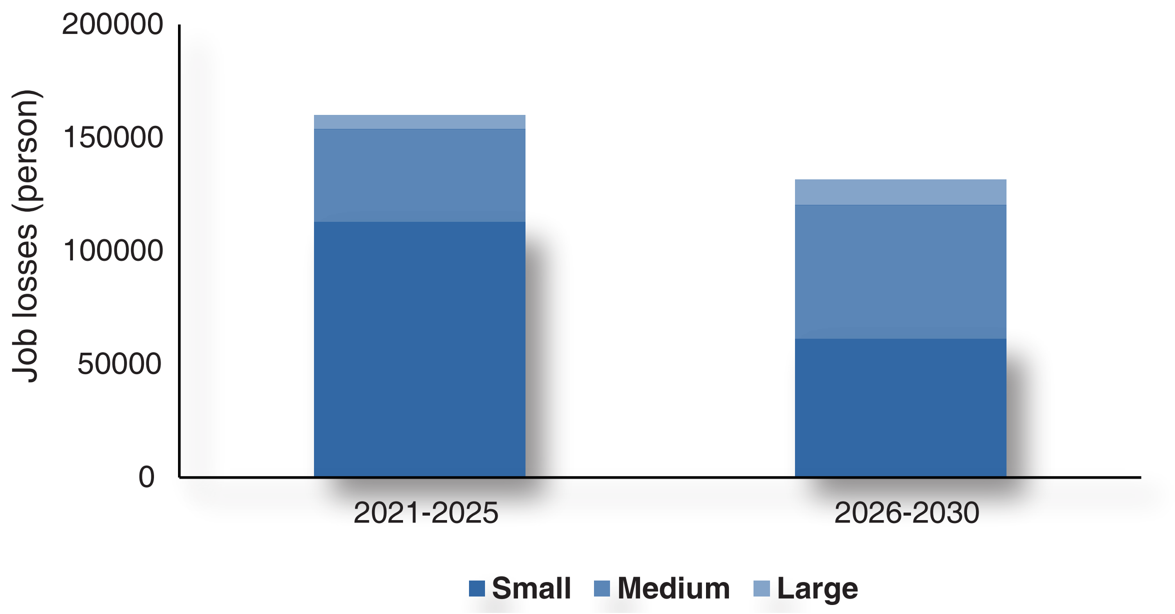
Temporal distribution of job losses

To make the transition smooth and manageable, coal power plants should be shut down in a phased manner to avoid concentrated job losses in a short time span. This provides workers, communities and the government enough time to plan, prepare and respond to unemployment and other potential unforeseen risks. As presented in Figure 10, the total job losses occur evenly along the 14th and 15th FYP period, rather than concentrating in one period. Our results also show that the incremental unemployment rate caused by phasing out LHF plants is only 0.02% in each period nationwide. This small percentage at this pace is manageable, especially given China's growing economy and the increase in renewable energy jobs.

Type of job losses: medium and high skill level workers

Based on the occupational structure and their responsibilities in the coal power plants, we identify the most impacted labor groups when closing the LHF plants. Then, detailed training and retaining strategies can be scheduled and well-prepared. We find that the group of employees facing higher laid-off risks are those working on the O&M of coal plants and that have relatively higher skill levels. Specifically (see Figure 10), around 226,000 thousand job losses happen in the operation, maintenance, and business management positions. The remaining unemployed workers come from the fuel system and other positions (like cleaning staff, cafeteria staff, guards, etc.), which account for only about one-fifth of the total job losses from the LHF plants.

FIGURE 9. Temporal distribution of job losses from retiring low-hanging fruit plants.

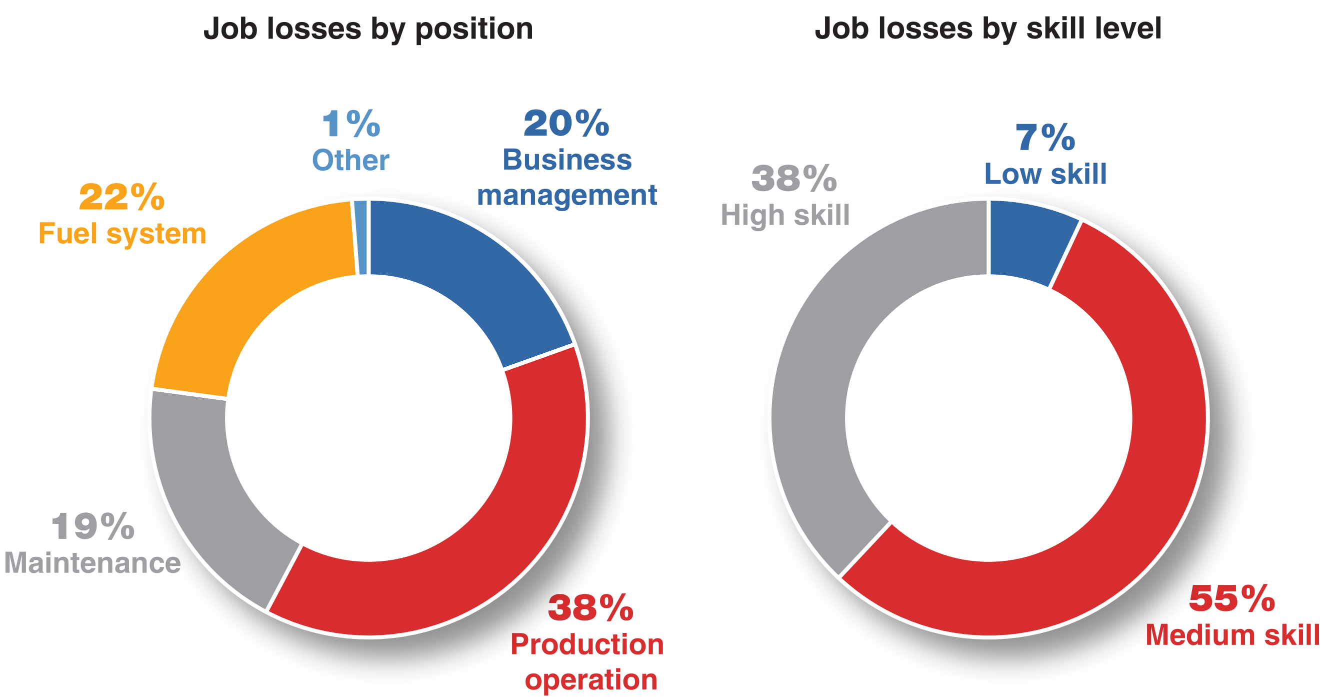


Small: unit capacity <= 300MW, Medium: unit capacity between 300-600 MW, Large: unit capacity >600 MW

From the perspective of the working skills of the potential laid-off workers, we find that 90% of them have medium or high working skills. Specifically, since the turbine operators and electric engineers in the coal plants have the skill set and working experience required by renewable power plants, it will be less challenging for them to be relocated to new positions in the renewable energy industry with proper retraining. Given their rich management experience and leadership, the business managers are easy to transfer to a new place within the same enterprise groups or even to a new industry.

The main challenges come from the coal pulverizer and conveyor operators who account for only a small portion of potential unemployment. Since renewable plants have no corresponding positions for those workers, and they usually have relatively lower working skills, it is more difficult for them to shift to other industries. Therefore, supportive policies and financial resources to prepare the workers from the coal sector to relocate in the expanding renewable sector are needed, especially for those low-skilled workers.

FIGURE 10. Characteristics of affected groups when retiring low-hanging fruit plants.



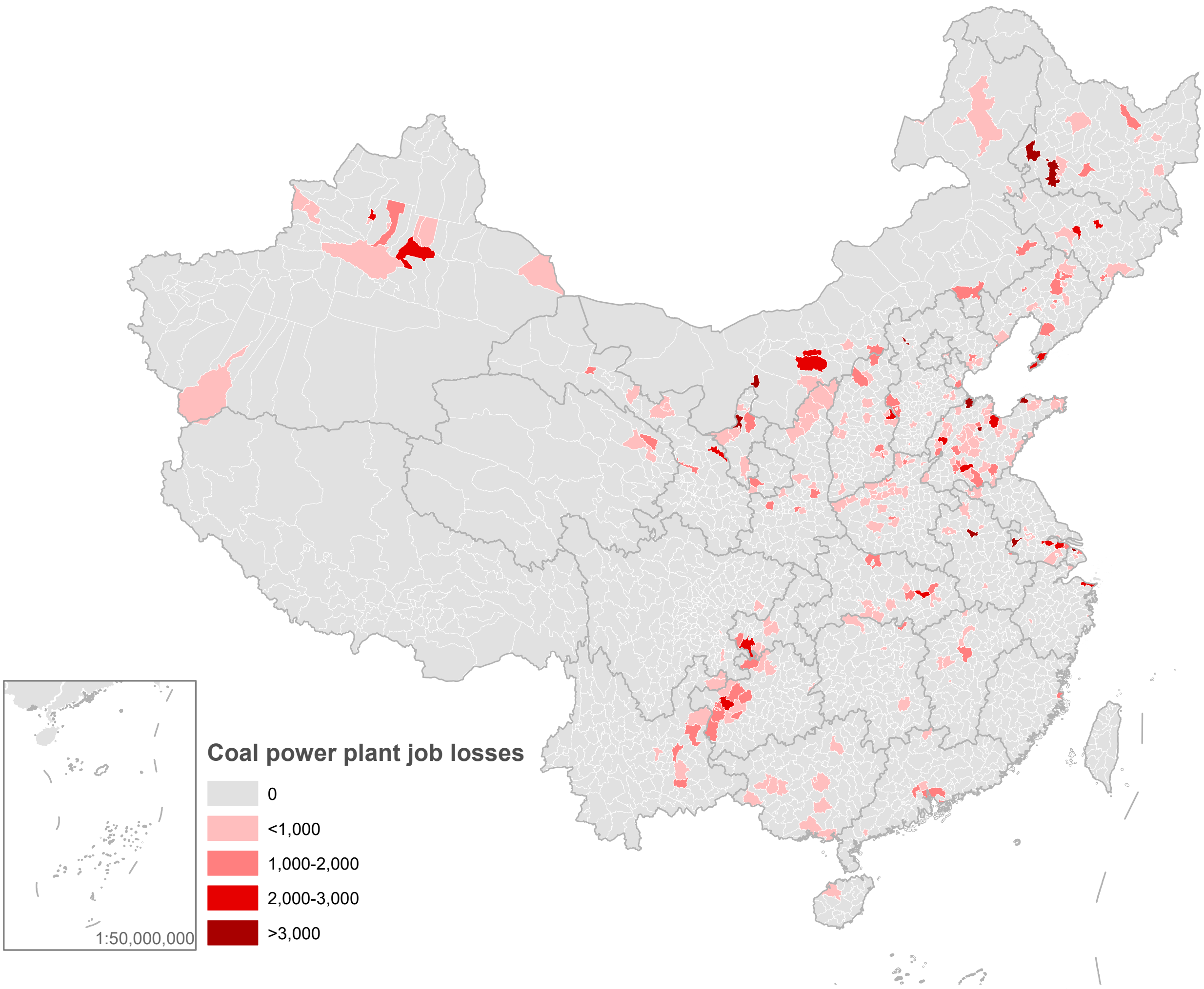
Region-specific needs and challenges should be addressed to make a just transition

Although the unemployment risks induced by phasing out LHF plants are affordable and manageable at the national level, there is significant regional inequality.[35] To ensure a just transition, region-specific needs and challenges should be addressed properly by targeted policies. Here, we identify the hotspot counties with a larger number of job losses or higher unemployment rates.

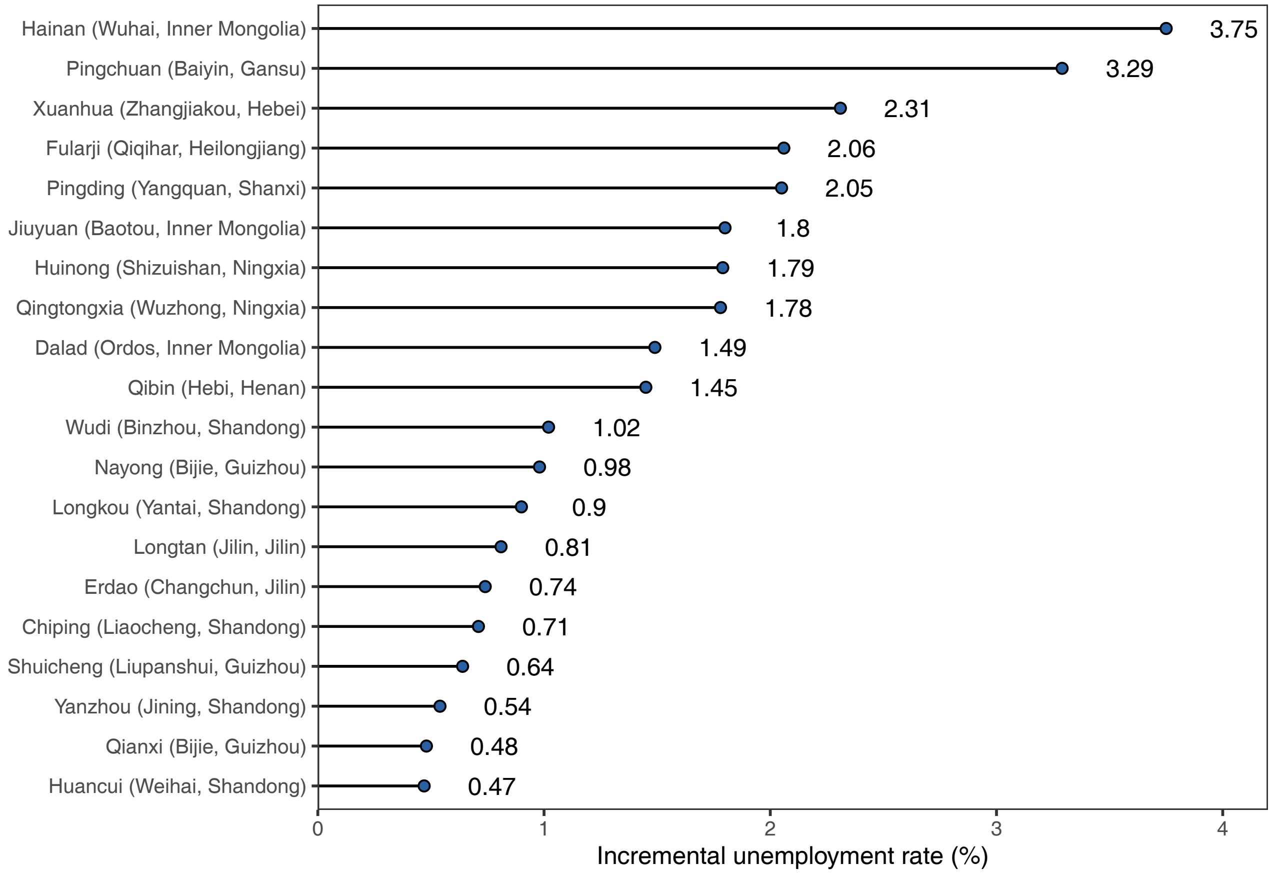
As shown in Figure 11, we find that most of the hotspot counties are located in heavily coal-dependent provinces, like Inner Mongolia, Ningxia, Shandong and Guizhou, etc. The laid-off workers account for about 0.047% of the nationwide total workforces. However, counties like Hainan (Wuhai, Inner Mongolia), Pingchuan (Baiyin, Gansu), Xuanhua (Zhangjiakjou, Hebei), Fularji (Qiqihar, Heilongjiang) and Pingding (Yangquan, Shanxi), etc., will face incremental unemployment rate ranging larger than 2%, over 40 times higher than the national average of job losses in the coal industry.

FIGURE 11. Hotspot areas with larger job impacts from the 14th and 15th FYP coal retirement.

(a)



(b)



Note: y-axis label as County/Disrict (City, Province)

Plant closures pose significant challenges to those hotspot counties. The closure of coal facilities will lead to laid-off workers, shrinking fiscal revenue and a weakened local economy as these regions usually depend heavily on the coal industry. Thus, these local governments need to enhance the economic diversification of coal regions through well-designed investment plans to green economies. Meanwhile, the governments should provide occupational training programmes to help skilled coal workers shift to new positions. Moreover, the governments should help to build an effective social security network for those old and low-skill workers who are not easily relocated to other industries. Targeted supportive policies that address the local challenges are needed to facilitate a socially and economically just transition away from coal for all regions, and ensure that coal-dependent regions will not be left behind.

This report only evaluates the job losses which are most directly impacted by closing coal power plants. More workers in the coal-value chain industries like coal mining and coal transportation are also facing similar or even higher unemployment risks and transition challenges. For example, compared with employees in the coal-fired power plants, coal miners face more challenges when transferring to other industries given their relatively lower working skills. Meanwhile, coal mining workers generally have closer ties with local communities, and thus are more difficult to relocate them. To leave no one left behind during the coal transition, supportive policies that help to retrain and relocate these laid-off workers should be carefully designed and implemented by both the central and local governments.

3.6. ENERGY SECURITY AND GRID STABILITY

One of the major concerns of retiring coal plants in the near-term is the potential impact on power supply and grid stability. As several provinces struggled with power outages in late 2021, stable power supply has become a high policy priority in China's 14th FYP. While reasons for the 2021 power cuts are complex, it is less of an issue of insufficient coal capacity, but rather shortages of coal supply and rigid power markets and systems.

Coal electricity plays an important role in providing baseload generation in China's power system and contributed to over 60% of total electricity generation in 2020.[3] With rapid growth of renewable energy in the past decade, the share of coal power in total electricity has been declining. As China sets up ambitious renewable deployment targets and its electricity demand continues to grow, coal plants are expected to gradually shift from baseload to peaking generation to help support an increasing share of renewables on the grid.[36] Meanwhile, it also means that coal plants will operate at a low utilization level with the ability to ramp up and down quickly without damaging the generators. To do this, it requires additional investments to retrofit existing plants for improved flexibility, which does not make economic or environmental sense for the low-hanging fruit plants identified in our analysis. It does not make economic sense to do this through large amounts of new builds either, which not only increases stranded assets risks but also makes the transition of existing plants harder.

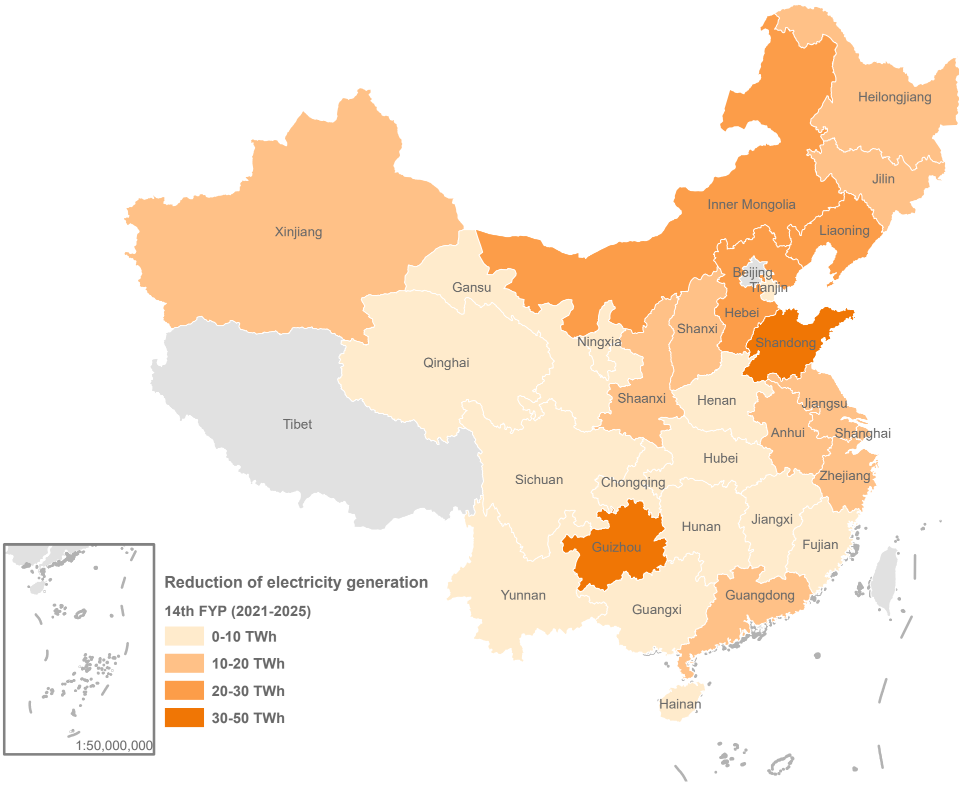
The 203 GW of LHF plants currently generates about 830 TWh of electricity, accounting for 11% of total electricity generation in 2020.[7] China has set a target of 1200 GW wind and solar capacity by 2030. Industrial experts and practitioners have more optimistic expectations that wind and solar installations will reach 1600 to 1800 GW by 2030,[36] which implies a continued buildout rate as of 2020 over the next decade with an average annual installation of about 120 GW. The newly-installed wind and solar could provide about 215 TWh electricity annually, or a total of 2,150 TWh by 2030.[36] At the national level, electricity generation from newly-installed renewables can offset the reduction due to the coal retirements and contribute to meeting growing demand.

While there is large uncertainty in future electricity demand, with a wide range between 9,317 TWh from the International Energy Agency (IEA)'s sustainable development scenario[37] and 11,300 TWh from China Electricity Council,[14] the remaining gap can be closed with a combination of multiple possible strategies, including energy savings and efficiency improvements at the end use sectors, increased generation from other low-carbon technologies (e.g., hydro, nuclear), and slightly increased generation from remaining coal plants if urgently needed.

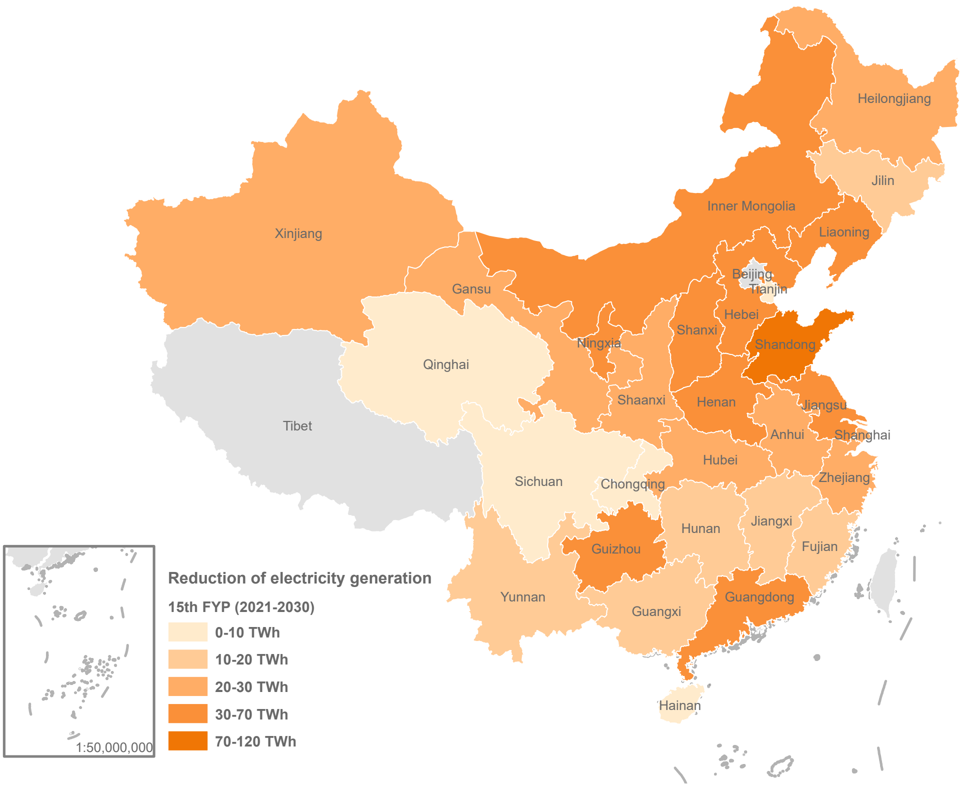
From a regional perspective, for the majority of provinces, retiring the proposed LHF plants would reduce power generation by less than 30 TWh by 2025 and less than 70 TWh by 2030 (see Figure 12). It is unlikely to have a large impact on electricity supply. Provinces with larger power losses, e.g., Shandong, Guizhou, Inner Mongolia, Hebei, etc., have abundant wind, solar or hydro power resources and ambitious targets on renewable energy and storage installation. Expected rapid installation of wind and solar capacity could meet the growing electricity demand in these provinces.

FIGURE 12. Reduction of electricity generation from retiring low-hanging fruit plants during 14th and 15th FYP (in TWh).

(a)



(b)



With the expansion of variable renewable energy (i.e., wind and solar) in the power mix, there is an increasing need for power system flexibility, the ability to respond to variations in electricity supply and demand in a timely manner. China has set ambitious development targets for pumped hydro storage throughout 2035,[38] with interim targets of 62 and 120 GW by 2025 and 2030, respectively. China also aims to install more than 30 GW of new energy storage capacity as a supplement to pumped hydro storage by 2025. With the rapid and continuous cost reduction, battery storage will become more commercially competitive in the coming years. At least 20 provinces in China have ordered renewable power developers to install supporting energy storage of wind and solar plants. China also encourages suitable conventional coal units to undertake flexibility retrofit for higher ramp capability and lower minimum power generation, and set a target of 200 GW renovation in total by 2025,[18] adding 30-40GW flexibility resources to the grid. China's ambition to build a nationally-unified electricity market would promote inter-provincial electricity transmission, and provide increased access to a variety of generation resources, and smooth out the fluctuation of renewable resource generation and electricity demand. The adoption of market-based pricing tools would also incentivize customers to use more energy at off-peak times to balance demand.

In addition, the volatility of coal price and introduction of the national ETS make it less certain that coal power plants can remain profitable and provide stable electricity supply. Therefore, reducing the dependency on coal and shift to alternative fuel could help to improve the energy security in the long-term. Retiring the LHF plants will be a critical first step of phasing out coal and increasing the use of renewable energy that will contribute to better energy security in China.

4 CONCLUSIONS

4.1. KEY FINDINGS

In this report, we develop a comprehensive plan to phase down coal-fired power capacity in China during the 14th and 15th FYP by retiring a small set of low-hanging fruit plants. We also demonstrate the value and effectiveness of this plan by quantifying the large benefits and small risks of these retirements with respect to broad societal outcomes. The well-structured and targeted near-term coal retirements, combined with rapid renewable deployment, efficiency improvements, and cross-region balancing, can help China achieve a rapid and orderly transformation of the power system in support of the national carbon neutrality goal and the global 1.5°C goal. It is also aligned with China's key policy priorities on air quality, public health, and water conservation.

Key findings include:

- Through a comprehensive review of existing policies on coal plant closure, retrofitting, and new builds, we estimate that total coal power capacity may grow by about 158 GW through 2030, with 202 GW of new builds and 44 GW of retirements, and reach 1,237 GW during the 15th FYP (or 1,139 GW with all early-staged plants canceled).
- Utilizing additional policy measures, including the national carbon trading scheme, the clean air action plan, and water conservation targets, total retirement potential can increase to 203 GW (19.4% of existing coal power capacity) by closing 1,040 low-hanging fruit units (34.8% of operating units) during the 14th and 15th FYP, reducing total coal power capacity to 981 GW with conservative coal buildout by 2030.
- This plan includes increasing retirements from the 14th to the 15th FYP (see Figure 3). 95 GW (9.1% of existing capacity) is expected to retire between 2021 and 2025, mostly driven by the implementation of the clean air action plan. The other 108 GW (10.3% of existing capacity) is expected to retire between 2026 and 2030, mostly driven by the implementation of the national carbon trading scheme and the water conservation target.
- Across provinces, retirements are evenly-distributed in the central east, northeast, and southwest of China, with the largest capacity retirement in Shandong, Guizhou, Henan, Inner Mongolia, and Hebei. Retirements account for a small share of existing coal power capacity for most provinces, except for Qinghai, Yunnan, and Guizhou (see Figure 3), where coal has a less important role in the power system with large renewable energy potentials.
- This retirement plan generates large societal benefits. It contributes to climate mitigation by reducing 925 Mt or 20.6% of CO_2 emissions, improves air quality and public health by lowering air pollutant emissions including SO_2 by 36.6%, NO_x by 29.3% and PM by 41.2%, enhances average efficiency of coal power generation by 3.3%, and reduces water withdrawals from power generation by 2.3 billion m^3 annually (Table 2).
- This retirement plan has limited and manageable risks on stranded assets and job losses. Only 5.7% of today's remaining assets values will be stranded through 2030. Although coal power employment experiences a 33% reduction due to higher labor intensity of small and old coal plants, the majority of laid-off workers have sufficient skills to be reallocated to new positions with proper training (Table 2).
- This retirement plan has negligible risk to the grid. Newly-installed solar and wind power can increase electricity generation by 2,150 TWh in 2030, offset the loss from the low-hanging fruit plants' retirement (830 TWh), and contribute to meeting growing electricity demand in combination with other strategies. It does not make economic or environmental sense to retrofit the low-hanging fruit plants for improved flexibility to provide peaking generation and support an increasing share of renewables on the grid.

TABLE 2. Total benefits and risks of the coal retirement during the 14th and 15th FYP*

Benefits			Risks	
Carbon emissions reduction in 2030 (% of 2020)		925 $MtCO_2$ (20.6%)	Total stranded assets between 2020 and 2030 (% of 2020 coal plants assets value)	US$25 billion (5.7%)
Efficiency improvement from 2020 to 2030		3.3%	Total job losses between 2020 and 2030 (% of 2020 coal plants jobs)	293,800 workers (33%)
Air pollutant emissions reduction in 2030 (% of 2020)	SO_2	143.8 kt (36.6%)	Reduced power generation from low hanging fruit plants (% of 2020 total electricity)	830 TWh** (11%)
	NO_x	160.5 kt (29.3%)		
	$PM_{2.5}$	25.1 kt (41.2%)		
Savings of water withdrawal in 2030 (% of 2020)		2.3 billion m^3 (23%)		

* $MtCO_2$: million metric tons of carbon dioxide; kt: metric kiloton; TWh: terawatt-hour; m^3 : cubic meters. SO_2: sulfur dioxide; NO_x: nitrous oxide; $PM_{2.5}$: fine particulate matter 2.5 microns in width.

* * Note: Newly-installed solar and wind generation from 2021 to 2030 is estimated to be 2150 TWh.

4.2. DISCUSSION

As discussed above, the growing environmental costs of continuing operating coal fleets in China and the environmental-social-economic benefits of coal phase down suggests the need to take early action by retiring coal power plants in China. This study provides a comprehensive and feasible strategy for retiring LHF plants in China by 2030. This type of strategy, which takes a long-term, national, and subnational perspective, provides a mechanism to spread coal retirements relatively evenly across the country and over time. This can proactively reduce shocks and risks for local communities, provinces, and regions to ensure that no region is overburdened. At the same time, it supports the necessary additional investments for building sustainable green economies and supporting workers and their families. It also provides the time for the appropriate regulatory, fiscal and technical planning and implementation for a sustainable energy transition.

Our study suggests that there will be different concerns at the regional and national scale. Some provinces such as Qinghai, Yunnan, and Guizhou have a higher share of plant closures. However, they also have large renewable energy potential and therefore the integration of renewables into their grids would likely accelerate the retirement of LHF plants. The advancement of regional power trading and the improved regional integration can give Guizhou, for example, access to renewable energy sources to replace the local coal power generation. This calls attention to the need to couple coal retirements within a wider renewable energy strategy that considers renewable energy investment, energy efficiency and transmission, and load balancing. Further, the retiring of LHF plants will have job implications on the local and regional levels, even though according to our analysis, there will not be large scale job losses at the national level. Due to these uneven impacts of closing the LHF plants, coordination between national and subnational governments is critical to ensure the transition is as fair and smooth as possible.

There is still more research that can be done to advance our understanding of retiring coal in China. More updated and accurate operating and emissions data, especially for small or self-use coal power plants, can be collected to refine the assessment of the benefits and risks of retiring LHF plants. Detailed health impact assessments using chemical transport models and exposure-response functions that quantify avoided premature death could better reveal the disproportionately large health benefits of targeted coal phasedown strategies. In addition, wind and solar resource availability assessment with higher spatial and temporal granularity can be integrated to evaluate the impacts of retiring LHF on energy security and grid stability, especially in regions with large capacity of coal retirement.

The report results offer a way forward and provide ample reasons for this work to start within the next five years. In order for a coal phase-down strategy to become reality, additional planning on the parts of the national and subnational governments will be required.

National and subnational government could begin implementation with the following steps:

1. Drawing on the report results, subnational and national governments can conduct a plant-level review to identify an early retirement schedule and strategy.
2. Combine this strategy with an analysis of renewable energy, grid, storage and transmission investment, and fiscal planning to fund these investments and to replace any lost tax revenues.
3. Building on the estimates provided here, evaluate the job losses and their composition at the county level and provide dedicated fiscal and capacity-building support for actions such as job training for impacted workers.

Through a strategic approach, the analysis presented here contributes to meeting China's long-term policy objectives of reaching carbon neutrality, becoming an ecological civilization, and supporting China's social and economic development. In the short-term, it advances multiple intersecting regional policy goals for water management and air quality, with rippling benefits for adaptation to climate risks and public health. Even though China is not yet part of the Global Coal to Clean Power Pledge (announced at COP26),[39] the implementation of retiring LHF plants domestically can offer some indication of its political ambition in decarbonizing its power sector, it would also stimulate further policy alignment with its pledge to stop coal financing overseas. [40] Through phasing-down coal, China can meet its goals, be a model to demonstrate a pathway for countries and regions facing similar challenges in their transition, and support global climate efforts.

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