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YSSP Report
Young Scientists Summer Program

Understanding the employment and fiscal consequences of coal phase-out in China

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Abstract

China hosts more than half of global coal-fired power generation capacity and has the world's largest coal reserves. If China's 2060 carbon neutrality goal is to be achieved, domestic demand for coal is expected to shrink by at least 90% by 2060. This analysis uses asset-level data on coal plants and mines to construct a coal production-consumption network and to model the impact of coal power plant phase-out on coal power industry employment and net tax revenue.

At a constant rate of productivity increase, significant job losses in the coal industry will occur regardless of climate policy. Under a carbon-neutral trajectory, coal power generation will peak within a few years and decline thereafter, accelerating declines in coal demand, and reinforcing the effect of productivity gains on on coal jobs. In turn, declining tax revenues from capital and labour reduce the net fiscal contribution of the coal power sector.

For labour-efficient provinces, productivity gains have less impact relative to total mining jobs, and vice versa. Under the baseline scenario (current policies), employment supported by coal power drops to under 1 million by 2036, 500,000 by 2042, and 250,000 by 2045. Fiscal revenues rise initially, peaking with capacity in 2023. The ¥350-400 billion in total tax revenue annually up to the mid-2030s compares to estimated annual subsidies of ¥300-350 billion, suggesting the net fiscal contribution of coal power is less than ¥100 billion per year, without accounting for unpriced externalities.

Changes in coal industry employment are relatively unaffected in all but the most aggressive of climate policy scenarios. The tax base for coal is more capital-intensive than labour-intensive, since initial job losses do not induce a decline in tax revenue, and in each scenario, sharp declines in tax revenues begin only when capacity retirements accelerate.

The largest sources of employment, through operation of coal plants, are the 'Big Five' power generation companies, supporting 41% of China's coal jobs between them. 30-40% of these jobs are lost by 2030, and another 30-40% by 2040. The Big Five are also the largest contributors to tax revenues nationally, at ¥140 billion between them. This remains steady until 2030, falling by over half by 2040 in most cases, and collapsing to less than 10% of the starting value by 2050.

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1. Introduction

China has been the world's largest emitter of greenhouse gases since 2005 (ClimateWatch, 2020) and hosts more than half of global coal-fired power generation capacity. Power plants are concentrated in the populous Eastern provinces, and increasingly in the coal-rich autonomous regions of Inner Mongolia in the North and Xinjiang in the West, as well as the Central province of Shanxi. In 2020, amid the global economic slowdown induced by the COVID-19 virus pandemic, capacity additions accelerated, accounting for three-quarters of globally commissioned coal capacity, and 85% of capacity under development (Shearer & Myllyvirta, 2021). China also produced 53% of the world's crude steel in 2019 and 60% of its cement in 2017 (Curry & van Oss, 2020; World Steel Association, 2020), both of which rely heavily on coal as an energy source. Replacing unabated coal plants with net zero emissions alternatives in China is therefore critical to global industrial decarbonisation.

In September 2020, President Xi Jinping announced China would set itself a target of reaching carbon neutrality by 2060, and to peak emissions "before 2030" (Myers, 2020). The 14th Five Year Plan (FYP), a guide to national policy priorities from 2021-25 published after the announcement, targets 20% non-fossil energy in final consumption by 2025 and 25% by 2030. While it mentions an 18% drop in CO_2 emissions intensity by 2025, the targeted 6% annual GDP growth means total emissions may still rise by 2025 (Myllyvirta, 2021).

Modelling of emissions pathways for China consistent with carbon neutrality by 2060 projects unabated coal power will be phased out by the mid-2050s under a 2˚C global warming scenario, or mid-2040s under a 1.5˚C scenario, with any remaining domestic or industrial usage eliminated by 2060. Even if carbon capture and storage (CCS) technologies reach commercial scalability and see wide deployment, the coal fleet – over 90% of which is estimated to be owned by state-controlled companies (Herve-Mignucci, Wang, Nelson, & Varadarajan, 2015) – shrinks by 90% or more by 2060 (J. He et al., 2020). Under China's neutrality targets, a near-total phase-out of coal power in China in the next 40 years is essentially inevitable. Assuming a 30-year operating lifetime, coal plants in China built after 2015 risk early retirement under a 1.5˚C scenario. Under a 2˚C scenario, any plant built after 2025 risks a similar fate.

Prior analysis of coal phase-out in China and beyond has focused on the financial implications of asset stranding for the owners of coal plants and mines (Bodnar et al., 2020; Cui et al., 2020; Gray & Sundaresan, 2020; Spencer, Berghmans, & Sartor, 2017; Yuan et al., 2020), and optimises plant-level phase-out processes according to profitability, environmental impact, or both. Relatively little work has examined the role of some of the other key priorities of government, namely employment and productive economic activity (for which energy costs, and fiscal revenues and costs, are partial proxies), as determinants and/or consequences of coal phase-out in China. Although strategies for managing the political economy frictions of phasing out coal in China have been examined qualitatively in Caldecott et al. (2017), the quantification of the employment and fiscal impacts has been challenging owing to the absence of detailed mine- and plant-level data.

This analysis uses plant-level data and a detailed reconstruction of the coal production-consumption network to model the impact of coal phase-out on employment and tax revenue from the coal industry in China under a range of plausible climate policy scenarios. It considers the implications for the political economy of coal transition, and for the design of corresponding redistributive policies in China. Part 2 presents an overview of international experience with the socioeconomic challenges presented by coal phase-out and strategies employed for managing the impact on consumers, workers, and public sector revenues. It situates these challenges within the context of the Chinese coal industry. Part 3 lays out a methodology for projecting the employment and fiscal impacts of coal transition in China. Part 4 presents results at national, provincial (through case studies), and firm levels. Part 5 analyses the implications of the findings for the Chinese government in managing the transition. Part 6 concludes.

2. Literature Review

Coal transition outside China

Literature and statistical evidence on the socioeconomic impact of coal industry maturation and transition outside China focuses mostly on the United States (U.S.), United Kingdom (U.K.), and European Union (E.U.) as examples of the few major economies that have been transitioning away from coal for a number of years. The market structures and political systems of these regions are very different to China, with lower or negative energy demand growth, and less dependence on coal for industrial energy supplies. The relationship between the volume of coal extracted and the number of long-term jobs it supports can vary depending on how automated the mining process is, size and accessibility of deposits, type and quality of coal being mined, regulation, competition, and physical proximity to coal and labour markets.

The coal industry had all but disappeared in the U.K. by the 1990s. A 90% decline in production from 216 Mt in the decade to 1962, to 20 in the decade to 2012, was accompanied by a 99% decline in jobs (from 664,000 to 6,000 in the same period) (Department for Business Energy & Industrial Strategy, 2020). The ten-fold labour productivity improvement that this suggests mirrors the Chinese experience.

The E.U. and U.S. have experienced chronic declines in coal mining employment. Across the E.U., coal mining jobs fell 50% to 130,000 between 2007-2017, with almost two-thirds of the remaining jobs located in Poland (Galgóczi, 2019, p. 17). In Germany, total direct and indirect employment in coal power and mining declined from over 700,000 in 1985 to under 100,000 in 2015, driven by a combination of factors including post-Soviet market liberalisation and coal price trends, industrial consolidation, competition in international markets, domestic renewables, and technical advances (Oei et al., 2020). In a study of E.U. coal mining regions, Alves Dias et al. (2018) estimate total employment in coal-related jobs at 238,000 in 2018 (less than 0.1% of E.U. employment). They suggest 160,000 of these will be lost by 2030, 25% of which are in a single Polish region where coal mining provides half of all employment. In the U.S., coal mining contributed just 40,000 jobs in 2020, compared to 89,000 in 2011 and 177,000 in 1985 (U.S. Bureau of Labor Statistics, 2021). Coal power plant-related jobs averaged 79,700 in 2019, compared to 363,000 in wind and solar generation alone in the same year (National Association of State Energy Officials & Energy Futures Initiative, 2020, p. 40).

The E.U. *Coal Regions in Transition* platform[1] explicitly acknowledges the geographic concentration of coal-related employment in a small number of regions, which in turn frequently exhibit robust opposition, from workers' communities and labour unions, to phase-out policies in the absence of support measures, even in countries with relatively small coal economies, such as France (Jakubowski, 2019, p. 94). Measures to dampen localised employment shocks, prevent deterioration of locally funded infrastructure, and divert labour to new markets, have been deployed in several European countries. Germany has established a €40 billion investment programme in education, innovation, and social safety nets in collaboration with trade unions; and Spain has allocated €250 million to transition support, while also requiring firms to submit just transition plans before closing production sites. The U.K. and France have no clear just transition policy in place other than small-scale local government support measures and company redeployment, but in both cases coal plays a very limited role in the national economy (Sandbag, 2019).

Bridle, Kitson, Duan, Sanchez, and Merrill (2017) review the effectiveness of coal transition policies in Wales, Spain and Kentucky, finding that policies to support mining regions in decline have in

[1] https://ec.europa.eu/energy/topics/oil-gas-and-coal/EU-coal-regions/coal-regions-transition_en

some cases effectively supported diversification into other industries, attracting investment and new jobs, but have not been successful in ensuring that former coal miners and their dependents benefit from this investment. Their findings specifically suggest that early retirement schemes for mine employees can soften the immediate impact of redundancies and reduce fiscal uncertainty for local governments, but dampen incentives for workers to seek alternative employment or retrain and risks creating long-term dependence on state support. These schemes can also be very costly to maintain through to retirement age, particularly for younger workforces.

The coal industry also benefits from public subsidies. Across the G20 economies, coal is estimated to benefit from at least US$63.9 billion in subsidies annually, with the majority going to coal-fired power generation, including US$15.4 billion in direct fiscal support, and US$20.9 billion in capital investments by state-owned enterprises (Gençsü et al., 2019). To the extent that reduced tax revenues are offset by reduced subsidies, coal phase-out can be revenue-neutral or even revenue-positive, in which case the primary difficulty for governments may not be macroeconomic stability or growth, but redistribution of fiscal support and investment among subnational regions or groups.

Coal transition in China

Besides being home to over half the global coal plant fleet, China is also the world's largest coal producer. Its coal mines supply much of the coal combusted in its power plants. Throughout the 13th FYP period (2016-2020), the central government pursued a coal consolidation policy, closing smaller mines in favour of large, centralised coal bases (People's Republic of China, 2016). An estimated 73% of mine closures from 2016-18 were small-scale, state-owned mines that were nevertheless still larger and more labour-efficient than private sector mines, and more often controlled by diversified companies able to redeploy workers within the same corporate structure (Hao, Song, Feng, & Zhang, 2019). The consolidation policy has also increased industry concentration: 10 mining companies accounted for 42% of output in 2018, and mines with over 1.2 million tonnes (Mt) annual production capacity made up 80% of national output (Hao et al., 2019). The total number of mines is expected to fall from 4,700 in 2020 to 4,000 in 2025, even as total coal production rises 1% annually to a cap of 4.1 billion tonnes in 2025. By this time, 25% of mines are expected to employ labour-saving "smart production techniques" (Z. Liu, 2021).

In 2016, the government projected 1.3 million jobs would be lost by 2020 in the coal sector as a result of capacity reduction and consolidation policies (Ministry of Human Resources and Social Security, 2016), and implemented measures including an ¥100bn (c. $15bn) "Industrial Special Fund" launched by the Ministry of Finance to support worker relocation and fund welfare payments (People's Republic of China, 2017). Consistent with these projections, direct employment by coal companies peaked at 5.3 million in 2013, falling to 3.2 million in 2018 (G. He, J. Lin, Y. Zhang, et al., 2020). Caldecott et al. (2017) project that improved technology will reduce coal jobs by a further 50% to 1.6 million in 2050, with restrictions on capacity reducing total coal jobs in 2050 to 900,000. Shanxi province, the second-largest coal producer in China, is expected to have drawn at least ¥3.5 billion from the national Industrial Special Fund by 2022 to support relocation, retraining, early retirement, and public sector job creation needed to cope with the effects of coal capacity control policies. Shanxi, which has also invested heavily in regeneration of depleted mining areas, energy source diversification, and other measures, remains a relative outlier, however (Bridle et al., 2017).

The labour intensity of coal mining diverges sharply across provinces (UIBE & Chinese Academy of Sciences, 2019). That of the most efficient province, Inner Mongolia (1.7 jobs/10,000 additional tons of coal production) is similar to contemporary Germany. At a constant rate of productivity increase, less labour-efficient provinces will see much greater job losses as a proportion of total mining employment in the short term. The fiscal contribution of coal power to China's public finances will be affected by this expected decline in jobs, to the extent that coal industry tax revenues are based on labour.

Based on these projections, China may expect large-scale job losses in the coal industry whether or not it introduces punitive climate policy measures, even if it continues to add new capacity. If the 2030 and 2060 targets are to be realised, coal power generation will peak within a few years and decline thereafter, accelerating demand for coal, which will in turn affect coal industry jobs, and drag down fiscal revenues from the sector. Understanding the trajectory of employment and tax revenues associated with the coal industry under different coal phase-out scenarios can help establish the scale of the changes that will occur and identify the options available to state institutions to distribute cost and benefits effectively.

Other regions' experiences with coal transition suggest China's coal industry is not anomalous in facing large-scale job losses, concentrated in coal mining areas, primarily as a result of productivity growth – although this effect has been compounded elsewhere by chronically declining coal demand, which is not yet the case in China. The challenge for China's government is the scale of the coal industry, the correspondingly large potential disruption to labour markets, and the ability of coal industry interests at subnational and corporate levels, including those nominally under the direct control of central government, to resist policies that will accelerate employment trends.

In meeting its policy targets, China will ultimately need to replace the coal economy with zero-carbon energy production and manufacturing, which in turn provide new sources of employment. In the electricity sector, this means replacing retired coal plants, and meeting demand growth, with a combination of renewable energy and various forms of storage (pumped, chemical and battery), complemented by nuclear power, with a less certain role for CCS. In heavy industry sectors reliant on coal for heat, the large-scale production of zero-emissions 'green' hydrogen (and derivative products, including ammonia) from renewable energy sources is likely to be required. Mealy and Teytelboym (2017) identify 'green adjacent possible' pathways for U.S. workers in high-carbon industries based on occupational skills data to guide the efficient reallocation of labour from high- to low-carbon occupations. Data limitations aside, this approach can in principle be applied to China.

Replacing tax revenue tied to coal is also challenging, particularly where it is a major component of local or city government funding for research facilities, hospitals, infrastructure, and delivery of other public services. At a national level, the withdrawal of subsidies for coal (implicit and otherwise) and introduction of a national emissions trading system (ETS) may help coal produce a net positive fiscal impact immediately, although these savings and new revenues would likely need to be redistributed to address localised fiscal or other economic losses. Short-term measures to stabilise revenues may include dedicated transition funding from central government – which can be funded through savings from reduced subsidy payments – and investment by development finance actors including policy banks and – to an extent – state-owned commercial banks, but longer-term measures require either raising revenues from clean energy without unnecessarily slowing its development, greater borrowing on the expectation of higher future growth, or reducing public spending. The latter may be unviable, not least due to the need to meet contingent liabilities (e.g. outstanding bonds and loans) held by government through ownership of state-owned enterprises (SOEs) in the coal industry, clean-up costs for former mining sites, long-term health, environmental and climate costs, and the cost of relocating and retraining labour supplies.

China's depleted coal mining areas have already faced these structural challenges, albeit driven by dwindling supplies rather than demand. Previously thriving cities built on coal have failed to diversify before supplies run out. Fuxin, in Liaoning province, once hosted Asia's largest open pit mine, with 500,000 city residents either employed or dependent on it at peak production. The mining bureau funded local hospitals, schools and other facilities. The mine entered bankruptcy in 2005, resulting in thousands of job losses, and ultimately civil unrest. Some jobs for younger, stronger workers were restored following restructuring, but at lower wages (Murtagh, Kan, Murphy, & Mayger, 2020). While Fuxin's decline was supply, not demand, induced, and it has partly recovered through investment in wind and solar industries, without proactive policy its trajectory may be repeated in many other locations as demand for coal declines and mining area consolidation proceeds.

3. Methodology

Using datasets of China's coal plants and mines, and applying a range of necessary assumptions on plant utilisation rates and productivity improvements, this study models the distribution of job and tax revenue losses across space and time in China's coal power sector.

The model overlays employment and tax calculations on a demand-driven coal production network constructed from plant and mine data, both of which also contain information on the corporate owners of each asset. It links employment in the coal power sector and coal mining industries to the building and retirement of plants from 2021 to 2060. Employment in the coal transport sector is not accounted for, nor does the model account for coal use outside the power sector, owing to a lack of sufficient data.

Coal demand is modelled on the basis of operating or planned coal power plants in China, using a composite dataset updated in February 2021.[2] Plant-level coal consumption is estimated based on 2019 province-level utilisation rates, to avoid pandemic-related distortions in 2020[3]. Coal consumption rates vary depending on the size and type of plant (subcritical, supercritical, or ultra-supercritical), its operating efficiency, and the type of coal it consumes (anthracite, bituminous, sub-bituminous, or lignite). Coal generation capacity (GW), utilisation rates (%), estimated generation (TWh) and production statistics by province (million tonnes of coal equivalent, Mtce) are summarised in Table 1. Coal supplies are modelled based on a dataset of coal mines producing over one million tonnes annually, last updated in June 2021.[4]

Table 1. Coal capacity, generation, and production statistics by province. Capacity and generation figures for 2021; production and utilisation rate figures for 2019.

Province	Capacity (GW)	Capacity factor (%)	Generation (TWh)	Coal production (Mtce)
Anhui	52.0	55.2%	251.4	70.4
Chongqing	14.0	39.4%	48.2	-
Fujian	27.1	49.1%	116.7	-
Gansu	21.6	45.2%	85.5	33.1
Guangdong	72.6	40.0%	254.5	-
Guangxi	20.5	47.4%	85.2	-
Guizhou	35.2	48.4%	149.0	8.8

[2] The power plant dataset is hosted by the Smith School of Enterprise and the Environment at the University of Oxford. It combines coal power plant information from the S&P Global World Electric Power Plant (WEPP) Database, Global Energy Monitor's Global Coal Plant Tracker (GCPT), and the World Resource Institute's Global Power Plant Database.

[3] Sourced with support from Carbon Tracker Initiative.

[4] The coal mine dataset is hosted by Global Energy Monitor and includes all mines with a capacity exceeding 1 million tonnes, accounting for the majority of China's domestic coal output. 80% of China's coal output is from mines producing over 1.2 million tonnes annually (Hao et al., 2019).

Hainan	3.9	53.3%	18.0	-
Hebei	58.2	55.4%	282.3	3.0
Heilongjiang	21.1	43.7%	80.9	12.2
Henan	80.8	40.2%	284.7	19.9
Hubei	33.8	44.6%	132.2	-
Hunan	21.9	45.7%	87.5	-
Inner Mongolia	103.3	61.1%	552.7	904.0
Jiangsu	89.6	49.4%	387.7	-
Jiangxi	27.9	58.8%	143.7	-
Jilin	19.2	42.9%	72.1	-
Liaoning	38.4	45.5%	153.2	8.0
Ningxia	32.6	52.5%	150.2	101.1
Qinghai	5.7	29.2%	14.6	5.8
Shaanxi	44.2	50.0%	193.9	467.9
Shandong	110.3	50.7%	490.3	49.1
Shanghai	15.9	35.6%	49.7	-
Shanxi	73.3	50.5%	324.2	498.0
Sichuan	15.5	34.7%	47.0	1.8
Tianjin	15.3	45.0%	60.2	-
Tibet	0.0	3.3%	0.0	-
Xinjiang	65.8	57.9%	333.8	237.3
Yunnan	14.7	18.0%	23.1	24.0
Zhejiang	45.5	46.5%	185.3	-
TOTAL	**1,180**		**5,058**	**2,444**

Sources: Capacity: Smith School composite dataset (2021). Coal production: Global Energy Monitor dataset (2021). Provincial capacity factors: various Chinese language public sources (in collaboration with Carbon Tracker Initiative).

Power generation and coal mining are distributed very differently across China. Inner Mongolia (904 Mt), Shaanxi (498 Mt), and Shanxi (468 Mt) supply 1.87 billion tonnes of thermal coal between them, or approximately 75% of the total, as shown in Figure 1 – although not all is consumed by thermal power plants, owing to differences in aggregate supply and demand of different coal types (e.g. an excess of lignite and shortage of anthracite). Xinjiang is the fourth-largest coal producer at 237 Mtce annually. Several coastal provinces – notably Guangdong (home to the Shenzhen industrial zone), Beijing, Tianjin, and Zhejiang – produce no coal at all, relying on imports from other provinces and international markets. Coal plants are much more dispersed, as Figure 2 illustrates. No single province hosts more than 9.4% of coal power generation capacity. While the densely populated coastal and Eastern regions host some of the largest provincial fleets at 110.3GW (Shandong), 89.5GW (Jiangsu), Henan (80.7GW) and Shanxi (73.3GW), the sparsely populated Northern region of Inner Mongolia is expected to become the largest by 2023 at 120GW, with Xinjiang in the Northwest also expected to reach over 70GW in the same year. This compares to a U.S. coal fleet expected to fall below 200GW by 2025 (Energy Information Administration, 2020) and reflects an ongoing shift, at least partly induced by public health concerns, from building coal power along the densely populated Eastern coast, to locating plants closer to production sites in less population-dense mining areas and exporting the resulting electricity along long-distance transmission lines.

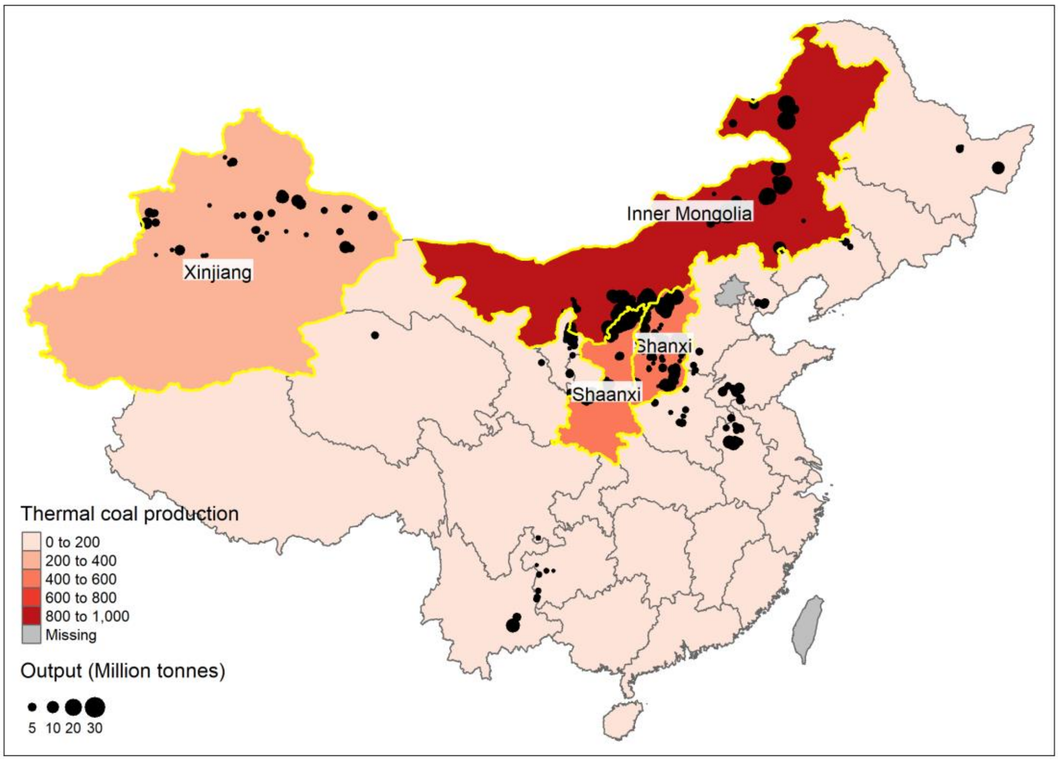

Figure 1. Distribution of coal production by province, 2021.

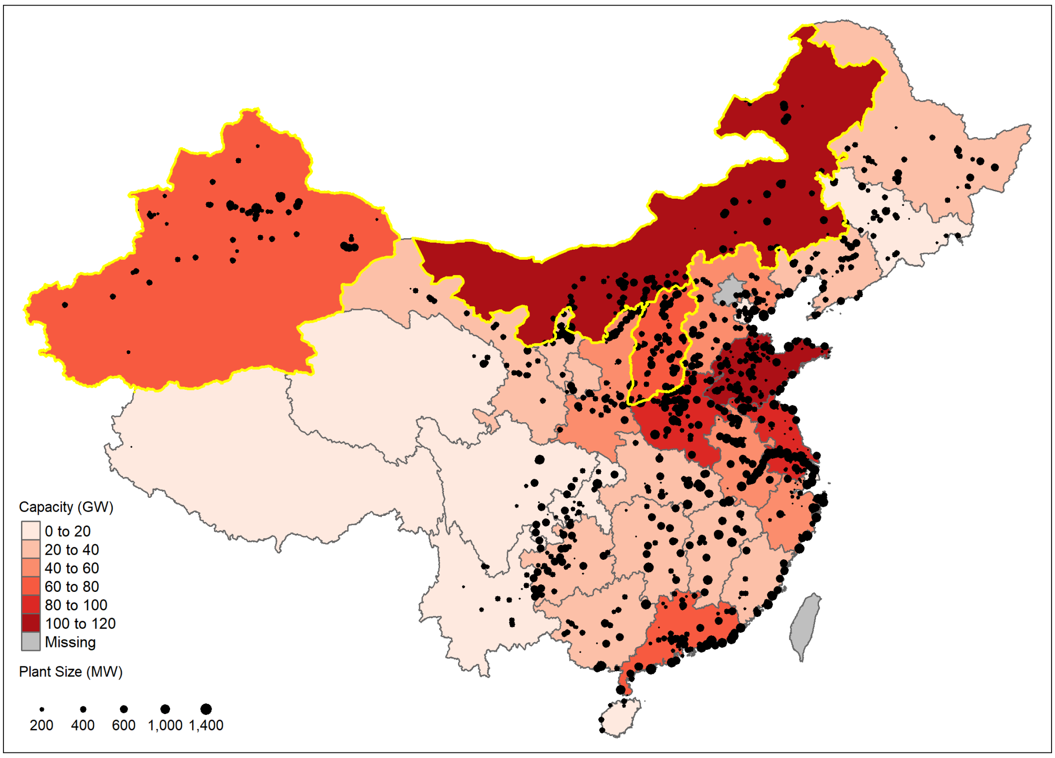

Figure 2. Distribution of currently operating and planned coal plant capacity by province, 2021

Data on coal trading pattens between provinces is not available, but plant and mine datasets alike contain information on the type of coal produced and consumed, such that anthracite mines only supply anthracite-consuming plants, and so on. Only thermal coal-producing mines are included in the analysis, given that thermal coal is typically used for power generation (while metallurgical coal is used for steel production). Matching first by coal type, coal plants consume coal from local (same province) mines where they exist first, and then import coal from other provinces on a pro-rata basis according to the distribution of supplies remaining once each province has met its own demand for coal. In effect, this means that the three largest coal producers supply 90% of the interprovincial coal trade: Inner Mongolia (an estimated 659 Mt in 2021, 40% of the total), Shanxi (426 Mt, 26%), Shaanxi (396 Mt, 24%). China imported 21% of its total coal consumption from abroad in 2019 (International Energy Agency, 2020), which is used as the baseline year due to possible pandemic-related distortions, a temporary Australian coal import ban in 2020, and unusually high coal import prices in 2021. In 2017, thermal coal made up 69.4% of imports (Research and Markets, 2019); in this analysis 70% is assumed. The proportion of total thermal coal demand met through imports is therefore roughly 14.7%.

While these figures are based on a best-effort reconstruction of the coal network in China, and subject to constant change based on market conditions, they should represent an approximation of where and in what quantities coal is produced and consumed in China. Associating coal plants with mines in this way makes it possible to link the operation (and retirement schedule) of specific plants with upstream mining jobs (both locally and externally to each province) and associated tax revenues.

Estimating employment

Data on the number of jobs supported by coal plants themselves is not easily available and may vary according to the age and type of plant, the use to which the coal is put, the location and corresponding technical and safety requirements, support staff, and other miscellaneous factors. A modern coal plant does not, in principle, require very many staff to operate at any one time, although the jobs associated with plant operation (e.g., staff for different shifts, as well as safety, financial and operational management, cleaning and maintenance staff) can be significantly more than this.

Allowing for each plant being subject to specific circumstances, published estimates of average direct employment in coal plants are scarce. Wenjuan (2020) calculates that total coal plant employment in China is approximately 500,000. Accurately estimating the number of employees in each specific plant is not feasible, since this can depend on a number of unknown factors linked to the plant's location, type, owner, age, and design. However, applying the following assumptions generates a total of approximately 500,000 jobs across the fleet as of the beginning of 2021:

- 100 jobs for plants under 100MW
- 125 jobs for plants between 100-300MW
- 150 jobs for plants over 300MW

Indirect employment in the mines supplying coal plants is more significant. National statistics place the number of jobs in coal mining and dressing at a peak of 5.3 million in 2014, falling to 4.5 million in 2015, 2.85 million in 2019 and 2.68 million in 2020 (CEIC, 2020). This decline, of nearly 50% in six years, reflects a combination of small mine closures and falling labour intensity, as noted above.

In some cases, the number of jobs supported by a specific mine is available in the coal mine dataset. Where it is not, the model estimates jobs on the basis of province-level labour intensity figures: jobs per 10,000 tonnes extracted in 2015, to which a 5% annual increase in productivity consistent with historical trends is applied each year from 2015 onwards (UIBE & Chinese Academy of Sciences, 2019, Table 4). This assumption does not account for the actual dynamics of labour elasticity of demand in the industry, like structural impediments to hiring and firing workers, and indispensable mining jobs unaffected by changes in output. The model estimates that 1.7 million coal mining jobs in 2021 (63% of reported job statistics in 2020) are supported by 2.08 billion tons of domestic thermal coal consumption (59% of total estimated coal production in 2019, which was 3.51 billion tons). This suggests both that thermal coal demand accounts for approximately 60% of both coal mining output and jobs in China at present, and that the model estimates aggregate employment in coal mining reasonably well.

The coal industry also supports jobs in the transport sector, particularly where dedicated rail, road and port infrastructure has been put in place for specific mines, depending on the degree of automation and efficiency of the transport process. The sensitivity of transport jobs to coal demand in turn depends on the substitutability of coal for other products or commodities not correlated with coal demand. However, sufficient data on coal transport jobs in China was not available for use in this project.

Estimating taxes and subsidies

The coal industry raises tax and social security revenues for provincial and central governments in several ways. Income taxes to central government, and social security contributions for investment in managed public funds, are calculated on the basis of employee wages, which vary by employment type and region (National Bureau of Statistics of China, 2020), using tax brackets and assuming only the standard deduction is made (PWC, 2021a, 2021b). Social security contributions vary across provinces and cities, but are assumed here to total 50% of base salary, with 30% employer-contributed and 20% deducted from wages (MS Advisory, 2020).

The 2018 Environmental Pollution Tax levies charges on several pollutants, with the level generally decided by provincial governments and set at higher levels for more populous provinces (see Figure 3). In this study, coal plants are subject to taxes on sulphur, nitrogen, particulates, and wastewater. Coal mines are taxed on gangue, tailings, ash, and wastewater.

Coal mines also pay fees for mining rights, averaging 1.18% of sales value (of which 80% goes to provincial government), as well as (minimal) prospecting and exploration fees based on estimated mine surface area. Resource taxes, based on the value of coal sales, accrue to provincial government and vary by province. Finally, Value-Added Tax (VAT), reduced in 2019 to 13% for coal products, is levied cumulatively on coal and, ultimately, electricity sales, using price data which is assumed to already include VAT.

Total tax revenues to central government therefore include income taxes, prospecting, and exploration fees, 20% of mining royalties, and VAT. Total revenues to provincial governments include environmental pollution taxes, resource taxes, and 80% of mining royalties.

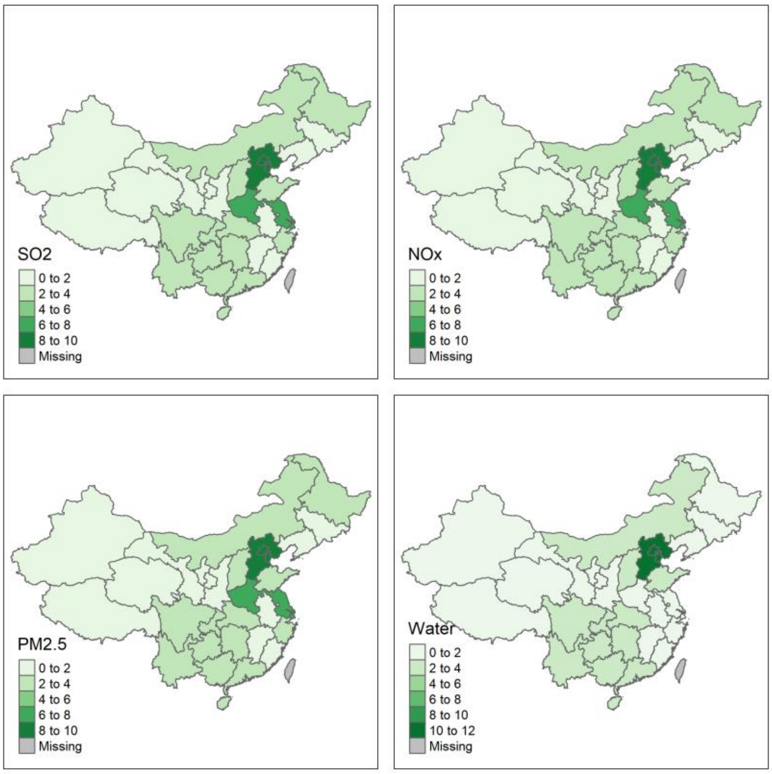

Figure 3. Environmental Pollution Tax rates for selected pollutants by province. Units: ¥/kg (¥/m^3 for wastewater)

Data limitations prevent estimation of subsidies at plant or mine level or distinguishing between subsidies benefiting coal power generation versus coal use in industry and heating. Subsidies are estimated in aggregate on the basis of point-in-time studies, themselves reliant on multiple assumptions and subject to uncertainty. They include subnational fiscal support to coal mines, VAT rebates and subsidies for R&D and coalbed methane production, the aforementioned Industrial Special Fund, price subsidies to electricity and coal transport, and credit support. Electricity price subsidies can be estimated at plant level based on the difference between the administrative benchmark price and spot price for electricity. Mines are assumed to take full advantage of available VAT rebates in aggregate. With the caveat that these are uncertain and highly aggregated estimates, they suggest an overall subsidy level of ¥300-350 billion to the coal industry and coal areas, not counting historical subsidies for plant pollution control equipment.

Negative environmental and health externalities to coal production are not included in this figure (although they are partially subject to taxation). Estimates of externalities per tonne of coal production (including impact on air quality, water and soil quality, global warming, prevalence of respiratory disease, and a range of other factors at various stages of production and consumption) vary. Coady, Parry, Sears, and Shang (2017) assess damages from all energy sources in China (to which coal is a major, if not majority contributor) at ¥3 trillion for global warming impact, and a further ¥12 trillion for local pollution, around 40 times higher than all other subsidies combined. Zhao et al.

(2017) use revealed preference methods to estimate the environmental cost of coal-fired power plants at ¥300 per MWh (implying a subsidy of ¥1.52 trillion in 2021, given 5,058 TWh of coal-fired generation), which is still five times all other subsidies. Meanwhile, Yuan et al. (2019) estimate annual externality subsidies to coal power generation at a more modest ¥180 billion, around 50% of all other subsidies.

4. Results

National level results

The model was constructed to run from 2021 to 2060 for four scenarios (see Annex 4: Scenario analysis), under which the life of each plant becomes progressively shorter: 30, 25, 20, and 15 years under the Baseline (B), Low-Cost Renewables (R), 50% lower emissions than 2015 (C50) and 80% lower (C80), respectively. Figure 4 shows the production-consumption relationships of thermal coal of all types between provinces in the baseline scenario, where each coal-consuming province (outside ring) consumes coal from local mines where it is available, and imports from other provinces where it is not (cross-circle links, where the colour of the link is that of the destination province). The prominence of Inner Mongolia (NM), Shaanxi (SN), and Shanxi (SX) as coal suppliers to many other provinces is clearly visible. All three produce a large amount of coal, consume a significant share of their own coal, and export the rest to other provinces. Inner Mongolia's and Shanxi's prominence as both producers and consumers continues to grow such that, by 2050, both provinces dominate coal demand, obtaining the vast majority of coal from their own local mines.

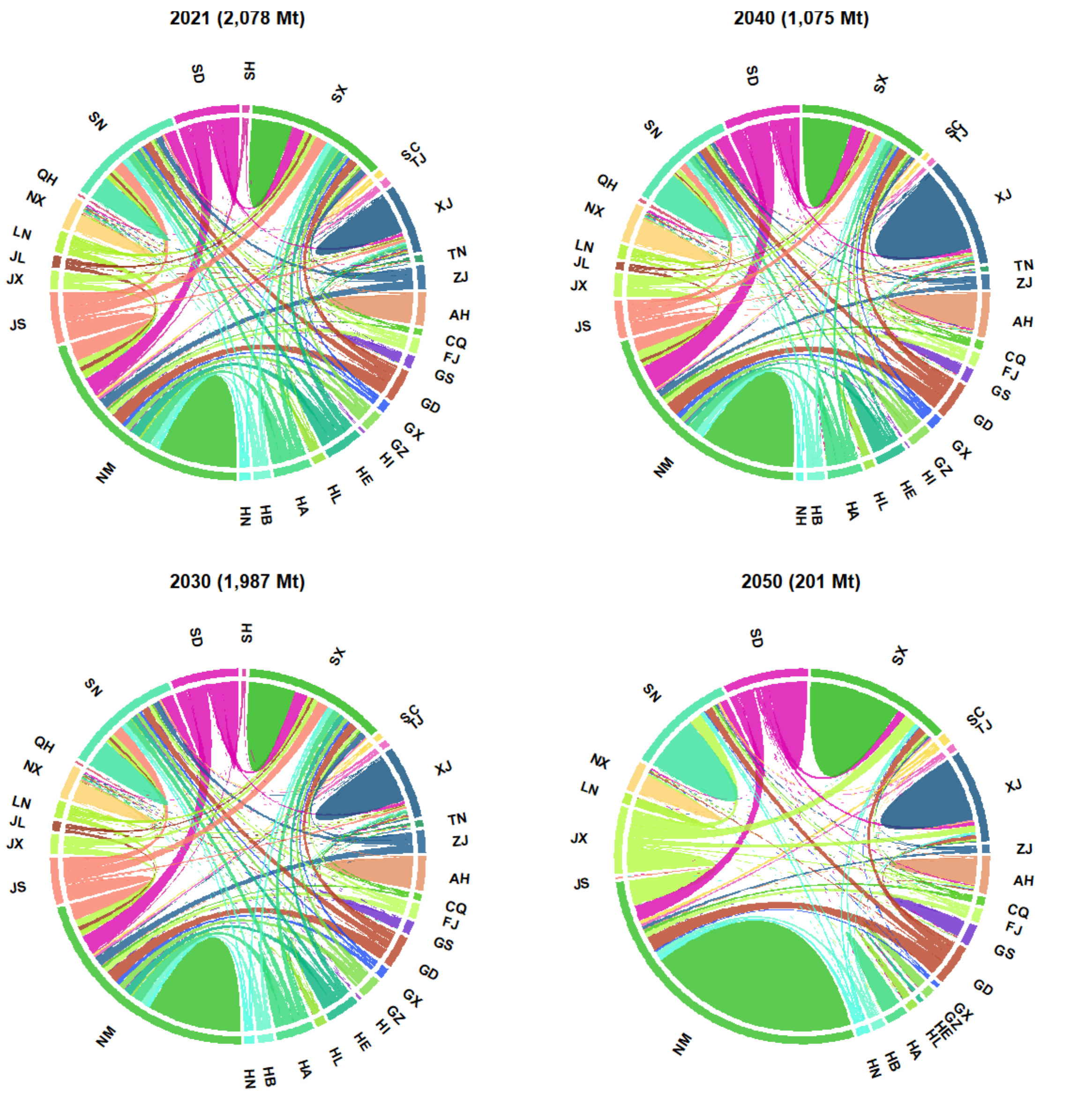

Figure 4. Coal production-consumption network by province, 2021-2050 (baseline scenario). For province codes, see Annex 0: Province Codes. 'Humps' represent coal consumed in the same province in which it is produced. 'Links' represent coal exported to other provinces, where the colour of the link is that of the destination province.

When 'internal' coal jobs in each province (jobs at coal plants, and jobs at coal mines in the same province that supply these plants), and 'external' ones (jobs at coal mines in other provinces supported by demand from coal plants) are overlaid on this network, the results follow a markedly different pattern, due to the differences in labour intensity between coal mines in different provinces (see Figure 5). Coal plants in Inner Mongolia, despite accounting for over 10% of China's thermal coal demand in 2021, support only 4% of total coal jobs in China because the coal mines supplying most of these plants are also in (highly labour-efficient) Inner Mongolia. Similarly, plants in Shandong account for 8% of coal demand, but support 27% of coal jobs nationally because of the higher average labour intensity of the mines supplying them – some of which are in Shandong, with most of the rest sourced from Inner Mongolia, Shaanxi, and Shanxi. By 2050, differences in labour intensity have converged significantly and interprovincial trade in coal has largely disappeared, such that most remaining coal mining jobs are supported by demand from plants in the same province, with Shandong remaining the only notable exception.

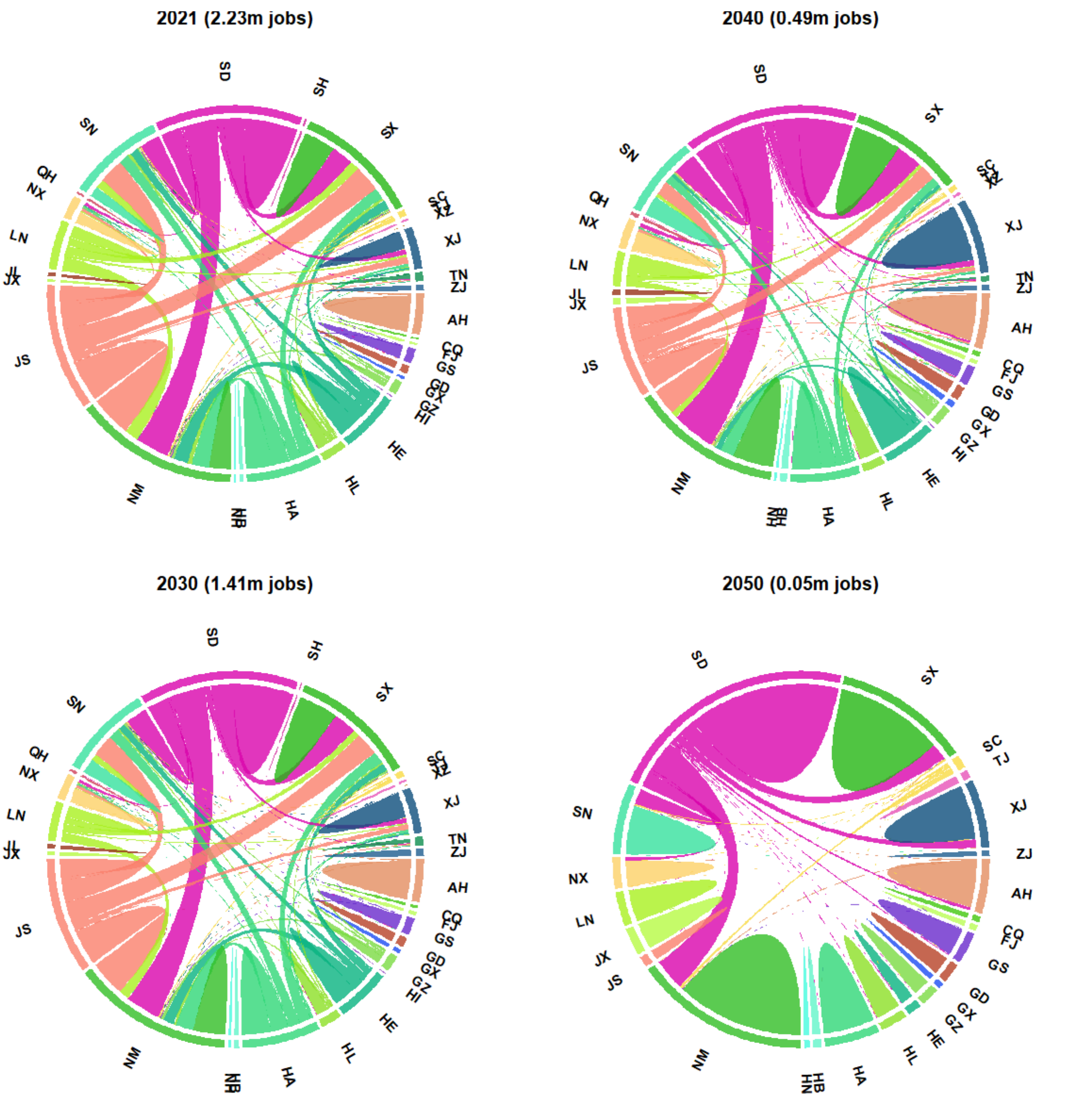

Figure 5. Coal jobs by province. Flows away from a province in the same colour represent jobs supported by that province through coal imports from other provinces.

For provinces that are already very labour-efficient, productivity improvements have less absolute impact over time relative to total provincial mining jobs, while for provinces with high labour intensity, annual job losses are much greater, reflecting the active consolidation, closure of small mines and rollout of automated mining infrastructure that are a feature of current government policy.[5] This means that more jobs are lost to efficiency than to planned or policy-accelerated plant closures and the ensuing effects on coal demand, at least in the short term, under current policies.

Table 2 summarises the number of jobs supported by each province's coal fleet, which is largely determined by the labour intensity of mining in that province and, where applicable, that of the provinces it imports from. Provinces themselves are more likely to be home to a greater number of coal

[5] In Shanxi province, for instance, the Yangquan Coal Industry Group is using 5G technology to monitor and run mining operations remotely at its Xinyuan mine. Having employed 3,000 workers in 2012, the mine expects to provide under 1,000 jobs by 2025 (Murtagh et al., 2020).

jobs (both locally and nationally) when they have a combination of large coal fleets, large mining capacity, and high labour intensity. Coal plants in Shandong support 465,000 jobs nationally, both locally and indirectly by importing coal from other provinces. Inner Mongolia's very large coal fleet supports only 73,000 jobs, although demand for coal from other provinces supports another 444,000 coal mining jobs in Inner Mongolia's mines.

Table 2. Summary information on coal industry employment.

Province	Jobs supported by coal power generation (000s, 2021) - Baseline	Coal consumption for power generation (Mt)	Jobs supported per 10,000 tonnes of coal consumed	Share of total jobs supported
Shandong	465.1	198.8	23.4	20.9%
Jiangsu	399.4	154.8	25.8	17.9%
Henan	238.6	114.4	20.9	10.7%
Hebei	192.7	115.2	16.7	8.6%
Liaoning	156.8	66.7	23.5	7.0%
Anhui	127.1	99.2	12.8	5.7%
Shanxi	108.2	131.2	8.3	4.9%
Heilongjiang	77.7	36.2	21.5	3.5%
Inner Mongolia	72.9	256.0	2.8	3.3%
Xinjiang	61.9	136.6	4.5	2.8%
Gansu	46.1	35.3	13.1	2.1%
Guizhou	42.3	58.8	7.2	1.9%
Ningxia	39.2	59.7	6.6	1.8%
Shaanxi	35.6	77.8	4.6	1.6%
Guangdong	24.7	101.6	2.4	1.1%
Sichuan	21.0	18.9	11.1	0.9%
Zhejiang	19.0	74.2	2.6	0.9%
Yunnan	17.4	9.4	18.5	0.8%

Hubei	12.8	52.1	2.5	0.6%
Jilin	11.5	36.9	3.1	0.5%
Guangxi	8.7	33.3	2.6	0.4%
Fujian	8.4	45.8	1.8	0.4%
Jiangxi	8.1	55.3	1.5	0.4%
Hunan	7.4	32.5	2.3	0.3%
Qinghai	6.5	6.0	10.8	0.3%
Shanghai	6.2	20.9	3.0	0.3%
Tianjin	6.0	24.5	2.4	0.3%
Chongqing	5.7	18.9	3.0	0.3%
Hainan	2.2	7.4	3.0	0.1%
Tibet	0.2	0.0	1179.4	0.0%
Total	**2,229**	**2,079**		

Figure 6 plots baseline scenario estimates for employment in the coal power industry from 2021-2060. Employment in coal mines starts at a higher level (1.72 million) but follows a steep downward trajectory, declining by over 60% by 2035. Employment in plants (starting at 512,000) falls by less than 30% in the same period. This reflects the effect of declining labour intensity in coal mining and the slow pace of plant retirements up to about 2034. From this point onwards, overall job losses accelerate as the pace of plant retirements increases, slowing slightly again in the 2040s and declining to zero in 2054 as the wave of plants built in the decade to 2020 reach the end of their operating lifetimes.

Under the baseline scenario, reflecting current policies, total coal power industry employment is projected to drop below 1 million by 2036, 500,000 by 2042, and 250,000 by 2045 (see Figure 6). This compares to a projection by the Chinese Academy of Social Sciences estimating 413,000 jobs in 2050 will be directly linked to the wind and solar industries, with a further 3.5 million indirect jobs - more than double total *current* employment in the coal power industry and many times its expected level in 2050 (Natural Resource Defense Council, 2015). As noted in previous work (Caldecott et al., 2017), the net employment impact of coal closure on the whole economy is unlikely to be significantly negative as other forms of energy production and supporting industries take its place. The public policy challenge is anticipating job losses sufficiently well across space and time to take early action to redeploy workers elsewhere or offer retraining programmes to avoid the potentially very large burden of mass early retirements, or chronic unemployment, on the social security system (with the Spanish experience serving as a cautionary tale). Methodologies have been developed to undertake this analysis by identifying green industries and skills that are 'adjacent' to emissions-intensive ones (Mealy, 2018), but their proper application to China depends on greater availability of detailed, province-level occupational and production data that is not currently publicly available.

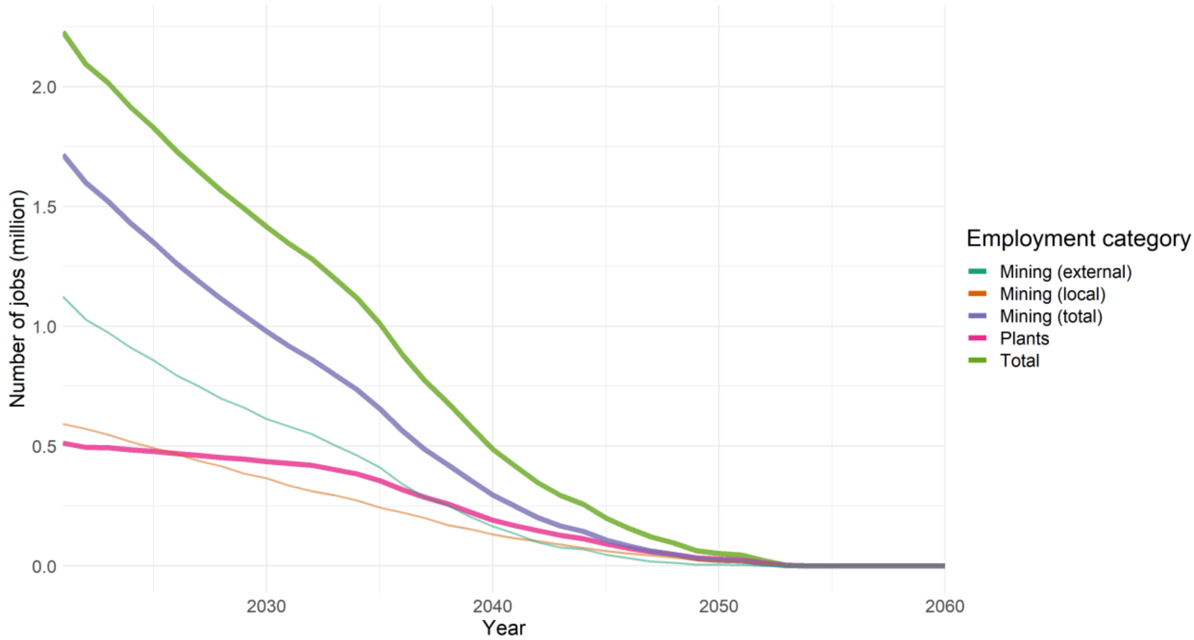

Figure 6. Employment in coal plants and mines, 2021-2060, baseline scenario. Assuming linear decline in labour intensity to 1.7 jobs/10,000 tonnes in 2050

The trajectory of fiscal revenues does not decline as sharply and in fact rises slightly in the short term. Income taxes and social security payments fall with the decline in employment, but total revenues rise initially since coal capacity does not peak until 2023 and taxes on capital (notably resource and environmental pollution taxes to local governments, and VAT to central government) are a greater proportion of total revenue than taxes on labour. In 2021, income taxes contribute ¥3 billion (1.4%) of central government revenue from coal, mining royalties ¥2.6 billion (1.3%), and VAT, ¥204.6 billion (97.3%), comprising roughly 3% of total VAT revenue nationally (Statista, 2021). For provincial governments, resource taxes generate ¥47.8 billion in revenue from coal (41.2%), pollution taxes on mines, ¥52.7 billion (45.5%), and pollution taxes on plants, ¥4.7 billion (4.1%).

As Figure 7 shows, fiscal revenues to central government decline slowly to just under ¥200 billion in 2030, before beginning to fall steeply around 2034 as coal retirements accelerate. Tax revenus, almost entirely based on capital, fall to ¥100 billion in 2041 and just over ¥20 billion in 2050. Revenues to provincial governments begin at approximately half this level, but follow a similar trajectory. Also plotted for comparison are social security payments (not strictly a tax, but certainly a contribution to publicly managed funds), which are based entirely on wages, and therefore decline mostly linearly from the beginning.

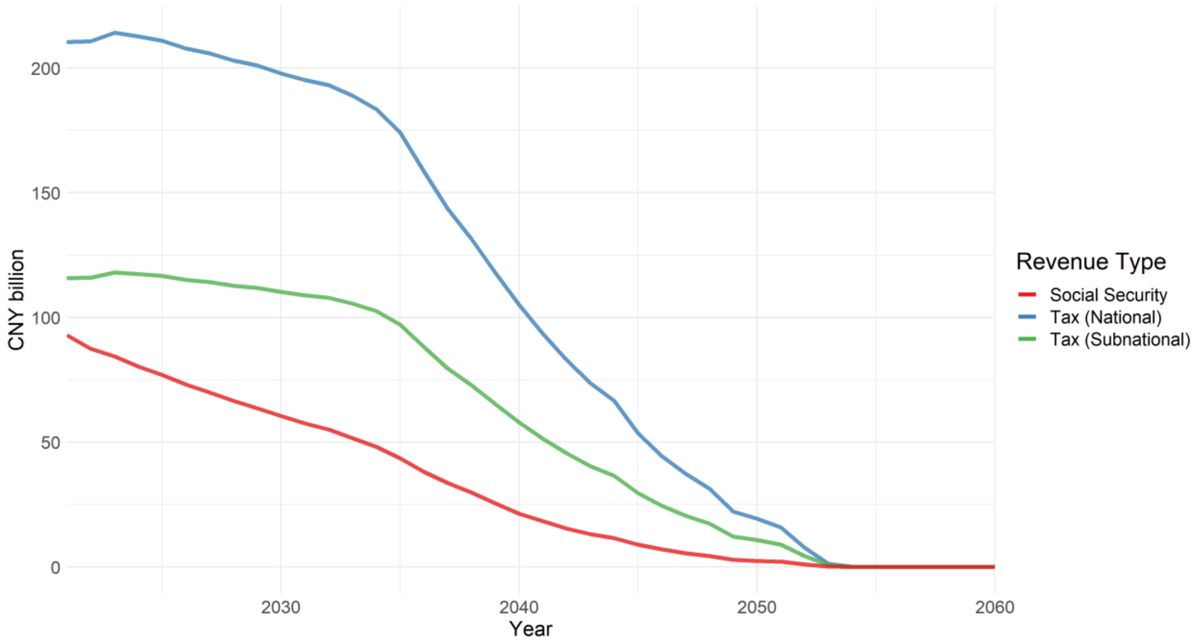

Figure 7. Breakdown of tax and social security revenues, and power price subsidy costs, 2021-2060, baseline scenario.

When compared to the estimated annual subsidy level of ¥300-350 billion annually, the total of approximately ¥350-400 billion in total tax revenue annually up to the mid-2030s suggests that the net annual fiscal contribution of the coal industry to public revenues is likely less than ¥100 billion. As the revenues associated with capital assets fall more sharply after 2035, it becomes increasing likely that coal will become a net fiscal drain on China, even without accounting for the public health, productivity, and other environmental and climate externalities that coal mining and combustion generates. While subsidies to capital assets, and power price subsidies for coal may fall as generation declines, other costs may rise to negate this, including contingent liabilities arising from state-owned power or mining company losses, defaults, or bankruptcies, restructuring efforts, and relocation/retraining costs for laid off workers.

Comparing the baseline against more aggressive phase-out scenarios helps to understand the marginal relevance of climate policy on both employment and coal's fiscal contribution. Under progressively stricter scenarios, the short-term drop in coal capacity (reflecting the retirement of older plants) needed to meet the target requirements becomes increasingly large. There are other ways of reaching the mid- and long-term goals around which the scenarios are calibrated; the rapid pace of initial closure implied by the C50 and C80 scenarios is only one.

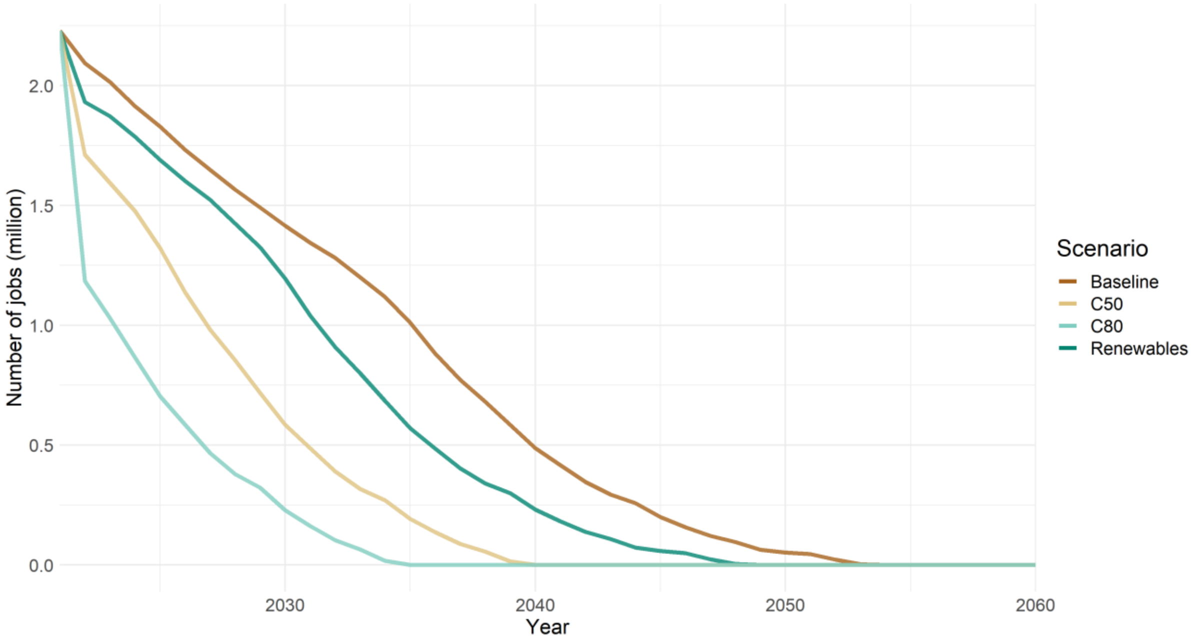

Figure 8. Employment in the coal power sector under different coal phase-out scenarios, 2021-2060.

The R scenario has relatively little impact on total employment, leading to about 200,000 fewer jobs in 2030 relative to the baseline (Figure 8). The differential between the two pathways widens to over 400,000 in 2035, before converging back to 140,000 by 2045. Under the C50 scenario, implying coal phase-out by 2040, over 800,000 additional job losses would be expected by 2030, while under the C80 scenario (phase-out by 2035), almost 1.2 million additional jobs disappear by 2030 – over half of total thermal coal industry jobs today. All told, the R scenario, which is compatible with coal phase-out by 2050, has relatively little additional impact on employment trajectories until the late 2020s. More ambitious phase-out pathways do have serious employment consequences in the short term. Absolute job losses by 2030, even under the C80 scenario, are still less than half than the 2.7 million coal industry jobs already lost between 2014 and 2020 (CEIC, 2020). If these projections prove even approximately correct, future changes in coal industry employment are not meaningfully affected by all but the most aggressive of climate policies. Even if 150GW of CCS-enabled capacity were kept open in 2050 (as in the 1.5C scenario described above), gains in labour intensity over time mean even this would be unlikely to support more than 100,000 coal plant jobs in the second half of the century, and fewer in mining.

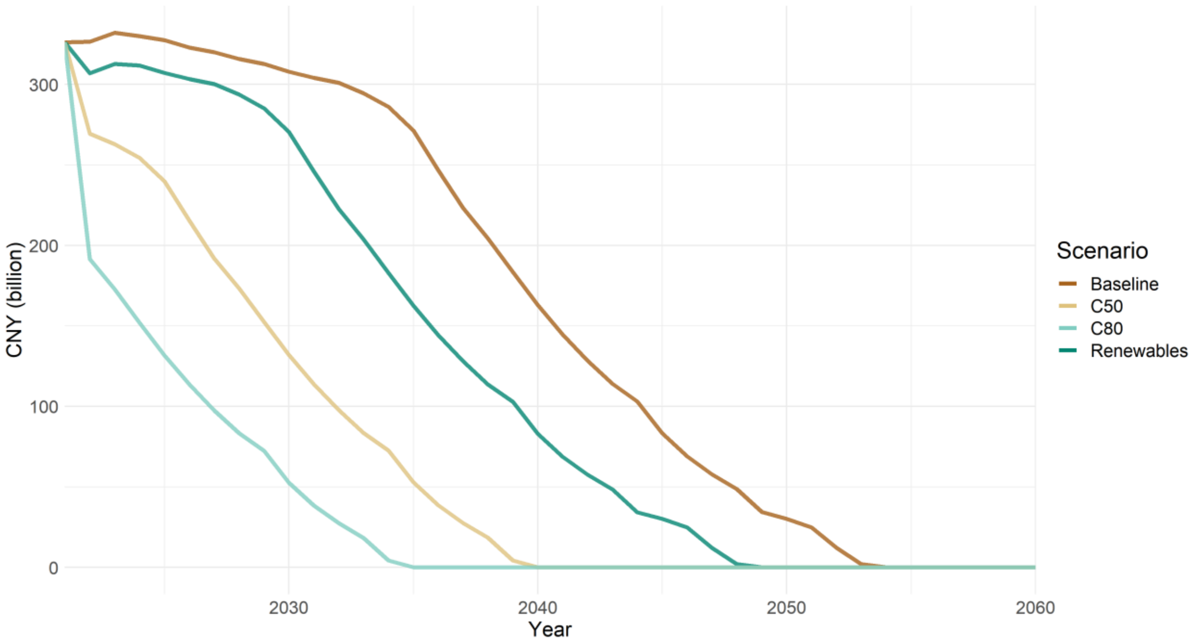

Figure 9. Total tax revenues under different coal phase-out scenarios, 2021-2060.

The fiscal picture (Figure 9Figure 10) is somewhat different for the first two scenarios. Total tax revenues remain relatively stable up to 2030 under the R scenario and decline rapidly thereafter, following much the same trajectory as the baseline but five years earlier, declining to zero in the late 2040s. In the C50 and C80 scenarios, the trajectory is also similar after a sharp initial drop in revenues, with subsequent rates of decline tracking the baseline, but starting 10-11 years and 15-16 years sooner, respectively. These patterns confirm that the tax base for coal is much more capital-intensive than labour-intensive, since initial job losses do not offset increasing tax revenues from new plants, and in each scenario, sharp declines in tax revenues begin only when capacity retirements accelerate.

Overall, scenario analysis suggests that the additional job losses associated with a pre-2050 coal phase-out target are relatively minor, even without counting job creation in the renewables sector. Job losses are much faster in the C50 and C80 scenarios but still slower than China has seen to date. The timing, rather than the rate, of tax revenue decline is most affected by more ambitious phase-out scenarios.

Province-level results

The impact of coal phase-out is very different across provinces, due to differential exposure to the coal industry. This section examines and compares the effects on a major net coal-producing province (Inner Mongolia) and a net coal-consuming province (Jing-Jin-Ji).

Inner Mongolia

Inner Mongolia is the largest coal-producing province in China, at over 900 million tonnes annually, almost 37% of national production and nearly twice that of Shanxi (20%) and Shaanxi (19%). As one of China’s most suitable locations for wind farm development (Gao et al., 2020), the province also hosts substantially more wind generation capacity than any other, at 11.4GW, with a further 3.3GW currently planned. Inner Mongolia has seen historically high curtailment rates for wind energy, that have since declined from an average of 15% in 2016 to 10% in 2018 (Energy Research Institute & China National Renewable Energy Centre, 2019, p. 65), supported by greater long-distance transmission capacity for generated electricity. Investment in additional transmission capacity appears to have grown since the onset of COVID-19, and is believed to be supporting the transmission of locally generated coal-fired electricity to demand centres in the East for at least 7.9GW of capacity commissioned in the first half of the year (Global Energy Monitor & CREA, 2020).

Inner Mongolia is also fast becoming China's largest consumer of coal. As of 2021, the province hosts 103 GW of capacity, nearly 9% of China's total and just shy of Shandong's 110 GW. Based on currently planned plants, Inner Mongolia will overtake Shandong in 2023 to become host to China's largest provincial fleet, reaching peak capacity at 120GW in 2024. This is more than the total combined fleets of Germany and Japan, and roughly half the size of the entire fleets of the U.S. and India. Its dependence on coal mining and other minerals, the use of coal for domestic heating, and the provincial government's support for coal (extending to enterprises under government control), support the continued expansion of the coal industry in spite of national policy.

In terms of employment, Inner Mongolia is however relatively well positioned to transition away from a coal-based economy, with appropriate planning. Its mining workforce is the most efficient in China, at 1.7 jobs per additional 10,000 tonnes produced (the second-least labour intensive are Shaanxi, at 3.3, and Xinjiang, at 3.5). Thus, despite massive coal mining and combustion operations, coal plants located in Inner Mongolia are estimated to employ, directly and indirectly, just 73,000 people, of which 27,000 are in the mining industry.

However, since Inner Mongolia exports about two-thirds of its coal and meets almost 40% of total interprovincial demand, the jobs associated with meeting demand from other provinces are several times those associated with supplying just its own plants. Over 470,000 additional coal mining jobs are associated with coal supplied by Inner Mongolia to other provinces. Once accounting for exported coal, about 517,000 jobs in Inner Mongolia depend on demand for thermal coal (see Figure 10).

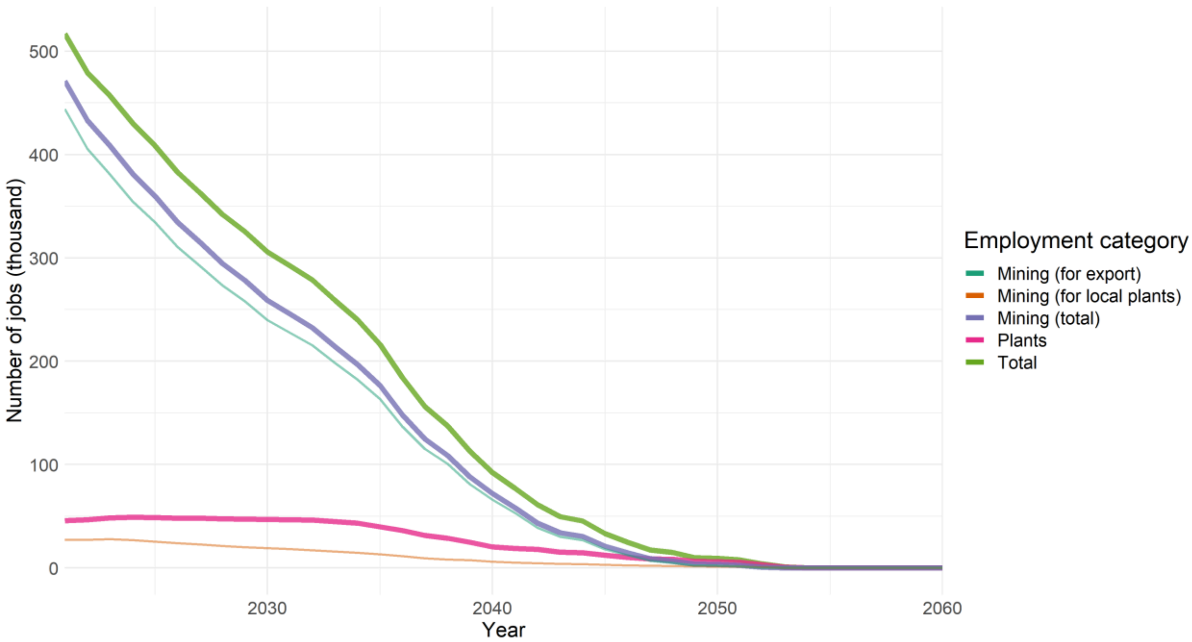

Figure 10. Coal mining and power generation employment in Inner Mongolia, 2021-2060

On the fiscal front, Figure 11 shows that Inner Mongolia's coal industry contributes, directly and indirectly, ¥32.3 billion to central government revenues (about 15% of national revenues from coal), peaking at ¥34.4 billion in 2024 before falling sharply after 2030 to under ¥15 billion by 2041. Contribution to provincial tax revenues (in Inner Mongolia and the provinces it exports to) start at a higher level, peaking at ¥38.7 billion in 2023 and falling below ¥15 billion by 2042. Of these provincial tax revenues, about a third are resource taxes. This is as expected: the relatively low labour intensity of coal production, low environmental pollution taxes, and the fact that most of Inner Mongolia's coal is exported, means that tax revenues associated with the local coal industry are closely tied to the production and sale of coal.

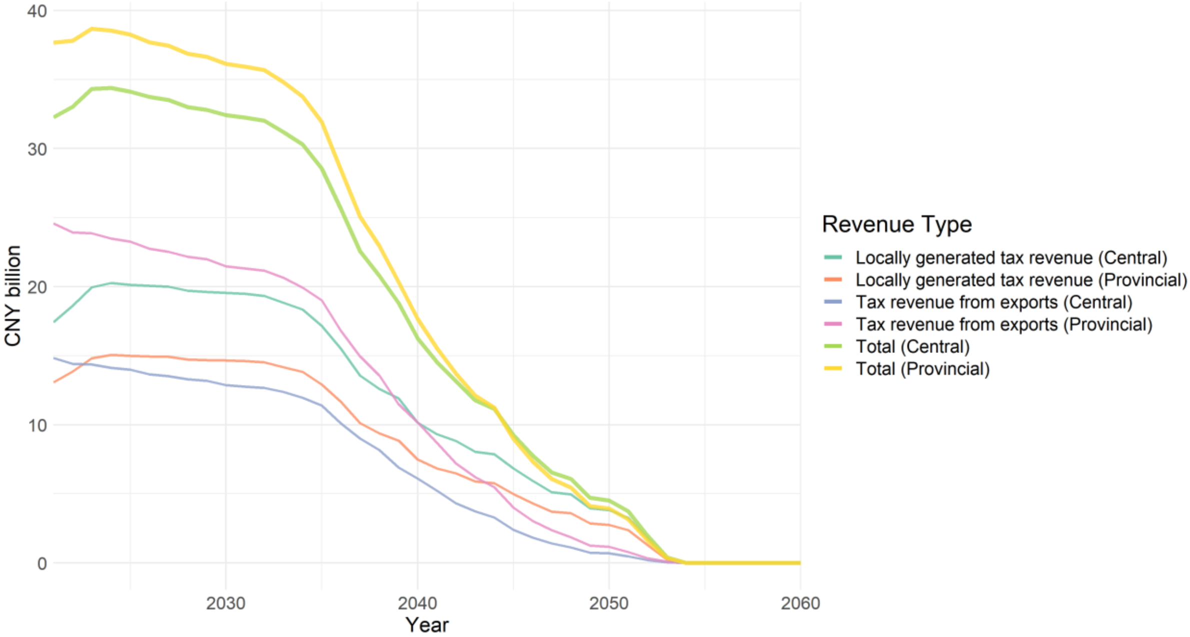

Figure 11. Central and provincial government tax revenues associated with Inner Mongolia coal industry, 2021-2060.

Estimates of subsidies directed to Inner Mongolia's coal industry in the past add some context to these estimates, suggesting that the apparent net fiscal boon from coal industry operations is not as great as it first appears. While subsidies vary from year to year depending on funding priorities, and are difficult to measure with any accuracy or certainty, Xue, Wang, Bridle, Gerasimchuk, and Attwood (2015) suggest that historically, Inner Mongolia has granted at least ¥720 million in temporary tax relief for coal price adjustments and coal rail transport. In 2013, the cost to the provincial government of providing coal users with rail transportation below market rate was estimated at ¥7.2 billion.

Jing-Jin-Ji

'Jing-Jin-Ji' is shorthand for the Beijing, Hebei and Tianjin area, a heavily urbanised region with a population of over 112 million. In Beijing's case, the municipality contains no coal mines, and recently closed its last coal-fired power plant. It imports large volumes of electricity, a majority of which is necessarily from coal plants given China's electricity mix, but does not directly contribute to employment or tax revenue in the coal sector. Tianjin does not produce any coal, but hosts 15GW of coal-fired power plant capacity, while Hebei hosts 58GW of generating capacity. Jing-Jin-Ji therefore hosts a combined total of about 72GW, just 6% of China's total operating capacity in 2021 of 1,180GW. Based on the coal mine dataset, Hebei produces about 0.1% of China's thermal coal (3 million tonnes annually). Jing-Jin-Ji does not currently plan to build any new coal capacity and will see its current capacity decline as existing plants are progressively closed.

The wealth and population density of Jing-Jin-Ji relative to other provinces, and its status as political capital, have direct implications for the political economy of coal phase-out. With the effects of local air pollution affecting a very large populace, pressure to address air quality issues that have plagued the area for decades has led to the relocation of coal power serving Jing-Jin-Ji away from city areas and the imposition of the highest environmental pollution tax rates in China. At the same time, a major priority for central government is maintaining stable, affordable electricity prices to support a continuation of high growth rates. Achieving these goals simultaneously requires importing electricity from sources cheap and flexible enough to offset transmission infrastructure costs and ensure uninterrupted power supplies, a role still played predominantly by coal.

Neither electricity prices (both benchmark and spot prices) nor coal prices in Jing-Jin-Ji are particularly high or low, hovering near the national median. This implies great tax revenue per unit of coal mined or consumed in Jing-Jin-Ji than Inner Mongolia (through greater unit VAT and resource tax revenues, both generated *ad valorem*). Beijing, Hebei, and Tianjin all impose maximum plant-level environmental pollution taxes (¥12/kg for air pollutants, and ¥14/m^3 for wastewater), the only provinces currently doing so. In Tianjin, these charges are relatively immaterial given the lack of a coal mining industry and relatively small amount of coal-fired generation. In Beijing they are non-existent. Hebei's significant coal plant and mining industry, however, faces higher charges per tonne of coal extracted or burned than other provinces. In combination, the Jing-Jin-Ji provinces collect ¥1 billion in environmental taxes on coal plants annually (compared to ¥0.43 billion in Inner Mongolia, which has nearly twice the generation capacity, albeit with fewer operating hours).

Notably, the estimated average labour intensity of coal mining in Hebei is 16.7 jobs per additional 10,000 tonnes extracted, more than five times that of Inner Mongolia (2.8). Consequently, despite having half as much coal power plant capacity, Hebei's coal plants support nearly 70% more local coal mining jobs (45,000) as Inner Mongolian plants do (27,000). Wages are also higher in Jing-Jin-Ji, meaning income taxes and social security payments are comparable to those contributed by Inner Mongolia.

Comparison and analysis

In terms of employment, Figure 12 shows that while the national coal industry supports ten times as many mining jobs in Inner Mongolia as Jing-Jin-Ji, and the gap will remain significant for the next two decades because of Inner Mongolia's superior labour efficiency and much larger scale, the absolute numbers converge sharply to within 60,000 of each other by 2040, not least because some coal mine employment in Inner Mongolia depends on demand from Jing-Jin-Ji, and Jing-Jin-Ji's coal demand supports Inner Mongolia jobs. The gap narrows to under 10,000 jobs by 2050. Plant jobs decline steadily in Jing-Jin-Ji as its remaining plants retire on a smooth trajectory to 2050. In Inner Mongolia, employment in plants is stable until the mid 2030s, before declining sharply to 2040 as plants built in the 2010s start to retire, and reaching zero in the mid-2050s.

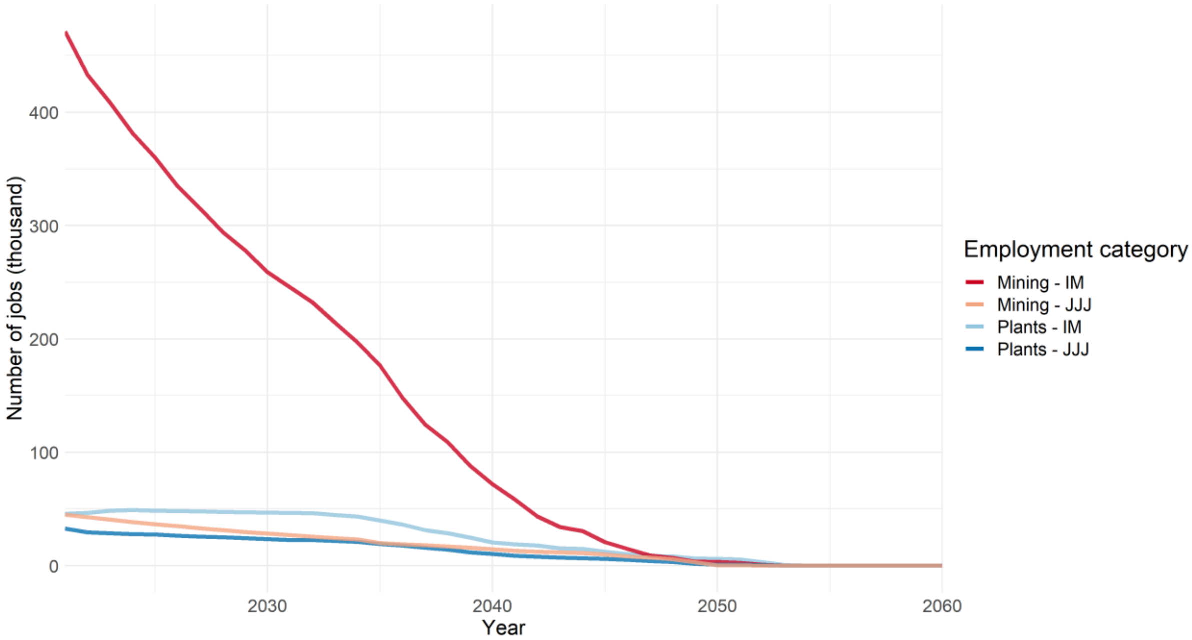

Figure 12. Coal jobs associated with mining and plants in Inner Mongolia and Jing-Jin-Ji, 2021-2060.

Where the focus for Inner Mongolia is on production, through continued industrial development, growth in electricity generation and upgrading its position on the electricity value chain, Jing-Jin-Ji is more likely to be concerned with securing reliable, affordable power to facilitate further economic development. These contrasting potential motivations, which mirror the relationship between net coal producers and consumers across China, are not incompatible – in fact, the provinces' respective interests are well-aligned, such that an expansion of coal power in Inner Mongolia benefits both, particularly in the context of power shortages induced by a shortage of coal supplies in late 2020 (New York Times, 2020) and autumn 2021 (Reuters, 2021).

Firm-level results

Since plant and mine datasets both contain company identifiers, it is possible to chart the composition and trajectory of jobs and tax revenues supported by plants operated by individual companies, at the parent level (since the large power generation firms in China each have a large number of subsidiaries). Since a plant is often owned in different shares by multiple companies, the number of jobs associated with each company is scaled by the proportion of equity ownership it has in a given plant.

Under the baseline scenario, the five largest sources of employment in coal power generation and the mines supplying them in 2021 are the 'Big Five' power generation companies (Huadian, Huaneng, Datang, State Power Investment Corporation (SPIC), and National Energy Investment Group (NEI) (formerly Shenhua, and also known as CHN Energy), each of which also controls a considerable amount of coal production (see Table 3).

Table 3. Largest 12 companies by capacity (in 2021), with corresponding coal production capacity, and jobs and tax revenues supported by each company's coal plants, baseline scenario

Company	Capacity (GW)	Coal production (Mt/year)	Jobs supported (000s)	Total tax revenue supported (CNY bn)
NEI / CHN Energy	142.7	183.0	224.1	38.8
Huaneng	117.0	65.0	187.4	32.8
Datang	84.8	8.0	161.0	23.7
Huadian	84.3	8.8	183.4	23.2
SPIC	67.8	19.3	116.0	18.1
China Resources	44.2	8.0	102.4	12.6
Shandong Weiqiao Group	22.4	0.0	94.5	7.0
Zhejiang Provincial Energy Group	19.6	0.0	8.9	5.4
Beijing Energy Group	18.8	1.9	20.0	5.4
Jiangsu Guoxin	17.6	0.0	71.7	5.2

Guangdong Yudean Group	14.9	0.0	5.8	3.8
Huainan Mining Group	14.7	1.0	26.9	4.5

Between them, the Big Five support 41% of China's coal jobs. The largest single source of employment, at 224,000, is NEI (see Figure 13). The coal activities of Huaneng, and Huadian support approximately 180,000 workers each, while Datang supports 160,000. SPIC supports 116,000, and China Resources (a state-owned mining company), 102,000. Among the remaining top ten firms, Shandong Weiqiao (a private sector aluminium producer), Jiangsu Guoxin (a diversified state-owned investment company) support over 50,000 workers. While a detailed classification of firms by private- or state-ownership has not been compiled for this study, it is clear from looking at the largest firms that close to half of all coal jobs in China are directly linked to coal plants in which state-owned enterprises have controlling or minority interests.

Mirroring the trajectory of job losses nationally, 30-40% of the jobs currently supported by the Big 5 are lost by 2030, and another 30-40% are lost by 2040, under the baseline scenario. By the 2040s, employment supported by all of the major firms declines by 80-90%. The outlier in this example is Shandong Weiqiao, where job losses are slower because of Shandong's high mining labour intensity and significant local resources.

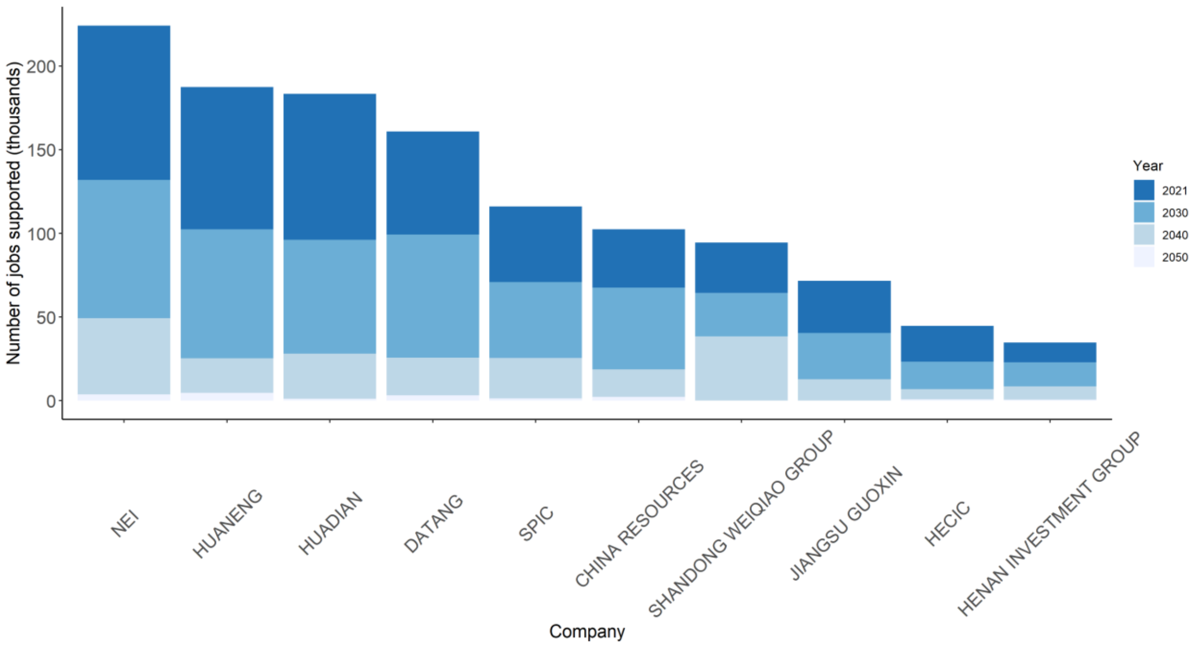

Figure 13. Largest parent companies by number of coal jobs supported, 2021-2050 (baseline scenario)

Unsurprisingly, the Big Five are also the largest contributors (directly and indirectly) to tax revenues nationally (see Figure 14), with the two largest supporting over ¥30 billion in revenue each, and the top five, almost ¥140 billion between them. However, mirroring the national trajectory, total tax contributions remain relatively steady until 2030, falling precipitously to between a third and half of their 2021 levels by 2040 in most cases, and collapsing to less than 10% of the starting value by 2050.

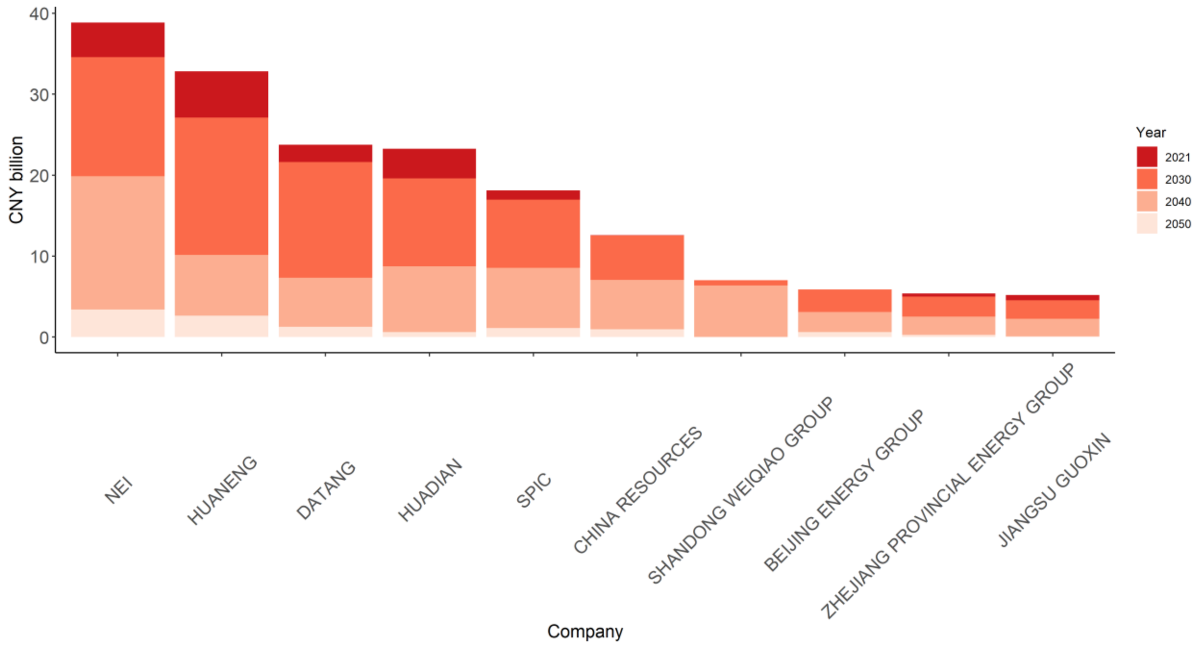

Figure 14. Largest parent companies by direct and indirect contribution to total tax revenues from coal, 2021-2050 (baseline scenario)

5. Discussion

A near-total phase-out of unabated coal power in the next 40 years, if not sooner, is implicit in the 2060 carbon neutrality target China has adopted, even if CCS is successfully implemented at scale. The corollary commitment to peak emissions before 2030 also signals a peak in coal consumption by the mid- to late-2020s. This analysis has examined how employment and tax revenues from coal-fired power generation may evolve over time under baseline and accelerated scenarios at the national, provincial and firms levels. Most job losses in the coal power sector are associated with mining, which represents three times the employment at plants. The magnitude of expected coal employment decline by 2050 in coal mines is significant, but largely driven by declining labour intensity rather than climate policy.

The experiences of the E.U. and U.S., as the preeminent economies experiencing a long-term decline in the coal industry, are instructive for China. However, the scale of China's coal industry and its central role in driving economic growth and development, as well as the dominance of SOEs in the sector, present unique political economy challenges. Existing policies have focused largely on worker relocation, an option that is more relevant for large, diversified SOEs but does little to support workers in smaller, local mines that have fallen victim to consolidation policies. This approach is not viable in the longer term, since relocation will not be an option as plants start to close *en masse*, and a much greater focus on retraining (where relevant) and redeployment of existing skills in clean power and industrial technologies is essential. Once sufficiently granular data is available, it is possible with existing methodological tools to identify opportunities for efficient labour reallocation through 'green adjacent possible' analysis.

Even without these data, managing job losses should be achievable given China's track record and prospects for growth in clean technology value chains. State-owned and private enterprises across the country have developed, at speed and scale, remarkable capabilities in the manufacture and development of complex low-carbon products (notably solar panels, electric vehicles, and third generation nuclear reactors) that have propelled China to a global leadership position in the production of each. In anticipation of the inevitable decline in coal sector employment, China's central and provincial governments, as well as its SOEs in energy and industry, should focus on identifying means for further scaling up these industries that can make use of the human capital at their disposal, and be supported by appropriate incentives for capital reallocation, including financial market design and regulation. Developing a package of mutually supportive measures for efficient labour redeployment is an important topic for further research.

The replacement of fiscal revenues tied to coal presents different challenges. Nationally, almost 80% of total tax revenues linked to coal power flow to the central government and remain relatively stable until the mid-2030s in the baseline scenario. For large coal producers, particularly Inner Mongolia, provincial government receives over 50% of total tax revenues. Since provincial governments and SOEs have relative fiscal independence and can issue their own debt, they represent a contingent liability for the central government, realised whenever they are unable to meet financial obligations, for instance if they borrow excessively to finance coal expansion that subsequently finds itself in insufficient demand. The risk of default and size of liabilities is greater for more ambitious phase-out scenarios.

Managing these potential fiscal risks is a task falling to the central government and its agencies across multiple ministries. The National Energy Administration's role, for example, in approving coal power is already under review following a recent critical evaluation by the influential Central Environment Inspection Team (CEIT), and will be an important instrument in preventing further investment in coal assets that may present fiscal risks to provinces either subsidising them or investing through locally owned SOEs. Similarly important is the China Banking and Insurance Regulatory Commission (CBIRC) in crafting regulation designed to prevent provinces with an interest in growing coal from doing so where the financial (and, by implication, fiscal risks) are significant.

The National ETS – effectively a technology standard – is unlikely to deliver significant revenues in the near term if current prices and trading volumes persist (Slater, de Boer, Guoqiang, & Shu, 2020), not least because the trajectory for free permit allocation, versus auctioning, is not yet clear. Even if provinces are allowed to retain a share of revenues from local permit trading, the incentive to keep prices low to avoid accelerating the decline of coal industries, particularly those run by SOEs, is strong.

The approximate magnitude of (non-externality) subsidies to the coal industry are of similar magnitude to revenues. This suggests that the net effect of coal phase-out may be revenue-neutral or positive, and further that the role of central government in managing the fiscal implications of coal-phase out in itself is likely to be largely redistributive, rather than requiring additional borrowing or monetary stimulus measures. Central fiscal support to provinces to aid their transition may be essential to weakening the destructive incentives for coal expansion in mining regions, like Inner Mongolia, that also have plentiful renewable resources able to compete on price with coal. In the longer term, ways of taxing clean technologies will be needed to replace the resource taxes (tied to coal sales) that represent a significant proportion of provincial revenue.

The extent to which additional investment is needed in reorienting labour resources to clean industries is a more complicated question, as large net fiscal outlays are likely to be necessary for China to accelerate the pace of decarbonisation, given the need for research and development spending, and infrastructure investment, in key technologies, notably hydrogen, nuclear, direct air capture, storage, and possibly CCS.

6. Conclusion

For China, a total phase-out of unabated coal use by 2060 is effectively inevitable, and the pathways for doing so are increasingly clear in the power sector. In industrial sectors dependent on coal for heat, the solutions are more ambiguous and likely to consist of a mixture of electrification and substitution with zero-carbon fuels. The role of CCS is as yet uncertain, but even if it proves both economic and scalable, is unlikely to prevent a long-term decline in coal demand or do much to slow the expected scale and timing of job losses in the coal mining sector.

This analysis focuses on the employment implications of transitioning a large economy away from coal, as well as the fiscal ramifications for areas dependent on the tax revenues it generates. A review of international experience in handling the socioeconomic implications of coal phase-out suggests that even in cases where coal is not a central pillar of primary energy supply, the effects of industrial decline and policy-induced mine and plants closures are keenly felt locally. Proactive measures to anticipate redundancies and lower local tax revenues can mitigate some of these effects, although the ultimate cost to taxpayers and society at large depends significantly on how policies are designed. Planned redundancies, as in the case of Asturias in Spain, can be effective but come at a high long-term cost to the public purse and corporate treasuries. Re-training programmes offer less protection to older workers and those with limited transferable skills.

Regardless of the pace of decline, the total number of mining and plant jobs at risk by 2050 is less than the total number of jobs shed from 2014-2020. Even under the most ambitious scenario (C80), coal employment does not fully disappear until 2035, implying job losses at less than half the rate experienced in recent years. The labour transition challenge facing China is therefore not unprecedented, but government should look to international, as well as its own, experiences to date in managing the localised effects job losses and finding productive alternative uses for labour. China's track record suggests this is achievable with the right package of public investment and regulatory tools.

The majority of tax revenues from coal flow to central government and are unlikely to decline until the 2030s. Coal-producing provinces like Inner Mongolia are more dependent on provincial tax revenues, both accentuating the need for diversification and making it more politically challenging to achieve. National-level regulation and enforcement will be essential in limiting provincial exposure to fiscal shortfalls caused by coal industry declines, although these are likely to be limited until the 2030s unless China pursues a much more aggressive phase-out strategy than currently envisaged. Almost half of total employment is driven by coal plants owned by five large state-owned enterprises that are integral to several local economies and providers of critical physical and social infrastructure, further accentuating the difficulties of embarking on such significant structural change. International experience suggests that fiscal redistribution will be necessary to offset some of the sharper costs of transition, but not at all sufficient to prevent long-term structural decline or stagnation. China is exceptionally well-positioned to divert coal subsidies and investment to clean technologies and skills, and renewable power, both to meet domestic policy goals, and as the world's largest exporter of green products.

This initial effort to reconstruct the coal network and associated jobs and tax revenues in China can be extended to include unpriced subsidies, particularly those typically considered to be externalities; it is also possible to overlay other economic, environment and financial metrics on the underlying network to consider, for example, how the marginal financial position of each plant and its owners are affected; and where and in what quantities pollutant emissions at source are "traded" across China's power system. As better data becomes available, the accuracy of the reconstructed network can be improved by accounting for price dynamics and transport availability between provinces, and matching specific mines to specific plants, which has not been possible in this analysis. Finally, this modelling effort raises pertinent hypotheses about China's coal transition that merit further multi-method investigation, particularly regarding political economy dynamics between agents driving, and affected by, the transition.

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Annexes

Annex 0: Province Codes

Province	Code
Anhui	AH
Beijing	BJ
Chongqing	CQ
Fujian	FJ
Guangdong	GD
Gansu	GS
Guangxi	GX
Guizhou	GZ
Henan	HA
Hubei	HB
Hebei	HE
Hainan	HI
Heilongjiang	HL
Hunan	HN
Jilin	JL
Jiangsu	JS

Province	Code
Jiangxi	JX
Liaoning	LN
Inner Mongolia	NM
Ningxia	NX
Qinghai	QH
Sichuan	SC
Shandong	SD
Shanghai	SH
Shaanxi	SN
Shanxi	SX
Tianjin	TJ
Tibet	XZ
Xinjiang	XJ
Yunnan	TN
Zhejiang	ZJ

Annex 1: The role of coal power in China's economy

Since 2005, China has produced more annual greenhouse gas emissions than any other country (ClimateWatch, 2020), a consequence of the rapid pace and intensity of its industrial development since the 1960s. China is also home to more than half of the world's coal power generation capacity, concentrated in Eastern and South-eastern provinces (both inland and along the coast), as shown in Figure 15. The strongest recent growth in capacity has been seen in the large Northern and Western regions of Inner Mongolia and Xinjiang, and Central province of Shanxi (highlighted). Following the outbreak of the COVID-19 pandemic, new coal power capacity was approved at an accelerated pace in 2020, accounting for 75% of commissioned capacity and 85% of coal power under development globally (Shearer & Myllyvirta, 2021). China also dominates production of industrial materials, accounting for 53% of global crude steel in 2019 and 60% of cement production in 2017 (Curry & van Oss, 2020; World Steel Association, 2020). In China, both industries are reliant primarily on coal as a source of heat. Replacing unabated coal with zero-emissions alternatives in China is therefore critical to global industrial decarbonisation.

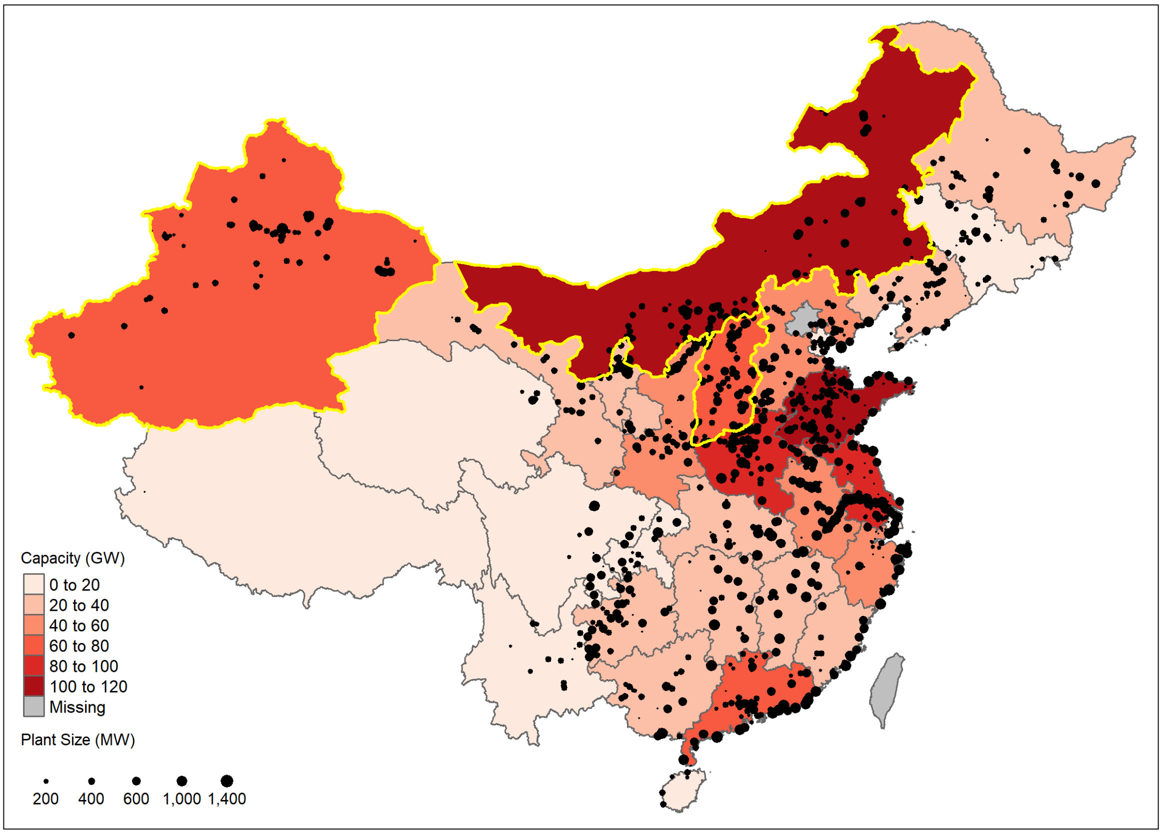

Figure 15. Distribution of currently operating and planned coal plant capacity in China

Climate policy and the coal sector

Recent national climate policy announcements are at odds with these developments. To the surprise of both international and domestic observers, Chinese President Xi Jinping's announced, in September 2020, a 2060 carbon neutrality target and a peak in emissions 'before 2030' (superseding the 'around 2030' commitment under China's first Nationally Determined Contribution to the Paris

Agreement) (Myers, 2020). China's 14th Five Year Plan (FYP), published since the announcement, includes a target for non-fossil energy to comprise 20% of final energy consumption by 2025 (25% by 2030) and an 18% drop in CO_2 emissions intensity that, even if met and exceeded, may not prevent emissions from rising overall, by approximately 1% per year, if the 6% annual GDP growth target is also met (Myllyvirta, 2021). Indeed, following a 7% year-on-year contraction in the first quarter of 2020, GDP growth returned to the 2018 level of 6.5% annualised growth by the fourth quarter (National Bureau of Statistics of China, 2021).

The recent acceleration in coal power plant approvals is consistent with the National Energy Administration (NEA) progressively loosening restrictions on new approvals across China's provinces[6] since 2017 (Baiyu, 2020). In 2020, the same year the announcement was made, the NEA, responsible for regulating the construction of new coal-fired power plants through a 'traffic light' system in place since 2016, oversaw provinces' approval of 36.9GW of additional capacity, and commissioned another 38.4GW, meaning 247 GW of capacity is currently under some stage of development, enough to take China's total fleet to well over 1,300 GW. The largest expansion of coal power in 2020 was seen in provinces that are also among the largest coal producers: Inner Mongolia and Shaanxi in particular, making up a third of construction starts and half of newly permitted capacity between them (Shearer & Myllyvirta, 2021).

Xi's 2060 target changed the policy context for these new capacity additions considerably. In addition, the Central Environment Inspection Team (CEIT), a task force staffed by officials from the Ministry of Economy and the Environment and charged with inspecting government agencies on behalf of the State Council, issued a highly critical report on the NEA in January 2021 for failing to take China's climate pledge seriously. Notably, the head of the CEIT is Han Zheng, a vice premier of China, member of the Politburo Standing Committee, and key advocate for climate and environmental policies. The report criticised NEA leadership for prioritising security and affordability of power supplies over climate considerations, and failing to place sufficient limits on the expansion of coal-fired power (Central Environmental Inspection Team, 2021). While the timing of the inspection may be coincidental, the coal industry will clearly face difficulty in expanding to the degree currently planned (H. Liu & Liu, 2021).

The short- and medium-term implications of China's increased climate ambition for the coal power and coal-reliant industrial sectors are subject to the execution of the sectoral 14th FYPs for the period 2021-25 and beyond. Nevertheless, analysis of national targets suggests that reaching net zero by 2060 will require the unabated use of coal for electricity generation to be largely phased out by the mid-2050s under a 2C global warming scenario, or mid-2040s under a 1.5C scenario, with any remaining industrial and domestic use of unabated coal being removed by 2060. Even if carbon capture and storage (CCS) technologies are widely deployed, allowing some plants to remain open, the coal power fleet is still projected to shrink by at least 90% from its current size (J. He et al., 2020). To the extent China's central government succeeds in enacting its stated policies, a near-total coal phase-out in China affecting the majority of the current fleet is inevitable and will have affect both existing and planned coal-fired power generation capacity.

Throughout the 13th FYP (2016-2020), the government pursued a policy of consolidation and scale, nominally as part of a strategy to combat growing industrial overcapacity, particularly in the coal mining and steel industries. By promoting the closure of smaller, less efficient mines and plants in favour of more centralised, larger and more efficient operations (People's Republic of China, 2016), coal has been brought further under the control of municipal, provincial or central state-owned enterprises (SOEs). An estimated 73% of coal mines closed in 2016-18 were small-scale state-owned mines (Hao et al., 2019). Even these smaller mines were, however, larger and more labour-efficient

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[6] China's provinces are divided into 'provinces', 'municipalities' (metropolitan regions), 'autonomous regions', and 'administrative regions'. For simplicity, all regions are referred to as provinces here.

than their private sector counterparts, and more likely to be controlled by diversified companies able to more easily redeploy workers within the same corporate parent. These restructuring efforts also saw industry concentration rise, with 10 mining companies accounting for 42% of output in 2018 and mines with over 1.2 million tonnes (Mt) annual production capacity making up 80% of national output (Hao et al., 2019). This process is expected to continue in the 14th FYP, with the number of coal mines expected to fall from 4,700 in 2020 to 4,000 in 2025, of which 25% will use "smart production techniques". Total coal production will reportedly be capped to 4.1 billion tonnes in 2025, or approximately 1% growth per year for the FYP period (Z. Liu, 2021).

Employment in coal mining

This progressive mechanisation and centralisation of coal production has already been associated with a continuous decline in employment in the coal mining, washing, transport and combustion industries in China, driven in part by increased automation and in part by mine closures. In 2016, the government projected 1.3 million jobs would be lost by 2020 in the coal sector as a result of capacity reduction and consolidation policies (Ministry of Human Resources and Social Security, 2016), and implemented a range of mitigation measures including a fund for supporting worker relocation and welfare support (People's Republic of China, 2017).

Direct employment by coal companies overall has declined from a peak of 5.3 million in 2013 to 3.2 million in 2018 (G. He, J. Lin, Y. Zhang, et al., 2020). Research published prior to the coal phase-out announcement suggested that improved technology and productivity would reduce the number of jobs by a further 50% to 1.6 million in 2050, and restrictions on total coal capacity would reduce this further to under 900,000 (Caldecott et al., 2017). The 2060 carbon neutrality target introduced since this estimate was made suggests the actual number of coal industry jobs in 2050 (across power, mining, and industry) may be substantially lower. Differences in coal mining labour intensity across provinces estimated in 2015 (UIBE & Chinese Academy of Sciences, 2019) suggest that many more jobs will fall victim to efficiency and automation in the coming years. Notably, the labour intensity of the most labour-efficient province, Inner Mongolia (1.7 jobs/10,000 additional tons of coal production) is similar to that of Germany, suggesting that the much higher figures for other provinces (32 jobs/10,000 tons in Shandong) are likely to converge on the lower figure in the longer term as industry consolidation, scale, and automation take effect. Assuming a constant rate of productivity increase, labour-inefficient provinces like Shandong will bear the brunt of efficiency-related jobs losses initially, although the absolute scale of coal production in these provinces is generally much lower. The trajectory of fiscal revenues from the coal industry is also affected by the decline in jobs, since at least some of the coal tax base is linked to labour.

Work to date on the socioeconomic impact of closing coal outside China has focused on OECD countries (notably the US, UK, and EU) with market structures and political systems very different to China, and less direct dependence on coal as the primary engine of economic growth and industrial production. China's own context is not, therefore, directly addressed by experiences and analysis by other countries on planning and executing an exit from coal, but some insights from international experience with coal phase-out can nevertheless be drawn.

Political economy of coal phase-out

The prominence of coal mining and power generation in the economies of coal-producing provinces, notably the largest producers (Inner Mongolia, Shanxi and Shaanxi) has the potential to place them at odds with central government position over coal phase-out policies.[7] In addition, coal mining enterprises are predominantly SOEs that also provide essential services to the communities their activity employs, and the urban areas built around the mines, including health and educational services such as hospitals and schools, and funding/maintenance of infrastructure such as roads and water services (Ruyin, 2020). The activities of SOEs are coordinated by State-owned Assets Supervision and Administration Commissions (SASACs), which convene at provincial or central levels depending on the ultimate owner of the SOE in question.

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[7] Attitudes to coal control policies do vary, however. Shanxi province pledged in 2020 to lower coal consumption to 80% of primary energy by 2021 while increasing the share of non-fossil-fuels to 5% and share of total capacity to 30%, placing restrictions on new coal and phasing out plants in breach of environmental standards. See Yang (2020).

Across coal mining, power generation and heavy industry, China's powerful National Development and Reform Commission (NDRC) has since 2007 driven a range of restructuring and consolidation policies among coal mining and power SOEs as a means of managing asset bases and implementing supply-side reforms (Rui, Morse, & He, 2015). A notable recent example is the merger of two of the former 'Big Five' power generators, Guodian and Shenhua, into the National Electricity and Investment Corporation (NEI), also known as CHN Energy, or China Electricity and Investment Corporation (CEIC) . Within the state-owned mining sector, the exhaustion of local coal resources in some areas has been followed by a redeployment of mining activity and associated personnel to other provinces with unexploited reserves. Under this policy, mining and power generation are being consolidated into a small number of massive 'coal power bases', from which electricity is sent directly to demand centres via long-distance transmission lines, reducing the need for long-distance coal transport and avoiding the need for heavily-polluting coal plants to be situated near large cities in the East. This is consistent with Beijing's strategy for reducing urban air pollution by relocating generators to Western China (Rui et al., 2015).

Annex 2: Experiences with coal phase-out beyond China

Coal in historical context

The experience of European economies and the US with coal phase-out has several facets. One is the decline of coal mining, which had all but concluded in the United Kingdom (UK) by the 1990s, following a long decline in mining output (from 216 Mt in the decade to 1962, to 20 in the decade to 2012) and employment (from 664,000 to 6,000 in the same period) (Department for Business Energy & Industrial Strategy, 2020). In the UK's case, much of this was driven by domestic industry economics and confrontation between the government and mining unions, as well as dwindling supplies: imported coal continued to be used for many years after domestic production ceased. Across the EU, direct employment in coal mining halved to 130,000 between 2007-2017, with almost two-thirds of the remaining jobs located in Poland (Galgóczi, 2019, p. 17). Total EU employment in coal-related jobs totalled about 238,000 in 2018 (Alves Dias et al., 2018), less than 0.1% of total European employment.

Elsewhere in Europe, coal mining (of both higher-grade thermal coal for power generation, and lower-grade lignite for heavy industry and other applications) remains a major component of several national economies, most notably Germany and Poland, but also Italy, Ukraine and Czechia (Euracoal, 2019). Several coal mining areas have already seen the decline and disappearance of previously flourishing industries. Bridle et al. (2017) review coal transitions in Wales, Asturias (Spain) and Kentucky, finding that mining regions in decline can effectively diversify by attracting investment and jobs in other industries under the right conditions, but that ensuring former coal miners benefit from this investment is particularly difficult. Their findings also suggest that early retirement schemes for mine employees can soften the immediate impact of redundancies and reduce fiscal planning uncertainty, but dampen incentives to seek alternative employment or retrain. Such schemes can also be very costly for governments or companies to maintain until retirement age, particularly for younger workforces.

In Australia, home to some of the world's largest deposits of high-grade thermal coal, there is little prospect of a decline in coal mining at present despite independent studies highlighting the economic risks of continued, if not expanded, production (Jotzo, Mazouz, & Wiseman, 2018). In the US, coal has been in decline for some time, despite favourable regulatory treatment in some cases, due to competition from gas and renewables, with coal mining contributing just 40,000 jobs in 2020, compared to 89,000 in 2011 and 177,000 in 1985 (U.S. Bureau of Labor Statistics, 2021). Coal power generation jobs averaged 79,700 in 2019, compared to 363,000 in wind and solar generation alone in the same year (National Association of State Energy Officials & Energy Futures Initiative, 2020, p. 40).

At least 14 of the 22 EU (+ UK) countries with coal power plants are planning a complete phase-out by 2030 (Galgóczi, 2019, p. 15). The routes to zero coal are varied. The UK has employed a carbon price floor and investment in offshore wind capacity to reduce dependence on coal and render it uncompetitive with gas in power generation, anticipating a complete phaseout by 2025. Spain committed in 2019 to close 50% of its existing capacity in June 2020, and Italy has announced the intention to phase out coal, but with little follow-up action to implement this goal (Sandbag, 2019). Germany is targeting a total phase-out by 2038, supported by compensation payments to electric utilities operating lignite-fired plants that have since been challenged by the European Commission (2021) under state aid legislation.

Analytical work on coal phase-out in China and elsewhere has focused on the financial implications for coal plant and mine operators (Bodnar et al., 2020; Cui et al., 2020; Gray & Sundaresan, 2020; Spencer et al., 2017; Yuan et al., 2020), with relatively little attention paid to some of the other key priorities of government, namely employment and productive economic activity (for which energy costs, and fiscal revenues and costs, are partial proxies). Phasing out coal, where it is the cheapest option for power or heat generation, also has implications for international competitiveness, whereby delaying phase-out may extend a competitive advantage in coal, energy prices, and manufactured goods production in the short-term. This delay can also slow investment, infrastructure deployment and technology learning rates in the longer term, however, decreasing competitiveness and raising energy and production costs while also emitting greater proportions of pollutants and greenhouse gases, and raising the risk of severe climate change.

Coal phase-out and jobs

Coal mining is a major component of the coal value chain, both in its industrial footprint and the jobs it generates. Immediately downstream of the mining industry are intermediate coal washing, processing (e.g., gasification) and transport industries. In Europe, coal tends to be consumed in relative proximity to the production site, while elsewhere, notably in the US and Australia, the coal transport and export industry is a major component of the industry's value chain. Coal is chiefly transported by rail, truck, or barge to the point of use. Coal is an intercontinentally traded commodity. Australia exports most of its coal regionally, to China, Japan, and Korea, for instance.

Further downstream are the sites at which coal is combusted, either for steam turbines in power plants (often in combined heat and power (CHP) configurations), or to generate heat directly for use in production processes that require it, e.g., for steel and cement. The value chain for coal-generated electricity extends to many ultimate uses for that electricity, while a similarly complex array of end uses applies to steel, cement, chemical or other products. This analysis focuses on the part of the value chain covering mining and combustion, since it is this – and not electricity generation or heavy industry (both of which can technically operate without coal, although viable, scalable pathways to coal-free production through electrification and zero-emissions hydrogen, are not yet clear) – that is the target of phase-out policies.

Long-term employment in coal industry operations (as opposed to the jobs associated with the design, engineering and construction of new mines, railways and power plants) is concentrated in mining and the supporting industries around it (G. He, J. Lin, Y. Zhang, et al., 2020). The relationship between the volume of coal extracted and the number of long-term jobs available varies significantly depending on how automated the mining process is, the size and accessibility of the deposit, the type and quality of coal being mined, regulation, competition, and physical proximity to markets. For instance, despite the intense current debate surrounding the employment impact of coal phase-out in Germany, total direct and indirect employment in coal power and mining has already declined from over 700,000 in 1985 to under 100,000 in 2015, driven by a combination of factors including market liberalisation and coal price trends, industrial consolidation, competition in international markets, domestic renewables, and technical advances (Oei et al., 2020).

Non-mechanised coal mining is physically demanding, requiring workers to manually harvest and move coal, often in dangerous or unsanitary conditions. While information on the gender of coal miners is not publicly available for China, the majority of mining jobs are likely to be held by men owing to factors including working conditions and cultural precedent, although employment opportunities for women will likely increase as previously manual tasks become automated or digitised, and energy sector employment shifts towards renewable energy sources. In rural areas, availability of renewable energy (including biomass and small-scale solar) can also dramatically reduce the labour and health burdens borne by women, and generate energy cost savings that can be used to raise living standards (Ding, Wang, Chen, Xu, & Li, 2014). This is not to say that the impact of job losses is not felt by women; the reverse may be true in communities where immediate and extended families are largely dependent on income from mining.

The coal industry also supports jobs in the transport sector, particularly where dedicated rail, road and port infrastructure has been put in place for specific mines. The number of jobs linked directly to coal mining depends on the degree of automation and general labour efficiency of the transport process, and the sensitivity of these jobs to coal demand depends on the degree to which coal transported on the network can be substituted with other commodities.

The final main category is the number of jobs at plants themselves. Data on the jobs supported by different sizes of coal plant is difficult to find and may vary significantly according to the age and type of plant, the use to which the coal is put, the location and corresponding technical and safety requirements, support staff, and other miscellaneous factors. A modern coal plant does not, in principle, require very many staff to operate at any one time, although in practice the jobs linked indirectly to plant operations (e.g., staff for different shifts, as well as safety, financial and operational management, cleaning and maintenance staff) can be significantly more than this.

Socioeconomic impact is an important consideration in the design and success of coal phase-out policies, particularly the short-term, localised effects on affected populations manifested through job losses, and declining provision of public and private goods funded by taxation. This is particularly true in areas where spending and investment by local authorities plays a large role in providing these services (e.g., locally funded schools, public transport, social services, and hospitals). Across the G20 economies, coal is estimated to benefit from at least US$63.9 billion in subsidies annually, with the majority going to coal-fired power generation, including US$15.4 billion in fiscal support, and US$20.9 billion in SOE investments (Gençsü et al., 2019). To the extent that reduced tax revenues are offset by reduced subsidies, coal phase-out can be revenue-neutral or even revenue-positive, in which case the primary difficulty for governments is not macroeconomic stability or growth, but redistribution of fiscal support and investment among subnational regions or groups. As will be seen below, this is likely the case for China.

In a study of coal mining regions in the European Union, Alves Dias et al. (2018) estimate that while total job losses by 2030 are estimated at 160,000, 25% of these are in a single Polish region in which the coal mining industry provides half of all employment. While the effects of jobs losses are felt immediately and require investment in retraining and low-carbon job opportunities to prevent structural unemployment, the longer-term fiscal impact, even if not significant at a national level, can be a source of institutional opposition or concern depending on the specifics of how, and from what sources, revenues are collected.

'Just transition' support measures to dampen employment shocks, prevent a deterioration in local infrastructure, and divert labour to new markets have been deployed in several European countries. Germany has established a €40 billion investment programme in education, innovation, and social safety nets in collaboration with trade unions; and Spain has allocated €250 million to transition support, while also requiring firms to submit just transition plans before closing production sites. The UK and France have no clear just transition policy in place other than small-scale local government support measures and company redeployment, but in both cases coal plays a very limited role in the national economy (Sandbag, 2019).

International experience to date in designing and implementing coal phase-out policies has demonstrated some of the challenges inherent in replacing an industry that, while not as prominent a feature of the energy and industrial economy as in China, often supports entire communities, directly and indirectly, in a small number of areas with highly concentrated coal jobs. Tension between interests at different levels of government and representing different societal cross-sections has proven to be a feature of coal phase-out efforts outside China. Worker and trade union opposition to phase-out is clear even in countries with relatively small coal economies like France (Jakubowski, 2019, p. 94). Subnational and local opposition to state-endorsed coal power projects in Asia is considered a major driver of the transition to cleaner sources (Stanley Center for Peace and Security, 2019).National governments also continue to oppose coal phase-out notably Poland (as one of the few EU countries not to currently target a full coal phase-out), which remains opposed to regional coal exit strategies despite the industry being under severe economic pressure (Europe Beyond Coal, 2020).

The experience in Europe demonstrates the importance of articulating, designing, and delivering on transitional measures to avoid 'stranded labour' and 'stranded locations'. This requires creating opportunities for individuals facing redundancy, and companies or entire areas facing labour reallocation and retraining needs, to use or adapt existing skills to other tasks, or other industries. The industrial materials that coal is used to produce – particularly iron and steel, and cement – will still be in demand regardless of coal's exit, and require significant, sustained investment in both electrification and hydrogen-based heat generation to remain viable. Indeed, large-scale investment in technologies essential to a decarbonised industrial economy can be a win-win strategy for replacing coal jobs at limited short-term fiscal cost, while increasing competitiveness in these technologies, contributing to improved trade balances and higher productivity in the longer term. Meanwhile, in rural locations where coal is cheap and abundant, research shows that a switch to gas may raise families' energy costs, strengthening the case for moving directly to renewable solutions (Li, Jin, Liu, & Zhou, 2021).

Fiscal impact: Taxation and subsidies

The taxes and subsidies linked to coal production, transport and consumption can be complex and various depending on the country and its specific regulatory and tax regime, as well as any subsidies or tax breaks provided to the coal industry, or to specific projects as an inducement to invest. In general, tax revenues associated with coal may include value-added taxes (VAT) or sales taxes associated with the sale and use of coal, charged incrementally at each point in the value chain in the former case, or in one transaction at the point of sale to the consumer in the latter case. Coal mines and plants are often also required to pay assorted royalties, rents, and fees to local or central governments, as well as a range of environmental charges (either volume-based taxes or as a tradable permit system). These charges can take the form of carbon pricing, as in the case of most coal plants in Europe and some in the US, as well as specific technology standards or fees associated with the emission of other pollutants.

Direct fiscal revenues are also associated with each job supported by the industry, in the form of income taxes on salaries, and social security payments, which vary in size (and ratio of employer/employee contribution) depending on the country, and may be managed privately (e.g., by a company pension fund) or fund entitlements to state benefits like access to healthcare, state pension, insurance, and benefit payments.

When considering the impact of coal phase-out on fiscal revenues, it is also important to determine the level of government affected: some revenues are municipal, others provincial, and others national. Sharp declines in revenues to local authorities are likely to have a much greater impact than those to national authorities since local government lacks the control over financial resources and redistributive capacities available to national government in confronting fiscal volatility and deciding funding priorities. In highly coal-dependent communities, the effects of reduced public investment and provision of public goods like healthcare and education, can have a serious deleterious impact across the population, with the effects potentially particularly acute for women and children.

A variety of indirect fiscal revenues are generated through the contribution of coal power to economic growth, consumption, and investment, as well as corporation tax. These are important but beyond the scope of this study and are likely to remain relatively stable independent of the energy source as long as China maintains similar overall growth rates under different energy scenarios.

How subsidies to the coal industry should be measured is contested, but in general terms can be separated into (a) direct subsidies to production, transport or consumption in the form of payments to the companies involved that allow them to render services at below-market rates or pay for the installation of equipment, (b) indirect subsidies in the form of tax breaks or benefits not extended to other parts of the economy, and (c) externalities, in the form of unvalued or under-valued negative effects, including but not limited to natural capital, human health, local air and water pollution, and greenhouse gas emissions. The last category is potentially the largest in magnitude by far, and included by the International Monetary Fund (IMF) in estimates of global fossil fuel subsidies (Coady, Parry, Le, & Shang, 2019). The definition of subsidies used in this analysis covers (a) and (b), essentially representing the fiscal transfers made in support of the coal industry and the impact of coal phase-out on government balance sheets. Of course, a full economic analysis of coal phase-out on China's economy should also account for (c). As a case in point, natural capital accounting analysis of Europe's largest open-cast lignite mine in Germany suggests the net gains of closing the mine 34 years ahead of schedule are €98-208 billion, 13-30% of the region's GDP, with savings from avoided pollution exceeding the cost of replacement with renewable energy infrastructure by a factor of six, and the cost of compensating job losses, by two orders of magnitude (Rafaty, Srivastav, & Hoops, 2020).

Learning from international experience

The UK government's experience in defeating coal mining workers' unions in the 1980s and 1990s, along with other factors including the discovery of North Sea gas resources in the 1970s, succeeded in essentially eliminating domestic production (followed later by declines in coal power generation and steelmaking) and has contributed significantly to the UK's climate ambitions today. Affected regions have largely failed, however, to generate sustained alternative forms of employment, or to attract sufficient investment, to offset the loss of the coal industry – reflected in high rates of unemployment, poor health, and poverty today that social safety nets like the state benefits system have done little to address, and have even exacerbated by creating chronic dependence on welfare payments (Beatty, Fothergill, & Gore, 2019). Nor is this a new phenomenon: ongoing research on Britain's economic history suggests that coal mining areas active as far back as the early 1900s experience persistent social and material deprivation today (Humphries & Thomas, 2020). Former and current coal mining areas in the US, notably in Appalachia, exhibit similar characteristics (Gohlke, 2021), including reduced local fiscal capacity driven by declining employment (Santopietro & Zipper, 2021). Germany's experience with the industrial transition is at an earlier stage. The proposed suite of policies to lessen the impact of the transition on coal-dependent communities, and avoid stranded labour, is far more comprehensive and includes significant investment in green alternatives (Euractiv, 2020). Justifying the generosity of compensation payments to utilities and workers in a highly-polluting industry is, however, an ongoing issue for policymakers to address (European Commission, 2021). Drawing together these experiences, it is clear not only that coal mining areas bear the brunt of phase-out costs in coal-producing economies, but also that a passive approach that relies on the redistributive function of social safety nets is not sufficient to address the long-term consequences for former mining areas. The German example of investing heavily in alternative employment, retraining, and the scaling-up of key low-emissions industries, are necessary (but perhaps not sufficient) for a successful transition. What is clear is that continued investment in coal may delay the need to confront the acute consequences of phase-out but will only prolong harmful uses of natural resources in the short-term, without avoiding the need for structural socioeconomic change in the longer-term.

Annex 3: Coal-related taxes and subsidies in China

Coal taxation

Fiscal and other public revenues from coal mining in China are generated in a number of ways. Income taxes and social security payments are contributed from the wages of employees in the industry. Average wages vary both by industry and by region in China. In this analysis, wages are separated into Eastern, Northeastern, Central and Western regions, and based on the average wage across 'manufacturing' and 'professional and technical' personnel, adjusted for each region and separated into different wages for mining jobs ('Mining') and power plants jobs ('Production and Supply of Electricity, Heat, Gas and Water') (National Bureau of Statistics of China, 2020).

Income taxes and social security payments are then estimated based on total employees. Income taxes are calculated according to the Chinese government's income tax brackets, assuming only the standard deduction is made, i.e. no other allowances are applicable (PWC, 2021a, 2021b). Income taxes are paid by employees at coal plants, and at the mines supplying those plants, both locally and in other provinces. The exact magnitude of social security payments varies by province, and sometimes also by city. In general, social security contributions are approximately 50% of gross wages, with three-fifths contributed by the employer (MS Advisory, 2020). To simplify, this analysis assumes 20% of gross employee salary is deducted from wages as social security payments, and 30% of salary value is paid by the employer.

Income taxes provide revenue to the central government, while social security payments are directed to publicly managed social security funds, centrally or locally, with some municipal or provincial authorities having some discretion over how contributions are invested. The components of social security payments cover housing, health, unemployment benefits, and pensions, with additional components varying by province and/or city. Social security, like income taxes, is paid both at plants and mines depending on the jobs associated with each.

China introduced reforms to pollutant taxation in 2018 under the 'Environmental Pollution Tax' regulation, in which emissions of specific pollutants are taxed either at a fixed rate or within a range specified by each province. Figure 16 reflects the mid-range estimates for each province. Revenues under the tax are collected by subnational governments.

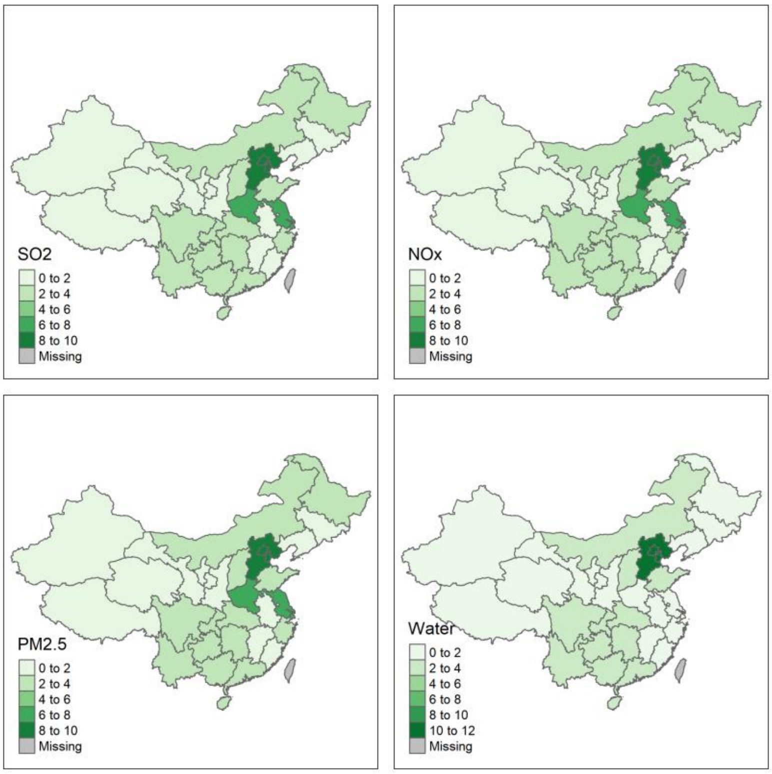

Figure 16. Environmental Pollution Tax rates for selected pollutants by province. Units: ¥/kg (¥/m^3 for wastewater)

For the purposes of this analysis, emissions of sulphur oxides (SO_x), nitrogen oxides (NO_x) and fine particulate matter ($PM_{2.5}$) are confined to coal plants, while gangue, mine tailings and coal ash are produced at mines. Wastewater is produced by both mines and plants, and taxed by volume as described in the table above. The resulting taxes are charged to plants and mines depending on their location.

Fees are paid by coal mines in the form of royalties and specific charges, as well as volume-based resource taxes. These taxes are listed in Table 4.

Table 4. Royalties and taxes paid by coal mine operators.

Tax	Unit	Value
Mining rights (occupancy fee)	% of sales	1.18% (average; 20% to central government)
Prospecting fee	¥/km^2/year	100 (rising by 100 per year from 4th year onwards, to a maximum of 500)
Extraction fee	¥/km^2/year	1000

Mining rights royalties (1.18% of sales revenue) are allocated 20% to central government and 80% to subnational government. Prospecting and exploration fees are based on the area being mined and calculated on the basis of an estimated relationship between mine size and annual production. This is likely to be fairly inaccurate, but the level of the fees is so low relative to other taxes that their contribution to total revenues is minimal and the impact of an incorrect estimate is small. Resource taxes are allocated to provincial or municipal governments and calculated on the basis of coal sales. Since it is not possible to distinguish cases where resource tax revenues are allocated to the former or the latter from available data, or the precise nature of the fiscal relationship between provinces and municipalities, they are assumed here to accrue at the provincial level.

The final category of taxation is value-added tax (VAT). The level of VAT varies by product and was recently reduced to 13% for coal products, which is the value used here. Assuming that average coal and electricity prices are inclusive of VAT, it is calculated as a proportion of each. Since VAT is paid incrementally along the supply chain based on the value added by each stage of production, the VAT paid by coal plants when selling electricity is net of the VAT already paid at the mine.

Total tax revenues to central government therefore include income taxes, prospecting, and exploration fees, 20% of mining royalties, and VAT. Total revenues to provincial governments include environmental pollution taxes, resource taxes, and 80% of mining royalties.

Coal subsidies

The various major subsidies (as defined above, i.e., direct and indirect, not including externalities) from which China's coal industry benefits are detailed in Table 5. It is not possible with available data to measure subsidies paid to the coal industry on a plant-level basis or in most cases to distinguish between subsidies benefiting coal power generation versus coal use in industry and heating. Estimates rely largely on point-in-time studies which themselves often rely on their own assumptions and vary widely in their estimates. These include subnational fiscal support to coal mines, subsidies for R&D and coalbed methane production, and an Industrial Special Fund subsidy specifically designated to fund resettling and retraining displaced or redundant workers in coal areas, although it is not possible to say how much of this is allocated to the coal industry.

Table 5. Summary of major non-externality subsidies to the coal industry in China

Subsidy	Value (¥ billion)	Source
Fiscal support	***8.1***	
VAT rebates (general)	1.7	Xue et al. (2015)
VAT rebates (coalbed methane)	1.1	Xue et al. (2015)
Local fiscal support	5.3	Gençsü and Chen (2019)
Direct subsidies	***104.7***	
R&D	0.3	Xue et al. (2015)
Coalbed methane production	0.4	Xue et al. (2015)
Industrial Special Fund	104	Gençsü and Chen (2019)

Public investment	***60.7***	
Fixed assets	7.7	Xue et al. (2015)
State power companies	53.0	Gençsü and Chen (2019)
Below-market rates	***119.6-151.7***	
Electricity retail prices[8]	52.0	International Energy Agency (2021)
Electricity wholesale prices (2021)	54.9	Model calculations/NCEPU/Cheng and Li (2020)
Railway rates	1.9	Denjean et al. (2016)
Railway rates (Inner Mongolia)	7.2	Xue et al. (2015)
Credit support	3.5-35.7	Xue et al. (2015)
Historical subsidies[9]	***122.6***	
Desulphurisation	48.7	Yuan et al. (2019)
Denitrification	32.5	Yuan et al. (2019)
Dust reduction	6.4	Yuan et al. (2019)
Ultra-low emissions (ULE) plants	31.7	Yuan et al. (2019)
ULE extra operation hours	3.3	Yuan et al. (2019)

Other subsidies include the use of state funds to subsidise retail electricity prices, and to reduce the cost of rail transport for raw coal. In the latter case, this refers to either direct payments or contracts that allow coal to be transported at below-market rates. Credit support refers to the ability of coal industry firms to obtain financing at below-market rates.

Retail electricity price subsidies apply to all electricity consumed. Historically, coal power has been sold not at market prices, but at administratively determined 'benchmark' prices in each province, constituting an additional subsidy to power generation. China has been gradually moving from benchmark trading to spot markets, which trade below the benchmark price in all of China's provinces, but some proportion of coal-fired power is still sold at benchmark prices.[10] The implied subsidy is based on the volume of coal-fired electricity sold in each province multiplied by the average difference between benchmark and spot prices and is calculated here at the plant level.

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[8] Based on coal power supplying 60.8% of China's electricity in 2020.

[9] These are subsidies that have largely already been spent and. For instance, subsidies for the installation of desulphurisation and denitrification equipment were provided from 2015-2020 order to bring the coal fleet up to the minimum standards set in the 13th Five Year Plan.

[10] Based on information supplied by Weirong Zhang at North China Electric Power University (NCEPU) and on Cheng and Li (2020).

It is also possible to estimate the magnitude of VAT rebates granted to coal mines. This takes the form of a general VAT rebate capped at a given amount; and a specific additional rebate based on the production of coalbed methane. It is assumed that mines take advantage of both rebates to the extent that they can, such that the maximum rebate is granted if sufficient VAT liabilities exist. This can only be calculated on an aggregate level, and is not broken down by province, but VAT liabilities are sufficiently large to ensure the full rebates are used easily.

With the caveat that subsidy calculations apply a range of assumptions and are therefore uncertain both in size and allocation to the coal industry, combining these figures suggests an overall annual subsidy of roughly ¥300-350 billion to the coal industry and coal areas, not counting historical subsidies for plant pollution control equipment. This is likely to decline in the absence of national or subnational government action as electricity market liberalisation continues and less coal-fired electricity is sold at benchmark rates.

While there is considerable debate over whether environmental and health externalities – local and global – technically constitute a subsidy, they do at the least reflect a mispricing of the social costs of coal production and combustion. The size of the externality associated with each tonne of coal production (including the impact on air quality, water and soil quality, global warming, prevalence of respiratory disease, and a range of other factors at various stages of production and consumption) is subject to wide variation in estimates, but are likely to be at least of a similar magnitude to all other subsidies combined. Coady et al. (2017) assess damages from all energy sources in China (to which coal is a major, if not majority contributor) at ¥3 trillion for global warming impact, and ¥12 trillion for local pollution. Zhao et al. (2017) use revealed preference methods to estimate the environmental cost of coal-fired power plants at ¥300 per MWh (implying a total subsidy of ¥1.52 trillion in 2021, given 5,058 TWh of coal-fired generation). Meanwhile, Yuan et al. (2019) estimate annual externality subsidies to coal power generation at a more modest ¥180 billion.

Annex 4: Scenario analysis

This study examines the impact of coal phase-out under four scenarios. In the baseline scenario, coal power plants operate for 30 years, and no further plants are built other than those already approved. This implies that coal use in electricity generation will not quite be fully phased out by 2050. Currently operating plants more than 30 years old are assumed to cease operating after 35 years, plants more than 35 years old, after 40 years, and all plants more than 40 years old are assumed to retire the following year.

This implies that 108GW of coal power remains online in 2050 (concentrated in Inner Mongolia, Shanxi, Shandong, Xinjiang, and Shaanxi), and coal is phased out entirely in the power sector by 2054. While the implications for carbon budgets are not addressed here, previous studies (Pfeiffer, Hepburn, Vogt-Schilb, & Caldecott, 2018; Tong et al., 2019) suggest that committed emissions from energy infrastructure built well before 2020 significantly exceed the global carbon budgets for both 1.5C and 2C and that compliance with these budgets will require a faster phase-out than projected here. Given China's major contribution to power sector emissions globally, the baseline scenario is unlikely to be compatible with either of the Paris Agreement targets without significant deployment of negative emissions technologies in the form of CCS (including variants such as co-firing coal with biomass) and direct air capture.

The baseline therefore represents a trajectory for China's coal power sector that reflects existing policies (including the 2060 carbon neutrality announcement) but is not necessarily in line with China's international commitments under the Paris Agreement, or with the best available science. Meeting these targets would require that CCS deployment be rapidly accelerated, and that coal with CCS remain competitive in the long term against available alternatives. Both appear unlikely at present.

Allowing plants to operate for this long reduces the financial risk of stranded or otherwise non-performing assets accumulating on coal and utility company balance sheets – although this does not eliminate them, since the economics of China's coal plants and decreasing utilization hours for coal suggest as much as half the current fleet is suffering operating financial losses (Gray & Sundaresan, 2020).

The baseline is, however, consistent with China decarbonisation pathway modelling by J. He et al. (2020), in which the unabated coal generation fleet stands at 123GW (+ 68GW CCS) in 2050 under a 2C scenario, and 32GW (+ 149GW CCS) under a more ambitious 1.5C scenario, partially reflecting the use of CCS as a means of justifying carbon budget overshoot before 2050. In the model in this study, 472 TWh of coal-fired electricity is generated in 2050 under the baseline scenario, similar to the 450 TWh (unabated; 850 TWh including CCS) in J. He et al. (2020) for a 2C scenario, and much higher than the 110 TWh (unabated; 900 TWh including CCS) in the 1.5C scenario, in which net zero emissions are achieved in the power sector between 2045 and 2050.

CCS does feature in the 1.5C and 2C scenarios, but since its scalability and competitiveness are not yet established, particularly when considering price trends in clean technologies, it is not considered as an option in the model. The potential for CCS to sustain existing coal sector jobs and create new ones will merit further study as its feasibility becomes clearer.

China may opt to phase out its coal plants more rapidly than in the baseline scenario, either as a matter of top-down policy (particularly if responding to new information on the climate system), or proliferation of cheaper, cleaner alternatives in the market, or both. Three alternative scenarios are modelled in which coal plants are closed more quickly than expected (i.e. an accelerated decline in capacity), assuming no additional CCS capacity.[11] In the first alternative scenario, 'R', the trajectory of

[11] An alternative route to a similar outcome is to keep plants open as originally planned, but with much fewer generating hours. This may help to preserve jobs at the plants for longer, but with severe financial consequences

accelerated plant closures is calibrated to correspond to match the share of coal capacity closures between 2020 and 2030 in the three scenarios presented in G. He, J. Lin, F. Sifuentes, et al. (2020), a power system model that optimises for cost given a set of energy technology prices and carbon constraints. In the 'R' scenario, a more rapid phase-out reflects the impact of lower-than-expected renewables costs on capacity additions. In the more aggressive 'C50' and 'C80' scenarios, emissions from coal power decline in absolute terms by 2030 to meet power sector emissions targets of 50% and 80% below 2015 levels, respectively.

To implement the scenarios, the only variable that is changed is the operating lifetime of each coal plant, which is calibrated to reflect the approximate capacity remaining by 2030 in the scenarios constructed in G. He, J. Lin, F. Sifuentes, et al. (2020), multiplied by a factor of 1.42 to account for the ratio between expected 2020 installed capacity in the source paper (832GW) and actual operating capacity in 2020 (1180GW) for scenarios B and R. The higher installed capacity in these scenarios is largely offset by lower operating hours, such that coal power generation is similar under the baseline (B) scenario, and slightly higher under the R scenario. In the C50 and C80 scenarios, no multiplier is used since they are based on emissions reductions from a 2015 (not 2020) baseline. The scenarios, and how they are implemented into the model in this paper, are summarised in Table 6.

Table 6. Characteristics of coal plant phase-out scenarios used in the model.

Scenario	**Description**	**Plant operating lifetime (years)**	**Capacity in 2030 (GW)**		**Generation in 2030 (TWh)**	
			He et al. (2020)	Model	He et al. (2020)	Model
B	Baseline; reflects existing policy of carbon neutrality by 2060	30 (35 if plant age >30, 40 if plant age >35, age+1 if plant age >40)	751 × 1.42 = 1,057	1,114	4,915	4,827
R	Low-cost renewables; reflects greater than expected declines in renewables costs	25	707 × 1.42 = 1,003)	984	3,676	4,270
C50	50% decline in emissions from coal power by 2030 relative to 2015	20; cancellation of plants under construction	498	486	2,371	2,125
C80	80% decline in emissions from coal power by 2030 relative to 2015	15; cancellation of all plants under construction	196	195	957	867

Note that these scenarios assume the province-level capacity factors are constant over time.

for plant owners that are, in many cases, already absorbing operating losses. We assume that the closure of plants, rather than running increasing portions of the fleet at increasingly large losses, is the preferred strategy in designing these scenarios.