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Estimating stranded coal assets in China's power sector

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Abstract: China has suffered overcapacity in coal power since 2016. With growing electricity demand and an economic crisis due to the Covid-19 pandemic, China faces a dilemma between easing restrictive policies for short-term growth in coal-fired power production and keeping restrictions in place for long-term sustainability. In this paper, we measure the risks faced by China's coal power units to become stranded in the next decade and estimate the associated economic costs for different shareholders. By implementing restrictive policies on coal power expansion, China can avoid 90% of stranded coal assets by 2025.

Keywords: China, Coal power, Overcapacity, Stranded assets

1. Introduction

Coal-fired power production in China has experienced severe overcapacity and financial losses in the past years (Yuan et al., 2016; Ren et al., 2021; He et al., 2020). With a slowdown in economic growth and an increase in renewable energy generation, the share of coal power generation has declined from 82% in 2009 to 66% in 2019, and the capacity factor of coal power units dropped from more than 55% in 2013 to about 48% in 2019, as shown in Fig. 1. Such a capacity factor is much lower than the statue capacity factor, 57%, to ensure that the benchmark coal-power feed-in tariff is high enough to cover the average cost of coal power generation in China, and it is much lower than the standard capacity factor suggested in the literature at about 60.5%–62.8% (CEC, 2018a, 2019; Polaris Power Net, 2019). By the end of 2018, the five biggest generation companies in China (Huaneng, Datang, Huadian, SPIC, and CHN Energy) had accumulated a total liability of RMB 1.1 trillion (USD 169 billion),[1] with an average debt-to-asset ratio of 73.1%. The state-owned coal power enterprises in 15 provinces suffered a financial loss in 2018, with serious long-term financial troubles for companies in the northwestern region (China Energy Newspaper, 2020). All these statistics suggest that China's coal-fired power production needs to be closely watched to prevent further inefficient investment that could provide short-term economic stimulus but lead to long-term damage to society.

There are several reasons why China has kept investing in coal power, and we discuss them from economic, financial, and political perspectives. Economically, as part of the decentralization policy of the State Council, the approval authority for new coal power projects was moved from the National Development and Reform Commission (NDRC) to the provincial level in 2014 (Tan et al., 2021). In order to promote local economic development, a large number of new coal power projects were approved by provincial governments between 2014 and 2015 (Yuan et al., 2017). As Ren et al. (2021) found, the approval rate of coal power was about three times higher after approval authority was decentralized, and provinces with more coal production approved more coal power projects. Financially, investment efficiency was further degraded as financial decisions were primarily made by state-owned enterprises, policy banks, and state-owned commercial banks instead of private entities (Shearer et al., 2019). Traditional risk management methods, designed to study the impact of external shocks on bank solvency in China's financial sector, cannot measure climate change-related risks. Assessing climate-related risks requires new stress testing tools to assess the profitability of coal-related assets (Yuan et al., 2018). To meet growing electricity demand, the China Banking and Insurance Regulatory Commission (CBIRC) also issued a policy to urge financial institutions to support coal power companies and project

[1] Exchange rate is assumed to be 1 USD = 6.5 RMB. The "Big Five" generation companies in China are: China Energy Investment Corporation [CHN Energy], China Da Tang Corporation [DT], China Huadian Corporation [HD], China Huaneng Group Corporation [HN], and State Power Investment Corporation [SPIC].

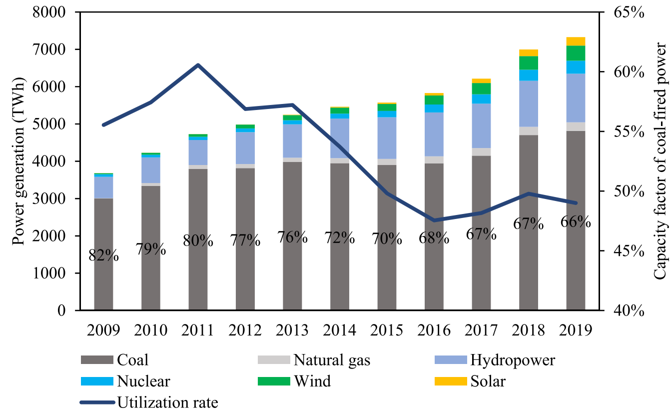

Fig. 1. Power generation by technology and capacity factor of coal power in China.

which further increased financial support for coal-fired power (CBIRC, 2021). Politically, parties with nested interests, such as China Electricity Council (CEC) and government-affiliated think tanks, have openly lobbied for further growth in China's coal power fleet by 2030 (Zhang et al., 2021). While Chinese President Xi Jinping announced that China would reach peak CO_2 emissions before 2030 and carbon neutrality before 2060 in the UN General Assembly in September 2020, the efforts towards the goal were largely compromised as the COVID-19 pandemic kicked in and local governments approved an additional 42 GW coal power projects in 2020 to stimulate local economic development. The conflict between ambitious carbon neutralization targets promoted by the national government and the short-term economic incentives of local governments, worsened by the lack of risk assessment tools for coal-related assets in the financial sector, has led to slow progress in containing coal power expansion in China.

From 2016 to 2020, the Chinese government made good progress in slowing down the massive expansion of coal-power capacity in China.[2] However, it has been controversial whether such strict constraints on new construction should be continued through the next five years (2021–2025). We estimate "reasonable" coal-fired power capacity using an electric power and energy balance model to shed more light on this question. Then we calculate the amount of "excessive coal power" by taking the difference between the possible development of coal-power capacity under three scenarios and the reasonable coal power capacity estimated in Step 1. Further, we identify the risks faced by each coal-power unit to be decommissioned due to policies since 2017 and rank the units by risk from high to low as the sequence to retire stranded units up to the amount of excessive coal power capacity. Lastly, we estimate the economic value of stranded assets by aggregating the unrecoverable initial investment, unpaid interest of bank loans, and the unrecoverable expected returns to equity due to forced early retirement. To do this, we built a comprehensive database of all coal-power units in China, including 4631 units in operation, 379 units under construction, 318 units being suspended or postponed, and 201 units to be approved by the end of 2019 (Endcoal, 2019; CEC, 2017; 2018b; MEE, 2014; Greenpeace, 2019), and this is by far the most complete and up-to-date dataset of China's coal power units to our knowledge. This paper is also the first in the literature to use a decision-tree analysis to quantify the risk of forced early retirement of coal power units in China.

We find that stranded coal assets will be significantly reduced with policy intervention to slow down the construction of new coal power plants. In the Business-as-usual (BAU) scenario, the economic loss from stranded coal assets will be about 532 billion RMB, compared with 299 billion RMB in the less restrictive policy scenario and 48 billion RMB in the more restrictive policy scenario in 2025.[3] Implementing a more restrictive policy on coal power expansion can help avoid 90% of stranded coal assets in China's power sector in the next five years. China's financial institutions (primarily banks) will share about half of the financial loss due to their loans to coal power generation companies, and smaller state-owned and private companies will suffer the most due to their ownership of smaller and less efficient coal power units.

The paper is organized as follows. Section 2 reviews the methodologies used to estimate stranded assets in the literature. Section 3 describes the methodology and data we use to estimate stranded coal assets in China. Section 4 presents the results, and section 5 concludes.

2. Literature review

Paun et al. (2015) defined stranded assets as those that lose value or turn into liabilities before the end of their expected economic life. In the market of fossil fuels, he summarized that stranded assets could occur due to risk of regulations (such as climate change and environmental regulations), risk of economics (price changes in commodities), and risk of technological innovations (efficiency gains in renewable energy). According to Caldecott (2015), stranded assets are those that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities due to a variety of risks. Simshauser (2017), on the other hand, recognized that asset stranding is a policy choice, not an analytical determination. Several other papers evaluated how climate-change policies could impact the risk of stranded generation assets (Farfan and Breyer, 2017; Johnson et al., 2015; Pfeiffer et al., 2016, 2018). Because China's electricity prices are still heavily regulated[4] despite a market reform since 2018 (NDRC, 2019a), we take a more analytical approach and define the excessive coal power capacity as the capacity beyond the minimum coal power required to ensure system reliability.[5] We assume that the cost of stranded assets will eventually fall onto taxpayers because both the shareholders – coal power companies and banks – are mostly state-owned in China.

Kelly et al. (2020) assessed the impact of stranded assets on U.S. and European utilities and found that the potential financial risk of stranded assets in the utility sector depends on three main characteristics: regulated status, fuel generation type, and political makeup at the state and federal levels. Despite the considerable risk to coal generation, regulated coal assets present minimal risk to investors due to favorable regulatory treatment. In other words, regulation can play a role in mitigating the financial risks of stranded assets. As Beecher and Kihm (2016) pointed out, lower risk to investors may come at a high price to ratepayers, namely, an offsetting loss of economic efficiency due to weak performance incentives. Therefore, it is important for Chinese policy makers to find a balance between a fair return to capital investors and a fair rate design for ratepayers. In particular, they should be aware that fixed charges over variable charges tends to favor investors over ratepayers. In 2017, the Chinese State Council issued a new policy stating that coal-fired power units approved after March 2015 will have to participate in the electricity market instead of receiving a fixed on-grid tariff (State Council, 2015). However, there is still no official policy on how to compensate and manage the stranded coal power assets in China.

Since 2017, the Chinese government adopted a series of policies to decommission small and outdated coal power units, and factors considered include (1) years of service since construction, (2) capacity size, (3) energy efficiency, whether qualified or not based on its size (4) technology type, especially whether it is Combined Heat and Power

[2] From 2016 to 2020, 90 GW of coal-fired power projects were suspended, 60 GW were postponed, and 35 GW retired, reducing the risk of overcapacity in China's coal-fired power sector (Polaris Power Net, 2017; Xinhua Net, 2017).

[3] All values in nominal terms.

[4] http://www.gov.cn/xinwen/2019-10/25/content_5444655.htm.

[5] We estimate the minimum coal power required to ensure system reliability using an electric power and energy balance model.

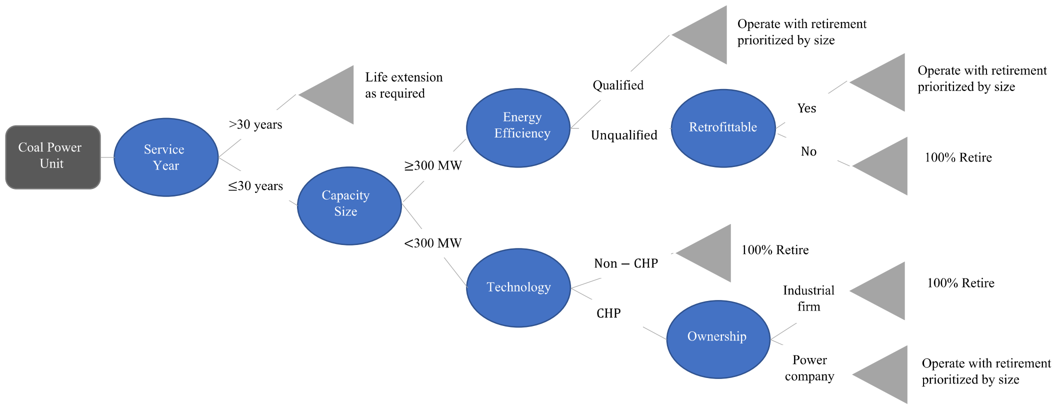

Fig. 2. Decision-making process of retiring coal power units in China.

(CHP) unit, (5) and ownership by a power company or industrial firm (Polaris Power Net, 2018; SAC, 2017; NEA, 2019; NDRC, 2019b).[6] We thus create a decision tree chart to illustrate the decision-making process of retiring coal power units in China. Fig. 2 shows the process, where blue bubbles are the key factors in retiring a coal power unit. We assume that 5% of units above 30 years of service can be extended based on an extension policy,[7] and for non-CHP units below 300 MW, 50% will keep operating due to constraints of local heating need (Jiangsu NEA, 2020). For units that are qualified for operating, we assume that the likelihood of their forced early retirement is negatively correlated with their capacity size so that smaller units, which are usually less efficient ones, will be decommissioned first if necessary.

Note: "Qualified" or " Unqualified" refers to whether the energy efficiency of the coal power unit meets the emission standards set by the government; "CHP" or " Non-CHP" refers to whether the technology of the coal power unit is also used to provide central heating.

3. Methodology and data

This paper takes four steps to estimate the economic value of potentially stranded coal assets in China. In the first step, we estimate how much coal-fired power capacity will be needed using an electric power and energy balance model, and we call it the "reasonable coal power capacity." In the second step, we forecast the expansion of coal power capacity in China under three development scenarios and derive the "excessive coal power capacity" by subtracting the reasonable coal power capacity from the constructed coal power capacity in three scenarios. In the third step, we identify the stranded coal assets following the retirement process in Fig. 2, decommissioning coal power units up to the "excessive coal power capacity" calculated in step 2. In the last step, we estimate the economic cost of those stranded assets under each of the three scenarios. To do these, we built a comprehensive database of all coal-power units in China, including 4631 units in operation, 379 units under construction, 318 units being suspended or postponed, and 201 units to be approved by the end of 2019 (Endcoal, 2019; CEC, 2017; 2018b; MEE, 2014; Greenpeace, 2019).

3.1. Reasonable coal power capacity

On the demand side, SGERI (2019) estimated that China's load demand will peak around 1500 GW in 2025 and 1680 GW in 2030. Yuan

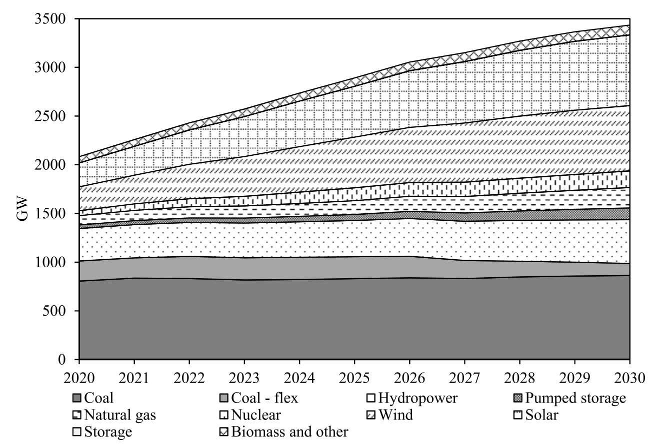

Fig. 3. Estimated reasonable capacity by energy source in China, 2020–2030.

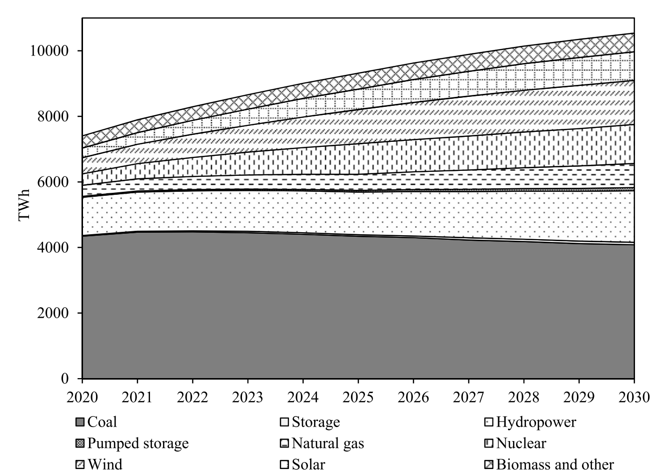

Fig. 4. Estimated power generation by energy source in China, 2020–2030.

(2019) and Liu (2019) estimated that China's total electricity consumption will be 9200 TWh in 2025 and 10,000 TWh in 2030. We extrapolate the annual peak demand for years between 2020 and 2030 based on these two-point estimates with a decreasing positive growth rate.

On the supply side, we conduct a national electric power and energy balance model to estimate the minimum coal power capacity required to

[6] http://news.bjx.com.cn/html/20180305/883418.shtmlhttp://www.cqjnw.org/res/2017/07-11/16/4599090c62bae67652b475c001ddd884.pdfhttps://www.chplaza.com.cn/article-5270-1.htmlhttps://www.sohu.com/a/227063974_645120.

[7] http://jsb.nea.gov.cn/news/2020-12/2020122102242.htm.

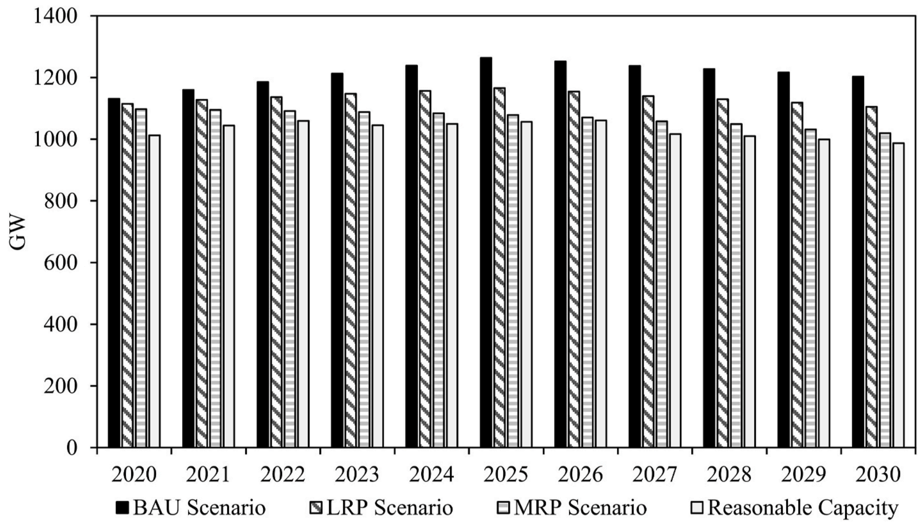

Fig. 5. Development of coal power under three scenarios in China, compared with reasonable coal power capacity, 2020–2030.

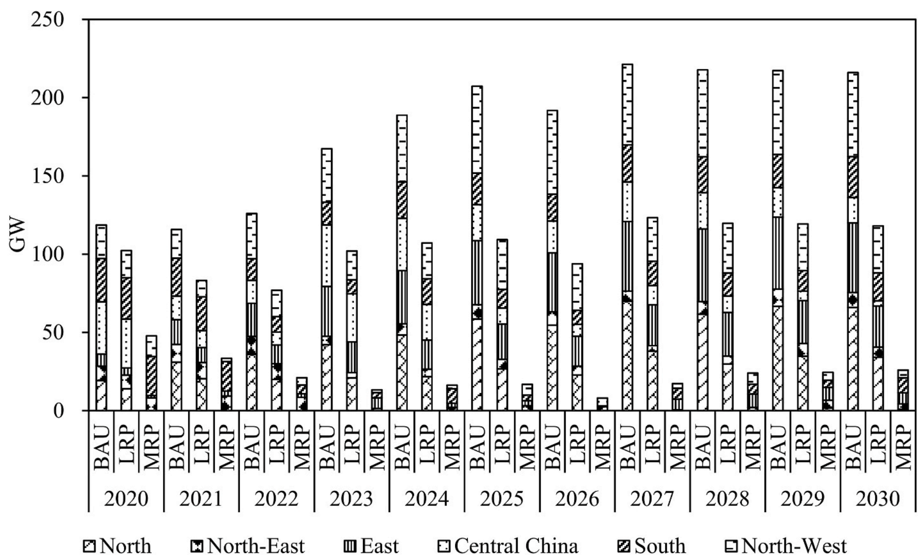

Fig. 6. Estimated excessive coal power capacity by region in China, 2020–2030.

ensure system reliability (Feng and Wang, 2018; Zhang and Yan, 2020). We assume a reserve margin ratio of 15% (EIA, 2012) and a demand response of 3%–10% (Hale et al., 2018).[8] Because the official target states that 50% of China's electricity should come from "non-fossil" sources by 2030, we added this constraint into the model. We present our estimates of the reasonable capacity of different energy sources in Fig. 3 and their associated annual power generation in Fig. 4. The darkest area at the bottom of Fig. 3 is the reasonable coal power capacity, which we derive by estimating the minimum coal power capacity required to ensure system reliability in the next decade.

3.2. *Excessive coal power capacity*

To estimate China's potential excessive coal power capacity, we first look into three established development scenarios: business-as-usual (BAU), less restrictive policy (LRP), and more restrictive policy (MRP). In the business-as-usual scenario, no policy effort is made to curtail investment in coal power under the current industry regime. Since there are about 200 GW of coal power units under construction at the end of 2019, and a recovery package is likely to pass to promote more investment in coal-fired power production due to COVID-19 (China Dialogue, 2020; Polaris Power Net, 2020; Sohu, 2020), we estimate that China will have an additional 200 GW of coal power capacity by 2025, and reach a total capacity of 1203 GW by 2030.[9]

In the less restrictive policy scenario, China will implement limited measures to reduce coal power investment. The most recent International Energy Agency (IEA) report predicts that China will continue to build an average of 17 GW of new coal-fired plant per year through to 2025, with many new projects in progress despite a current excess of power capacity, weakened electricity demand outlook, and recognition of the imperative to reduce coal use to address climate change (IEA, 2020). Therefore, under this scenario, China will have an additional 102 GW of coal power capacity from 2020 to 2025 and reach a total capacity of 1105 GW by 2030.

In the more restrictive policy scenario, China will implement ambitious measures to reduce coal power investment. Chinese President Xi

[8] The model and data are detailed in the "Appendix".

[9] The 1203 GW takes into account the automatic retirement of outdated units.

Table 1
Characteristics of China's coal power units built after 2000.

Total Capacity (MW)	Construction Year	2001–2005	2006–2010	2011–2015	2016–2019
Capacity Size	≥ 300 MW	101,554	334,300	283,192	90,990
	< 300 MW	43,712	41,328	25,227	6669
Technology	CHP	59,126	122,648	140,678	41,534
	Non-CHP	86,140	252,980	167,740	56,126
Ownership	Industrial Firm	14,793	22,398	60,784	12,901
	Power Company	130,473	353,230	247,635	84,758
Energy Efficiency	> 320 gce/(kW·h)	60,497	106,644	71,075	20,280
	≤ 320 gce/(kW·h)	84,769	268,984	237,344	77,380
Total		145,266	375,628	308,419	97,659

announced that China will reach its peak of CO_2 emissions before 2030 and achieve carbon neutrality within 40 years, before 2060 (BBC, 2020). To achieve this target, the government needs to make serious efforts to restrict the expansion of coal power capacity. Therefore, we estimate that China will have no additional coal power capacity installed by 2025, and only 27 GW of coal power units in North and Central China will be given permission to extend their life for strategic reserve purposes, and by 2030, China will have no more than 1019 GW of coal power capacity.

We summarize our estimate results in Fig. 5, which compares the reasonable coal power capacity needed in China to serve projected demand and likely development of coal power capacity under three scenarios. The difference between the coal power capacity in each scenario and the reasonable capacity is the "excessive coal power capacity" in the system under different scenarios each year. Given the existing overcapacity of coal power in China right now, even the more restrictive policy scenario would generate some "excessive coal power capacity" each year in the next decade.

We further decompose the excessive coal power capacity at the regional level in China, as shown in Fig. 6. We defined excessive coal power capacity as stranded coal assets, which means the capacity beyond the "reasonable coal power capacity."

3.3. Stranded coal power units

To identify coal power units at risk of being forced to retire early, we follow the policy directions announced by the government since 2017 to retire small and outdated coal power units in an orderly manner and summarized the decision-making process in Fig. 2. Since the most important factors are (1) years of service since construction, (2) capacity size, (3) energy efficiency, (4) technology type (CHP or not), and (5) ownership (industrial firm or power company), we create a summary table for all of China's coal power units constructed since 2000 on these characteristics. Table 1 shows how much capacity was constructed in each 5-year interval from 2001 to 2019 by characteristics of the units. As one can see, China has been building a lot fewer units under 300 MW in recent years, from 43,712 MW from 2001 to 2005, almost 1/3 of the total coal power capacity installed in that period, to 6669 MW from 2016 to 2019, less than 7% of total coal power capacity installed during that period. Total installed coal power capacity also dropped from the early 2010s to the latter half of the decade. Following the flow chart in Fig. 2, we can rank all the coal power units by their likelihood of retiring each year and strand the assets up to the amount of excessive coal power capacity calculated in Fig. 6.

3.4. Economic value of stranded assets

To estimate the economic value of stranded assets, we sum up the unrecoverable initial investment, unpaid interest to bank loans, and the unrecoverable expected returns to equity due to forced early retirement. Equation (1) shows the method, where V_{SA} is the value of stranded assets; V_{UIN} is the value of the unrecoverable initial investment; V_{UBL} is the unpaid interest on bank loans; and V_{UERE} is the unrecoverable expected returns to equity due to forced early retirement.

$$V_{SA} = V_{UIN} + V_{UBL} + V_{UERE} \tag{1}$$

To calculate the initial investment, we aggregate the capital cost of generation units, desulfurization equipment, denitrification equipment, and dedusting equipment (NEA, CEPEI & CRERI, 2006; 2011, 2016). We assume that the initial investment can be recovered by operating for 20 years under the current regime of the power industry in China. Equations (2) and (3) show the method to calculate unrecoverable initial investment, where V_{IN} is the initial investment in a coal power unit; V_{IU} is the investment in the generation units; V_{IDS}, the investment in the desulfurization equipment; V_{IDT} is the investment in the denitrification equipment; and V_{IDD} is the investment in the dedusting equipment. The unrecoverable initial investment would be a portion of the investment expected over the remainder of the 20 years. If the unit has already run for more than 20 years, it will have zero unrecoverable initial investment.

$$V_{IN} = V_{IU} + V_{IDS} + V_{IDT} + V_{IDD} \tag{2}$$

$$V_{UIN} = V_{IN} * \max\left(0, \frac{20 - \text{Years of Service}}{20}\right) \tag{3}$$

Investments in coal power projects are made partly by bank loans and partly by enterprises, and the ratio of invested capital is usually 80%: 20% (NEA, 2018). Once the unit is commissioned, it needs to recover bank loan interest costs and the expected return on the capital invested by the enterprises, as shown in Equations (4) and (6).

Equations (4) and (5) show the method to calculate the unpaid interest on bank loans of a random coal power unit, where V_{BL} is the total interest on the bank loans and R_{bl} is the annuitized interest rate of the loans (%) to be paid off in 15 years. The unpaid interest on bank loans would be a portion of the interest expected over the remainder of the 15 years. If the unit has already run for more than 15 years, it will have zero unpaid interest.

$$V_{BL} = 15 * 80\% * V_{IN} * R_{bl} \tag{4}$$

$$V_{UBL} = V_{BL} * \text{Max}\left(0, \frac{15 - \text{Years of Service}}{15}\right) \tag{5}$$

Similarly, Equations (6) and (7) show the method to calculate the unrecoverable expected returns to equity, where V_{ERE} is the total value of expected return on equity in 30 years, and R_m is the expected market return on equity investment. If a unit retires early, the equity investors will lose the investment return expected over the remainder of the 30 years.

$$V_{ERE} = 30 * 20\% * V_{IN} * R_m \tag{6}$$

$$V_{UERE} = V_{ERE} * \frac{30 - \text{Years of Service}}{30} \tag{7}$$

When coal power units are stranded, investors neither recover their capital nor repay the bank loans. So, we further divide it into *bank loss* (financial loss incurred to banks) and *enterprise loss* (financial loss

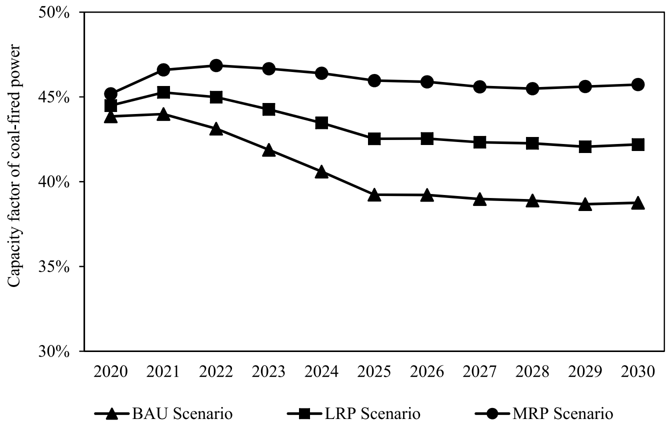

Fig. 7. Capacity factor of coal power plants under three development scenarios in China, 2020–2030.

incurred to equity owners) when the stranded value is positive. *Bank loss* includes 80% of unrecoverable initial investment and the unpaid interest on the loans (Equation (8)), while *Enterprise loss* includes 20% of unrecoverable initial investment and unrecoverable expected returns on equity (Equation (9)). V_{SABL} represents the bank loss due to stranded coal assets, and V_{SAEL} represents the enterprise loss due to stranded coal assets.

$$V_{SABL} = 80\% * V_{UIN} + V_{UBL} \tag{8}$$

$$V_{SAEL} = 20\% * V_{UIN} + V_{UERE} \tag{9}$$

4. Results

For each of the three scenarios of coal power development in China, we calculate the capacity factor of an average unit in the system. As shown in Fig. 7, the capacity factor of China's coal power plants will drop significantly from 2020 to 2025 in the BAU scenario, where no restriction is assumed to be in place in this scenario. In the less restrictive policy scenario, where China will have an additional 102 GW of coal power capacity by 2025, the capacity factor will dip by about 2–3% in the next five years. In the more restrictive policy scenario, coal power plants in China would maintain a capacity factor at about 46% in the next ten years based on our assumption of demand growth and supply expansion of alternative energy sources.

We estimate the economic value of the stranded coal assets for each scenario. Fig. 8 shows the annual stranded value of coal assets in China, and we differentiate the stranded value by Bank Loss (grey area) and Enterprise Loss (blue area) as defined in Equations (8) and (9), and they together account for the total economic value of stranded coal assets in China in each year, as the height of the bars indicates.

As one can see from Fig. 8, stranded coal assets will be dramatically reduced in the more restrictive policy scenario compared with the BAU and less restrictive scenarios. In the BAU scenario, the economic loss from stranded coal assets will be about 532 billion RMB, compared with 299 billion RMB in the less restrictive policy scenario and 48 billion RMB in the more restrictive policy scenario in 2025. Implementing a more restrictive policy on coal power expansion can help avoid 90% of stranded coal assets in China's power sector in the next five years. Also, one can see from the figure that banks and equity owners will share the loss relatively equally. That means a substantial financial loss in the coal power plants will pose a non-trivial burden to financial institutions in China, creating unnecessary financial risks in the broader economy. Therefore, we strongly recommend that China take a more conservative approach in expanding its coal power fleet and consider more flexible measures, such as retrofitting existing coal power plants and improving inter-regional power trade to meet peak demand during extreme weather and accommodate more renewable power in the system. To do this, we suggest China to build an ancillary service market that awards flexible operation of coal power generation, which would incentivize more retrofitting of coal power units and reduce stranded coal power assets by increasing their value in balancing of the power system, especially when renewable penetration is high. In addition, we suggest expanding the current provincial dispatch mechanism to regional dispatch, so that power unit commitment can be more efficient, and peak demand can be better served without adding additional coal power plants. All of these efforts would require regulators to focus on incentive regulation instead of micromanaging generation companies (Beecher and Kihm, 2016).

To look into the details, we further calculate the economic value of stranded coal assets at the regional level in China, which will be of great importance to the regional power grid and regional banks to understand the risks. As shown in Fig. 9, northern and northwestern regions in China

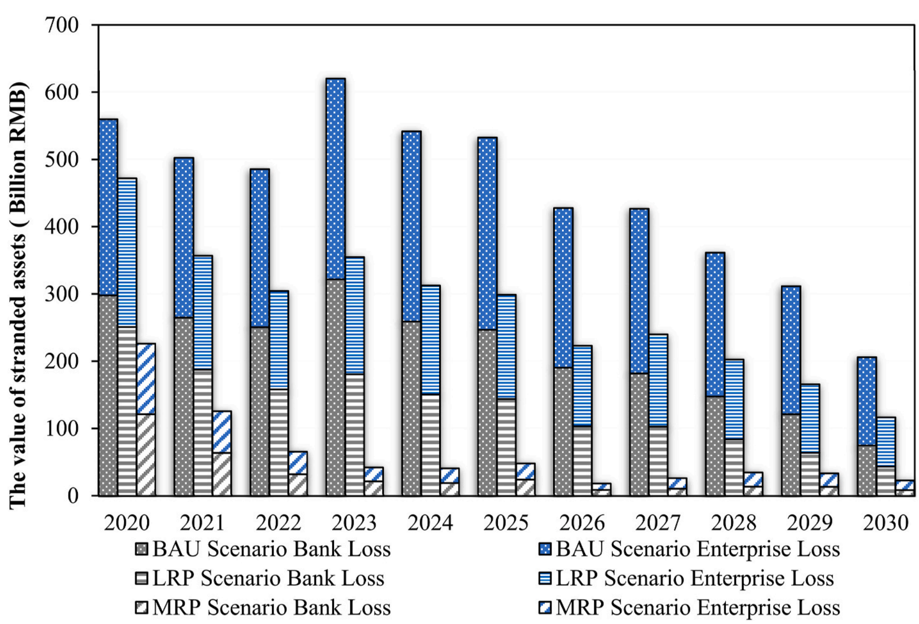

Fig. 8. Economic value of stranded coal assets in China, 2020–2030.

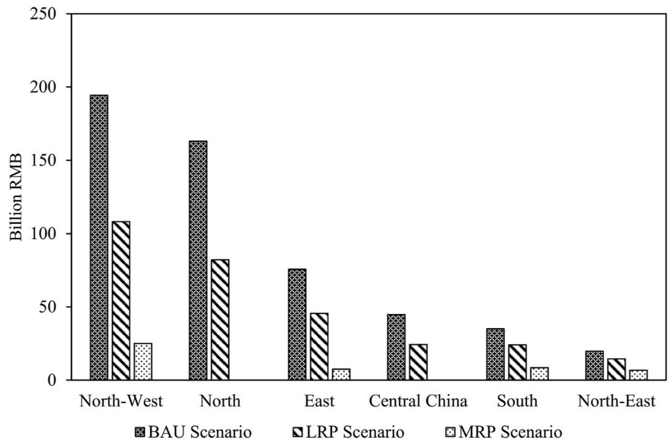

Fig. 9. Stranded coal assets of across regions in China in 2025.

will have the highest risk of stranded coal assets due to their over-expansion of coal power capacity in the past few years. Under BAU and less restrictive policy scenario, four provinces (Xinjiang, Shaanxi, Shandong, and Inner Mongolia) will still have over 10 billion RMB of stranded coal assets in 2030.

Because we also have the company information for each coal power unit, we can look at the financial loss incurred to every company if China were to decommission excessive coal power capacity. We focus our analysis on the "Big Five" power companies in China: Huaneng, Datang, Huadian, SPIC, and CHN Energy, who together account for about 50% of thermal power generation assets in China. For example, as shown in Fig. 10, China Energy Investment Corporation will have a stranded asset of 60, 69, and 15 billion RMB in 2020, 2025, and 2030 under the BAU scenario. However, under the less restrictive policy scenario, the numbers will be reduced to 56, 22, and 7 billion RMB, and under the more restrictive policy scenario, they will be much lower at 19, 1, and 1 billion RMB. The total value of stranded coal assets of other local state-owned power plants will be much higher than the five major power generation companies because smaller companies have historically invested in smaller coal power units that are less efficient and more likely to be retired early.

To summarize, the policy restrictions will significantly limit the new construction of coal power plants and prevent a massive amount of stranded assets in China's power sector in the near future. Banks will share about half of the burden in the economic loss, and smaller state-owned and private companies will suffer the most due to their ownership of smaller and less efficient coal power units.

5. Conclusion

In this paper, we probe the heated question of whether China should further expand its coal power capacity in the next few years and, if so, what consequences might be expected. China has been known to have overcapacity in coal power since 2016, and the government has taken noticeable measures to suspend the development of coal power from 2016 to 2019. However, in the face of still-growing electricity demand and an economic crisis due to the Covid-19 pandemic, putting aside those restrictive policies on coal power development seems to lure at present. However, a short-term urge for a larger coal power industry is fundamentally contradictory with China's long-term goal to become greener and more sustainable, and impulsive investment on particular assets like coal power plants could be costly to the society if they turn out to be not needed. Therefore, in this paper, we intend to estimate how much coal power could become excessive and stranded under different scenarios of coal power development in the next decade.

The study is conducted in four steps. First, we estimate how much coal-fired power capacity will be needed using an electric power and energy balance model, and we call it the "reasonable coal power capacity." Then we forecast the expansion of coal power capacity in China under three development scenarios and derive the "excessive coal power capacity" by subtracting the reasonable coal power capacity from the forecasted coal power capacity in three scenarios. Further, we identify the risks faced by each coal-power unit to be decommissioned due to policies since 2017 and rank the units by risk from high to low as the sequence to retire (strand) the units up to the amount of excessive coal power capacity. Lastly, we estimate the economic value of stranded coal assets by aggregating the unrecoverable initial investment, unpaid interest of bank loans, and the unrecoverable expected returns to equity due to forced early retirement. To do this, we built a comprehensive database of all coal-power units in China, including 4631 units in operation, 379 units under construction, 318 units being suspended or postponed, and 201 units to be approved by the end of 2019, and this is by far the most complete and up-to-date dataset of China's coal power units to our knowledge. To our knowledge, this is also the first research in the literature to use a decision-tree analysis to quantify the risk of forced early retirement of coal power units in China.

We find that stranded coal assets will be significantly reduced with

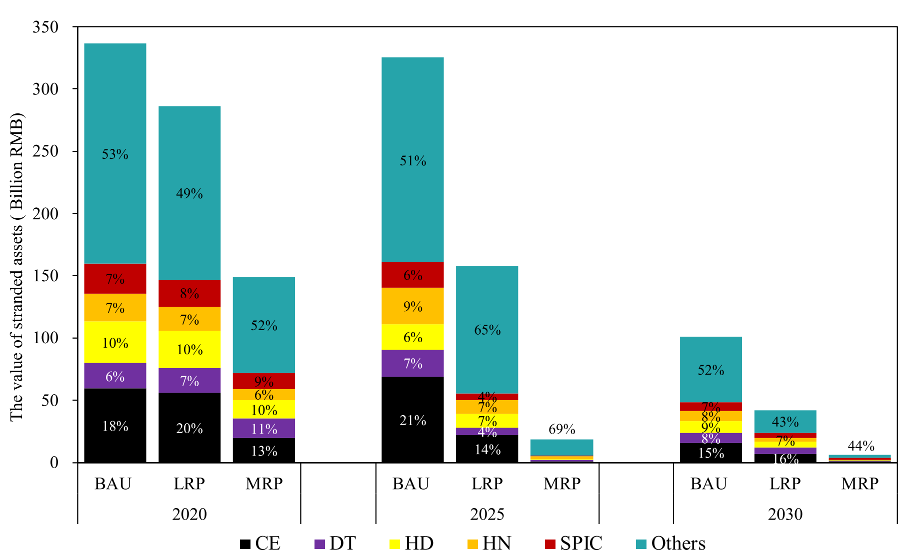

Fig. 10. Stranded Coal assets by company in China in 2020, 2025, and 2030.

policy intervention to slow down the construction of new coal power plants. Implementing a more restrictive policy on coal power expansion in the next five years can help avoid 90% of stranded coal assets in China's power sector in 2025. In terms of the financial losses, China's financial institutions will share about half of the burden due to their loans to the coal power generation companies, and smaller state-owned and private companies will suffer the most due to their ownership of smaller and less efficient coal power units. We strongly suggest that China take a more conservative approach in expanding its coal power fleet and consider more flexible measures such as retrofitting existing coal power plants and improving inter-regional power trade to meet peak demand during extreme weather and accommodate more renewable power in the system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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