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LIST OF ACRONYMS

BAU	business as usual
BUCM	bottom-up cost model
CCS	carbon capture and storage
CCUS	carbon capture, utilization and storage
CFB	circulating fluidized bed
CHP	combined heat and power units
DD	distance to default
CLIMAFIN model	climate finance alpha (www.climafin.com)
CNY	Chinese yuan
ER	early retirement
GDP	gross domestic product
GFSG	Green Finance Study Group
IGCC	integrated gasification combined cycle power generation
LU	low utilization
NBV	net book value
NEA	National Energy Administration
NGFS	Network for Greening the Financial System
NDRC	National Development and Reform Commission
NPV	net present value
O&M	operation and maintenance
TCFD	Task Force on Climate-Related Financial Disclosures
UHV	ultra high voltage
VAT	value-added tax

Executive summary

Coal power is one of the major sources of carbon emissions in China, whose lock-in effect is the highest of all sectors. With more than half of China's coal power industry in deficit, a low-carbon transition will lead to a higher risk of stranded assets and lower expected returns. Bank loans provide nearly 70% of the construction financing for coal power projects in China. Profits decline and asset depreciation will affect the solvency of coal power enterprises, causing credit default risk. Credit default may even cause macroeconomic crisis and transmission through the financial system, which may trigger cross-regional and cross-industry chain reactions. Given that coal power plays a key role in achieving China’s carbon neutrality target before 2060, an accurate assessment of the economic impact of the transition on coal power companies is the basis for the scientific formulation of the transition strategy.

The market value of coal power assets may be damaged in the process of the low-carbon transition, and the ability and willingness of enterprises to repay loans decreases, which in turn may lead to higher credit default rates. Previous studies about transition risk mostly focus on the assessment of coal-fired power stranded assets, paying less attention to the financial risk. The transition risk theory is developing rapidly, but no direct linkage has been established with the transition pathway of sectors and micro-enterprises. Regional differences of China are not paid sufficient attention. Therefore, previous research has not provided enough reference to the low-carbon, smooth and inclusive transition of China's coal power.

To measure the financial status accurately, we have established a coal power plant-level financial framework and database. The database includes 2,991 coal units (1,137 plants) put into operation after 2000, totaling 946 million kW. Plants cover 30 provinces in China except for Tibet, Hong Kong, Macau, and Taiwan. According to the constraints of China's carbon neutrality target on coal-fired plants, several coal power transition scenarios are designed, including BAU scenario, Early Retirement scenario, Low Utilization scenario, and CCS retrofitting scenario.

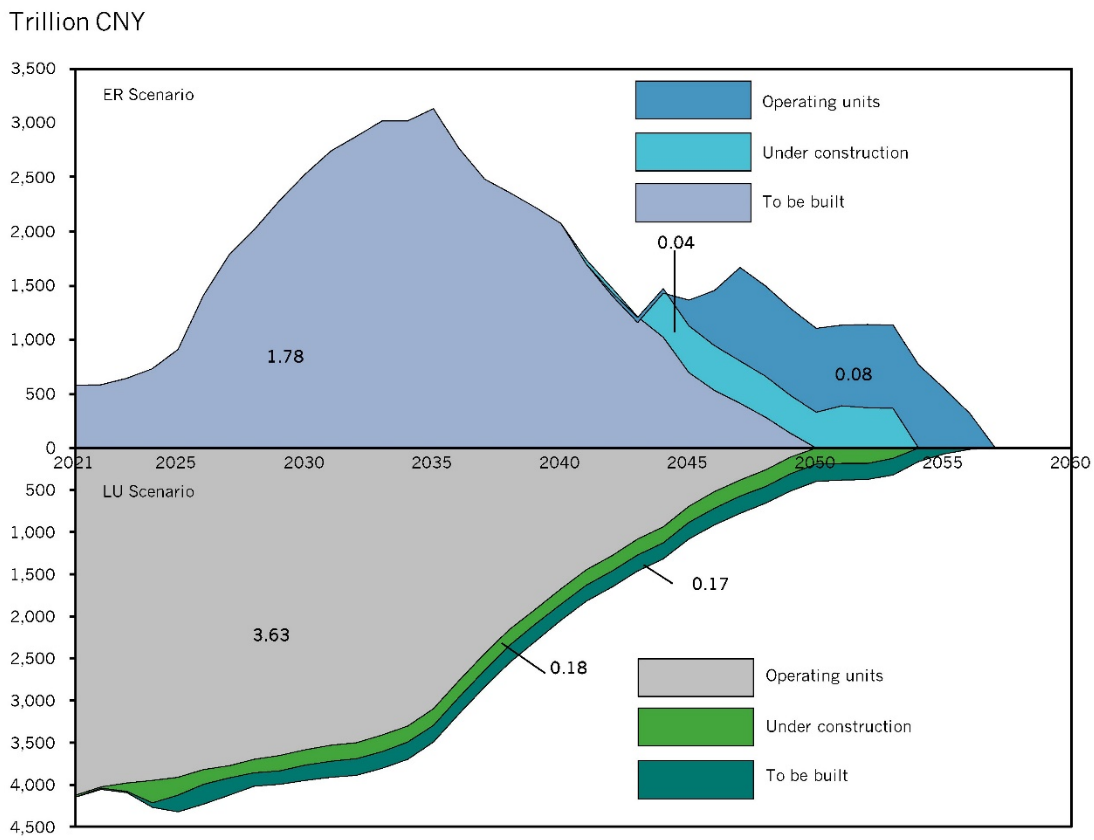
Table 1.
Scenario setting of coal power industry transition in China

Scenarios	Description
BAU scenario	Operating life of 30 years, generating hours remain at 2020 level
Early retirement scenario (ER)	Operating life of 20 years, other consistent with BAU scenario
Low utilization scenario (LU）	Improve coal power flexibility. The generating hours are significantly reduced to 40~50%, and others are in line with the BAU scenario
CCS retrofitting scenario （CCS）	Supercritical and ultra-supercritical units are retrofitted with CCS equipment, and operating lifetime and generating hours are consistent with BAU scenario

NPV method are used to calculate the stranded assets of coal-fired power units under different development scenarios. Further, basic assumption is that default will occur when the asset value of a coal power plant is less than the book value of the liabilities that the plant needs to settle. The distance between the expected value of the asset's future value and the default point is the Distance to Default. The farther the distance, the less likely the plant will default. Based on the scenario setting, the KMV model was used to measure the credit default risk of coal power plants in different transition pathways.

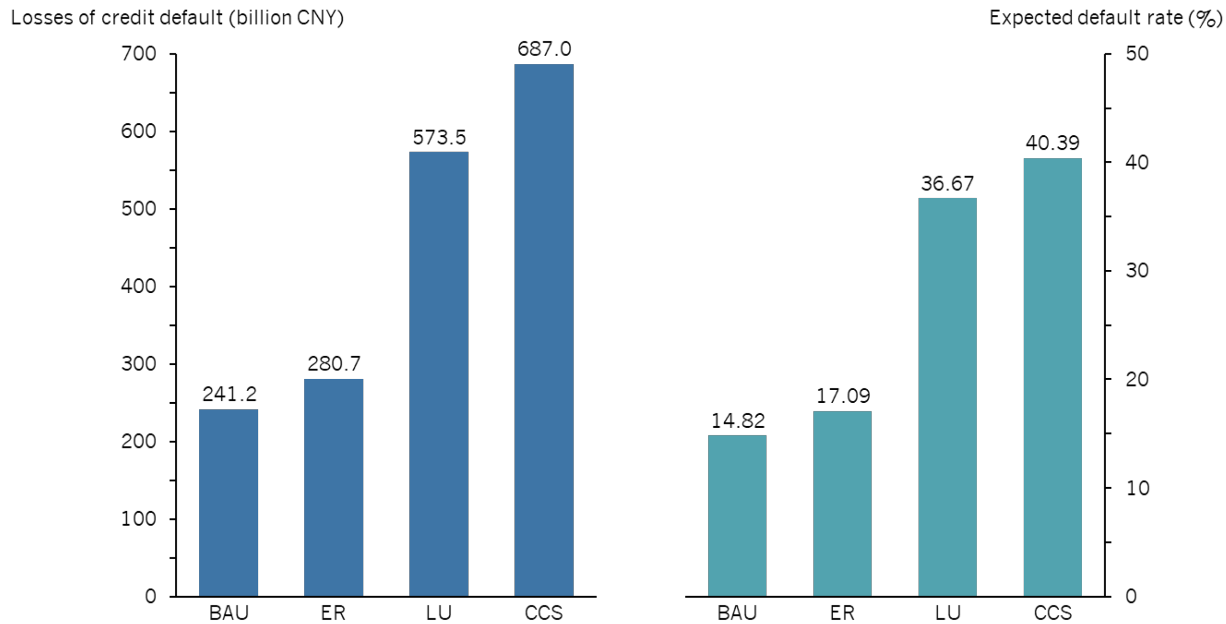
China faces trillions of stranded assets as a result of the coal power transition. With a large number of newly-built units invested and constructed, early retirement (ER scenario) and improve coal power flexibility (LU scenario) will make China's cumulative scale of stranded assets reach 1.90 trillion and 3.98 trillion CNY, respectively (Fig. 1). 2030-2040 is the period with the highest coal power stranded asset risk under the ER scenario. In 2035 the stranded asset risk will reach to the peak, with a net cash flow loss of 313.2 billion CNY. While under the LU scenario, the generation of stranded assets is mainly concentrated in the recent 15 years, that is, coal power units may face a comprehensive net cash flow loss. Shandong and Inner Mongolia have both the largest coal power installed capacity and the highest stranded asset risk. Flexible operation will double the stranded assets. It is the same to many provinces such as Shandong and Inner Mongolia, of which the stranded asset reaches 437.4 billion and 473.4 billion CNY respectively, in the LU scenarios. When coal power lock-in effects are equal in emissions, the flexibility operation generates more stranded assets than early retirement. It has a greater impact on coal power companies and regional economies. Therefore, attention needs to be paid to the role of flexibility operation on the impairment of coal power assets. Low-carbon transition of China's coal power needs to achieve manageable stranded risk under carbon budget constraints. Through the combination of multiple transition measures, we can realize the complementarity of stranded assets in terms of spatial and temporal staggering, trying to avoid the sharp escalation of stranded assets in the short term.

Fig. 1. Annual stranded assets under ER scenario and LU scenario



The study found that total coal power credit accounted for only 0.8% of total credit nationwide, but the ratio was higher in several provinces, with the highest being close to 8%. The remaining loans for coal power plants are more than 80 billion CNY in several provinces, such as Xinjiang, Inner Mongolia, Shandong, Anhui, Jiangsu, Henan, and Guangdong. The expected default rate in BAU scenario is about 14.82%, and probability will increase to 17.09% under ER scenario. If the coal power increases their flexibility operation according to the policy guidance, LU scenario and CCS scenario will result in a significantly higher credit default probability of 36.67% and 40.39%, respectively (Fig. 2). Credit default losses of BAU scenario are only 214.2 billion CNY, while the credit default losses of ER, LU and CCS scenarios are 280.7, 573.5 and 687.0 billion CNY, respectively. There are 199 plants (17.5% of plants nationwide) with default distances less than 0 under the BAU scenario, meaning that predictable credit defaults will occur in the short term (Fig. 3).

Fig. 2. Credit default losses and probabilities under different transition scenarios



Regional credit default pressure varies greatly. The probability of default for coal power reaches 50% in Qinghai, Xinjiang, Gansu, and Yunnan provinces under BAU scenario, much higher than in other regions. Among them, Xinjiang is expected to default on losses of up to 866.6 billion CNY, accounting for more than one-third of the national default losses. This is due to its more coal plants and worse profitability. In contrast, Shanxi, Inner Mongolia, and Shandong, which have some of the highest installed coal power units in China, have much lower average default probabilities of about 10.17%, 9.29%, and 7.31%, respectively. Attention should be paid to possible regional defaults caused by low-carbon transition. Therefore, the phasedown of coal use should be decided in a comprehensive manner in terms of multiple dimensions such as asset value, financial risk, and carbon emission reduction. A classified transition strategy should be adopted according to the regional credit risk differences (Fig. 4).

Fig. 3. Plant-level Credit Risk Map of China in BAU Scenario

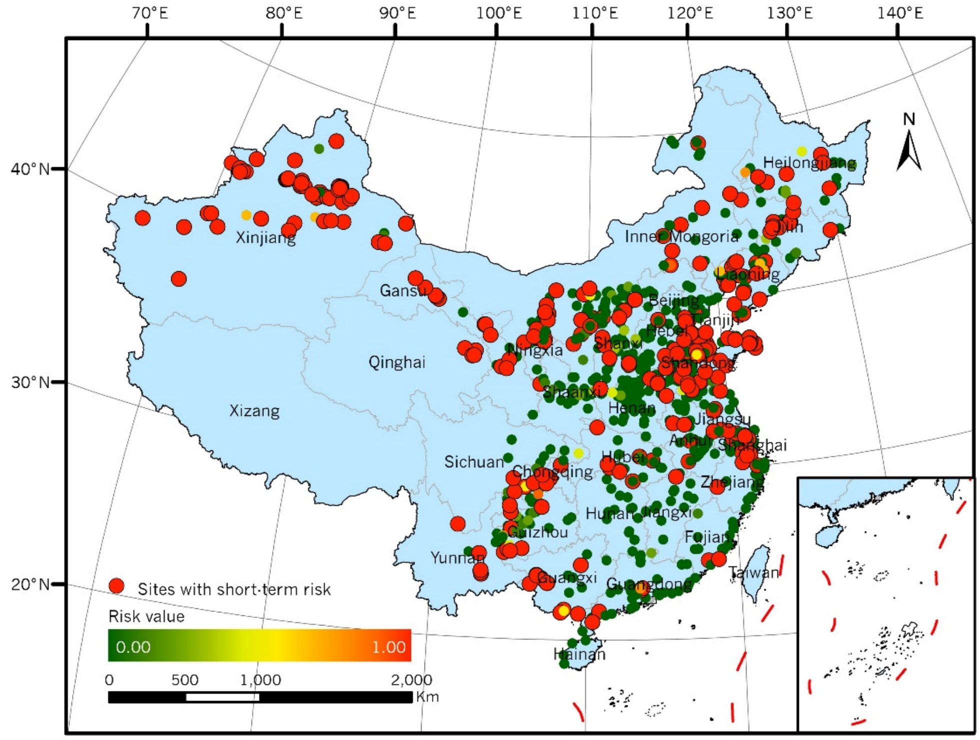
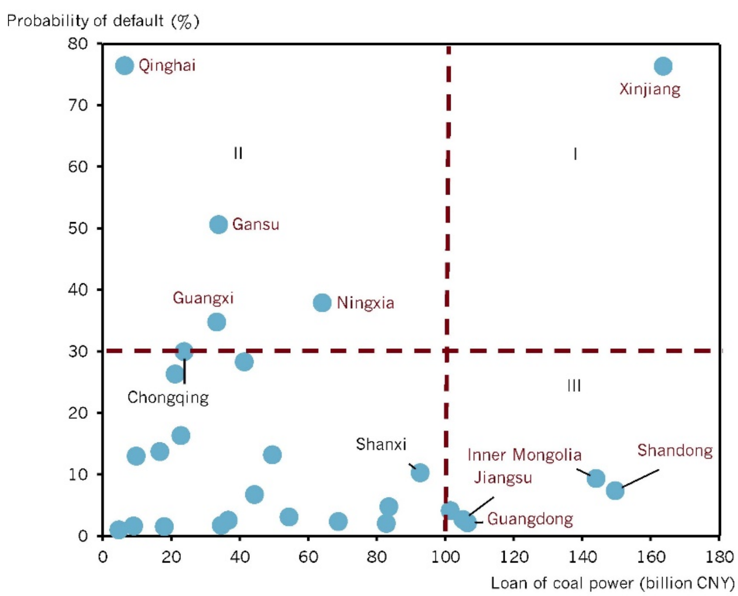


Fig. 4. Provincial differences of credit default coal power



1. Introduction

China's coal power carbon emissions own the highest lock-in effect in energy infrastructure emissions (Tong, 2019; Zhang & Tong, 2021). Controlling coal consumption and reducing carbon emissions in the power sector plays a key role in achieving carbon neutrality goals (IEA, 2021). Considering difficulty of emission reduction in various sectors, the power sector needs to take the lead in taking transitional actions (EFC, 2021). The average operating life of Chinese coal power units is 12 years (IEA, 2021), well below the global average. With more than 80% of coal power companies losing money in 2021 (CEC, 2022), economic condition will be one of the most important factors affecting the transition. Low-carbon transition has a great impact on financial status of coal power companies, leading to a decline in the asset value or conversion to liabilities of high-carbon infrastructure like coal power units, that is, stranded assets (Gray et al., 2018; Pfeiffer et al., 2018). Stranded assets will affect the solvency of coal power companies. Since nearly 70% of its funds come from bank loans in China, the decline in income and the depreciation of assets will affect the solvency of the coal power companies, resulting in credit default risk. The coal power industry has always been an important part of China's power structure. In 2021, coal power units accounted for 46.7% of the total power capacity and it generated 60.8% of the total electricity (CEC, 2022). Therefore, identifying the impact of low-carbon transition on coal power stranded assets and credit default risk is critical to safeguard China's 2060 carbon neutrality goals. It is also important for promoting the transition to high-quality economic development and maintaining the stability of the financial system. The impact of the low-carbon transition on asset quality and financial safety has been explicitly highlighted by several organizations in recent years, such as G20 Green Finance Study Group (GFSG), Network for Greening the Financial System (NGFS) and Task Force on Climate-Related Financial Disclosures (TCFD).

Most of the existing studies focus on the technical feasibility of the transition pathway for power sector (Tong et al., 2018). Several "bottom-up" models are used to analyze emission trends and technology choices in the power sector (Cui et al., 2019; He et al., 2016; Liu et al., 2019). These studies find that the main low-carbon transition pathways for coal power include early retirement, flexible operation, and CCS retrofit. Further, it is analyzed that the optimal power sector transition pathway under multi-objective and the effect of different transition pathways on China's emission reduction targets (Cui et al., 2021; Chen et al., 2021). Researches on the socio-economic impact of low carbon transition is dominated by stranded assets. 51%-58% of the world's coal power plants are at risk of being stranded (Pfeiffer et al., 2016), and China's coal power stranded assets account for more than 45% of the world's stranded assets (Saygin et al., 2019). China's stranded assets is basically between 0.3 and 7.2 trillion CNY affected by different research methods (Gray & Sundaresan, 2020; Caldecott et al., 2017; Spencer et al., 2017). Energy related assets such as coal power are generally at risk of being stranded, and financial regulators are highly likely to increase the risk weighting of these kind of assets. Related companies will face increased financing costs, deteriorating financial conditions and increased default rates (Semieniuk et al., 2021). Changes in the assets quality with coal power may affect from the power sector to the financial sector through network effects, leading to adverse credit effects (Skott & Zipperer, 2012; Batten et al., 2016).

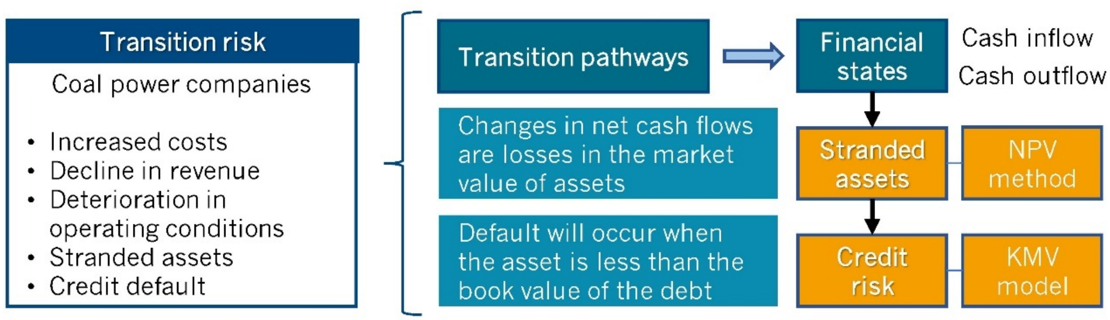
The low-carbon transition has become a new source of risk affecting economic and financial stability. Theories related to transition risk are still in the process of development. Compared with traditional risks, transition risk has a series of new characteristics, such as nonlinearity, showing a growing trend over time, significant spatial imbalance problems, endogeneity (Battiston, 2019), and systemic chain reactions (Lenton et al., 2019. Galaz et al., 2018). Studies have shown that low-carbon transition will increase bank crisis by 26% to 248%, the additional fiscal burden from government bailouts for failed banks accounts for 5% to 15% of GDP, and the public debt will triple (Lamperti, 2019). Battiston et al. (2019) analyzed the risks of financial institutions to fossil energy production and high-carbon industries by establishing CLIMFIN model. The results show that the Top 20 listed banks in Europe will face impairment risks ranging from 8% to 33%. In addition to influencing asset value, low-carbon transition will have a significant impact on investor confidence (Batten et al., 2016; Dafermos et al., 2017; Bovari et al., 2018).

The low-carbon transition risk concept has developed rapidly, but has not yet established direct links with industrial sector transitions and small enterprises. There are studies exploring coal power stranded assets, but not yet linked to credit default risk. The existing risk assessment of coal power stranded assets and credit default risk does not reflect coal power technology, and it pays insufficient attention to regional differences. Therefore, previous researches have not provided enough reference to the low-carbon, smooth and inclusive transition of China's coal power.

2. Modeling Approach

Under the constraints of carbon budget and coal power lock-in emissions, low-carbon transition may increase the cost and reduce the benefit of coal power generation. It results in a decline in the assets value of its infrastructure like coal power units, that is, stranded assets. Coal power is a kind of asset-intensive industry, and its funding often comes from bank loans. The basic assumption is that default will occur when the asset value of a coal power plant is less than the book value of the liabilities that the plant needs to settle. When the market value of assets is lower than the liabilities that the company needs to pay off, it will generate credit default risk. Therefore, we have established a coal power plant-level financial framework (Figure 1) and database to show the mechanism between asset value and credit default. Then, this paper measures the stranded assets caused by the low-carbon transition of coal power. Finally, the KMV model is used to measure the credit default risk of coal power plants caused by assets impairment in different transition pathways.

Figure 1. Research modeling of stranded assets and credit default risk



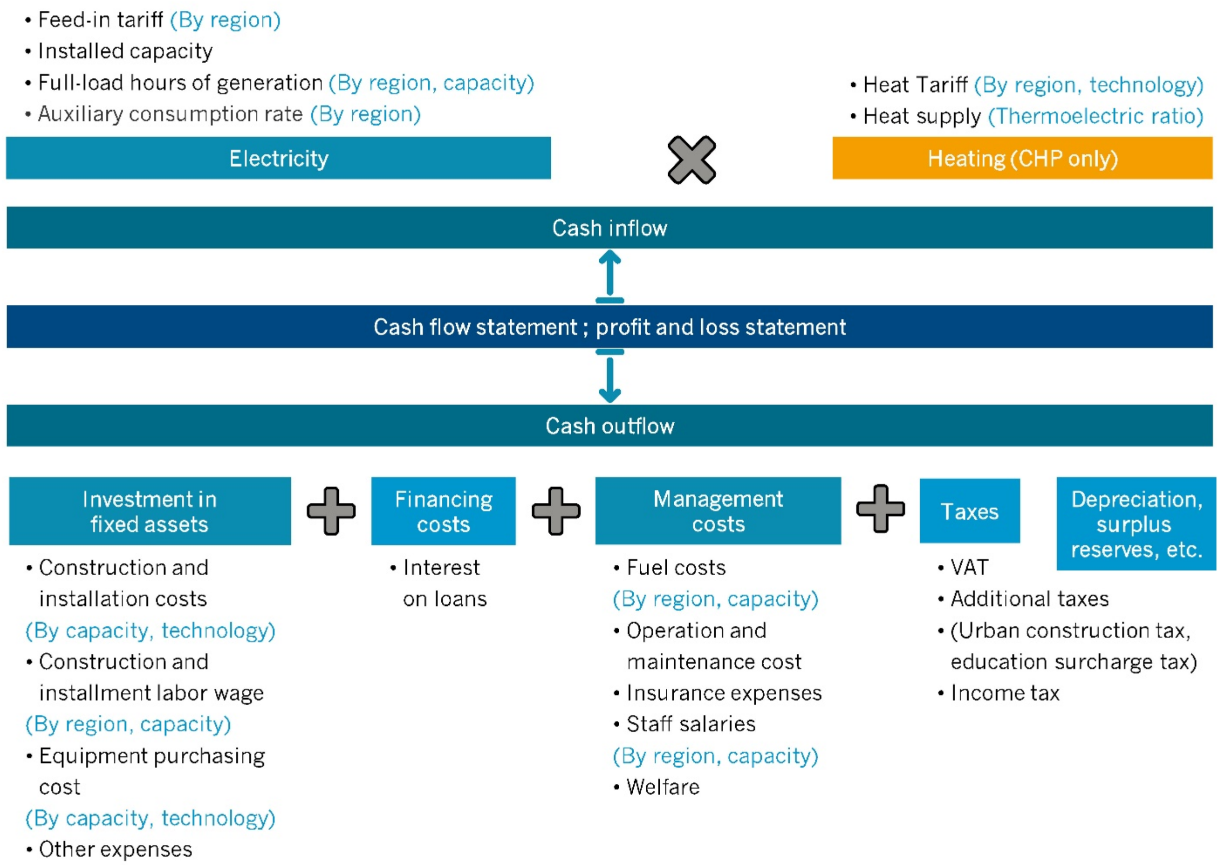
2.1 Financial accounting framework of coal-fired unit level

Bottom-up cost model (BUCM) is a financial model that links the various costs and economic variables (McNerney, 2011; Kumar et al., 2015). In order to measure the risks of stranded assets and credit default risk of coal power transition, this study establishes a dynamic financial accounting framework for coal power which considers the uncertainty and is linked with mid- and long-term carbon emission reduction goals, including financing costs, depreciation, taxes, etc. Accounting items, cost categories and charging standards are in accordance with *Guidelines for Economic Evaluation of Thermal Power Projects*, *Regulations on* *the Compilation and Calculation of Thermal Power Project Construction Budgets* and *Electric Power Construction Project Budget Quota* issued by the National Energy Administration of China. According to the technical characteristics, installed capacity and regional characteristics of coal power units, this paper makes the financial model of a single coal power unit. Several financial indicators are added in increases such as the remaining loan amount and fixed asset value, which are used to evaluate asset value accounting and credit default risk of coal power unit through NPV method and KMV model. The unit-level financial accounting framework provides a comprehensive analysis of China's coal-fired plants.

The financial status of each type of coal-fired units is affected by three main factors, namely installed capacity, technology type, and the province where they are located. According to the capacity of all units, they are classified into six categories, <100MW, 100–200MW, 200–300MW, 300–600MW, 600–1,000MW, and ⩾1,000MW. According to the technology type of units, they are subdivided into five types, including subcritical, supercritical, ultra-supercritical, integrated gasification combined cycle power generation (IGCC), and circulating fluidized bed (CFB). The technology of a small number of units is unknown and set as the dominant technology of units of the same capacity.

The financial accounting framework of coal-fired units is shown in Figure 2. The revenue of coal power units is mainly from electricity sales. Some units also have revenue from heat sales. The cost mainly includes initial construction investment and operation cost. Among them, the initial construction investment includes installation engineering cost, labor cost, equipment purchases cost and other expenses, while the operation cost includes fuel cost, operation and maintenance (O&M) cost, insurance premium, employee salary and welfare, tax, loan interest and depreciation. Taxes and fees are subdivided into value-added tax, urban maintenance and construction tax, education surcharge, income tax, etc. China has a large number of combined heat and power units (CHP), accounting for about one-third of the operating units. The financial accounting framework distinguishes between condensing units and CHP units. The income of CHP units includes the heat sales revenue, taking into account the differences in heat prices between regions. Costs of CHP units include O&M costs of heat boilers and related equipment.

Figure 2. Financial accounting framework of coal-fired unit level



2.2 Stranded asset assessment of low-carbon transition of coal power

China proposed to "strive to achieve carbon neutrality" before 2060. In order to achieve the goal, the power sector needs to accelerate the low-carbon transition, reducing the proportion of coal-fired power generation. This requires the power system to achieve a dramatic shift to renewable energy. Infrastructure such as coal-fired power generator will face the risk of becoming stranded assets. The definition of stranded assets has gradually developed from assets that have lost economic value before the expected service lifetime to infrastructure investments that cannot obtain expected economic returns due to climate policies, market regulation, etc. Stranded assets now have more emphasis on the written-down value, depreciation of asset's market-value. The assessment methods of stranded assets mainly include net present value (NPV) (Gary et al., 2018), net book value (NBV) (Saygin et al., 2019), cost method (Caldecott et al., 2017), etc. NBV method and cost method more reflect the historical value of assets, and cannot show the operation status of coal-fired power units under different operation scenarios in the future. NPV method makes up for this defect. Therefore, this study uses NPV method to calculate the stranded assets of coal-fired power units under different development scenarios based on the unit-level coal-fired power database, that is, the asset loss caused by the reduction of net cash inflow in the expected life.

$$Value_{SA} = NPV_{BAU} - NPV_{scenario\ i} \quad (1)$$

NPV under different scenarios is calculated as follows:

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+i)^t} \quad (2)$$

Among them, CF_t is the cash flow of the t^{th} year in the future coal power operation period, which is the discount rate, taking 8% here.

For existing units, the calculation is as follows:

$$CF_t^{operating} = R_t - C_t \quad (3)$$

Among them, R_t is the cash inflow during the operation period, and C_t is the cost expenditure during the operation period.

$$R_t = R_t^E + R_t^H + DEPR \quad (4)$$

The cash inflow is mainly the income from selling electricity R_t^E. If the unit is a cogeneration unit, it includes the income from selling heat R_t^H, otherwise R_t^H is 0, and DEPR is the recovery of residual value of capital, which is generated only when the operation life reaches 15 years.

$$C_t = C_t^{O\&M} + C_t^R + C_t^W + C_t^I + C_t^T + C_t^{fee} \quad (5)$$

The cost expenditure C_t during the operation period mainly includes fuel cost C_t^F, operation and maintenance cost $C_t^{O\&M}$, insurance cost C_t^I, employee salary and welfare cost C_t^W, tax C_t^T, loan interest and other expenses C_t^{fee}.

For new units, there are mainly two types: under construction and proposed. The cash flow during the construction period is the cash outflow of the initial construction cost, and the cash flow during the operation period is consistent with the existing units.

$$CF_t^{new} = \begin{cases} -C_t^{con} & \text{During construction} \\ R_t - C_t & \text{During operation} \end{cases} \quad (6)$$

C_t^{con} C is the initial construction cost, mainly including construction and installation engineering cost, construction and installation labor cost, equipment purchases cost and other costs.

$$C_t^{con} = C_t^{C\&I} + C_t^{Labor} + C_t^{INS} + C_t^{Others} \quad (7)$$

2.3 Coal and electricity credit default risk assessment

The credit default risk is carried out in the following three aspects: first, the market value of assets, that is, the cash flow of the research object in the future period is discounted according to the discount rate; Second, asset risk, that is, the possibility of changes in assets owned by the analysis object; Third, liabilities which mainly refer to the book value of the analysis object. Changes in coal power costs under different transition pathways affect the cash flow of coal power units, i.e., the market value of asset. It can be found that when the asset value of coal-fired power units is lower than the face value of liabilities that enterprises need to pay off, default will occur. The distance between the expected value of the future value of assets and the default point is the default distance DD (Distance to Default). The farther the distance, the less likely the company will default. The systemic financial risk-asset default rate model allows to obtain credit default rates and default losses under BAU scenario and transition scenarios. The KMV model is a typical method to evaluate credit default risk. Formulas of KMV are shown below.

$$DD = \frac{E(V_T) - DP}{E(V_T) \times \sigma_t} \quad (8)$$

$$P(V_T \leq D) = \mathrm{N}(-\mathrm{DD}) \quad (9)$$

Where, E (V_T) is the expected value of coal-fired power unit assets at the end of T period; DP is the default point, which is a measure of the balance point of assets and liabilities; σ_t is the value volatility, which describes the interference of an analysis object's external risk on the KMV model system during its experience of financial crisis.

$$DP = STD + 0.65 \times LTD \quad (10)$$

STD is the short-term liabilities of coal-fired power units; LTD is the long-term liabilities of coal-fired power units; The short-term liabilities of the company is the liabilities of the company within one year. Long-term liabilities can actually alleviate the pressure of the company itself to repay its debts. 0.5 is the default long-term debt coefficient of KMV model in domestic and foreign studies. Long-term debt coefficient generally calculated by the research literature of the Chinese market is between 0.6–0.9. After fitting and enumeration, it is found that when the default point coefficient is 0.65, KMV is most realistic in determining the default probability of Chinese listed companies. Therefore, 0.65 are adopted as the long-term debt coefficient.

2.4 Scenario setting of coal power industry transition

Coal power has been the largest source of electricity generation and heating in the China. The designed service lifetime of coal-fired units is up to decades, which leads to a significant lock-in carbon emissions during operation. The carbon neutralization target restricts the cumulative carbon emissions of coal-fired power units (Yin et al., 2019), and act as the backward force in the transition of coal-fired power units. In November 2021, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) jointly issued the *Notice on Carrying out the Transition and Upgrading of Coal-fired Power Units Nationwide (FGY [2021] No. 1519)*, which clearly proposes measures to increase the flexibility of coal power units and phase out inefficient units. In order to realize the carbon neutrality target before 2060, the emission reduction of China's power sector need to be significantly improved. Coal power needs to be transformed from baseload to peak load. It is necessary to reduce the full-load hours of coal units to make coal more flexible. Some units need to retire before designed lifetime or retrofit carbon capture and storage technology (CCS). Therefore, this paper designs several transition scenarios of coal-fired power plants, including the business-as-usual scenario, early retirement, low utilization scenario, and CCS retrofitting scenario (Table 1).

Table 1.
Scenario setting of coal power industry transition in China

Scenarios	Description
BAU scenario	Operating life of 30 years, generating hours remain at 2020 level
Early retirement scenario (ER)	Operating life of 20 years, other consistent with BAU scenario
Low utilization scenario (LU）	The generating hours are significantly reduced to 40~50%, and others are in line with the BAU scenario
CCS retrofitting scenario（CCS）	Supercritical and ultra-supercritical units are retrofitted with CCS equipment, and operating lifetime and generating hours are consistent with BAU scenario

Note: This paper distinguishes the historical generation capacity and cost of coal-fired power from the future scenario generation capacity and cost. Scenario design assumptions are based on the operating parameters of coal-fired power units after 2021.

2.5 Data Sources

As of December 2021, the unit-level database has collected 3,500 units' information, including 2,991 operating coal-fired power projects, with a total installed capacity of 1.043 billion kW. Based on the database and the financial accounting framework, we integrate data on the operation status and profitability of coal power projects of different sizes, technologies and regions.

Table 2.
Data sources of coal-fired power units

Index	Data sources	
Feed-in tariffs	China Power Yearbook-average on grid electricity price of coal-fired power generation enterprises	By province
Construction and installation labor cost	China Statistical Yearbook-average wages of construction industry	By province
Wages and welfare	China Statistical Yearbook-average wages in the power industry	By province
Coal price	China power coal price index	By province
Auxiliary power consumption rate	China Power Yearbook	By province
Initial construction cost	Reference cost index for quota design of thermal power projects and Budget estimate quota of power construction projects	By capacity and technology
Construction period and investment proportion	Regulations on budget preparation and calculation of thermal power engineering construction	By capacity
Staff quota	Organization setup and staffing standards of coal-fired power plants (discussion draft)	By capacity
Full-load hours	Annual development report of China's power industry, Wind database	By province and capacity
Coal consumption	Annual development report of China's power industry, Wind database	By capacity and technology

3. Stranded asset risk of coal power's low-carbon transition

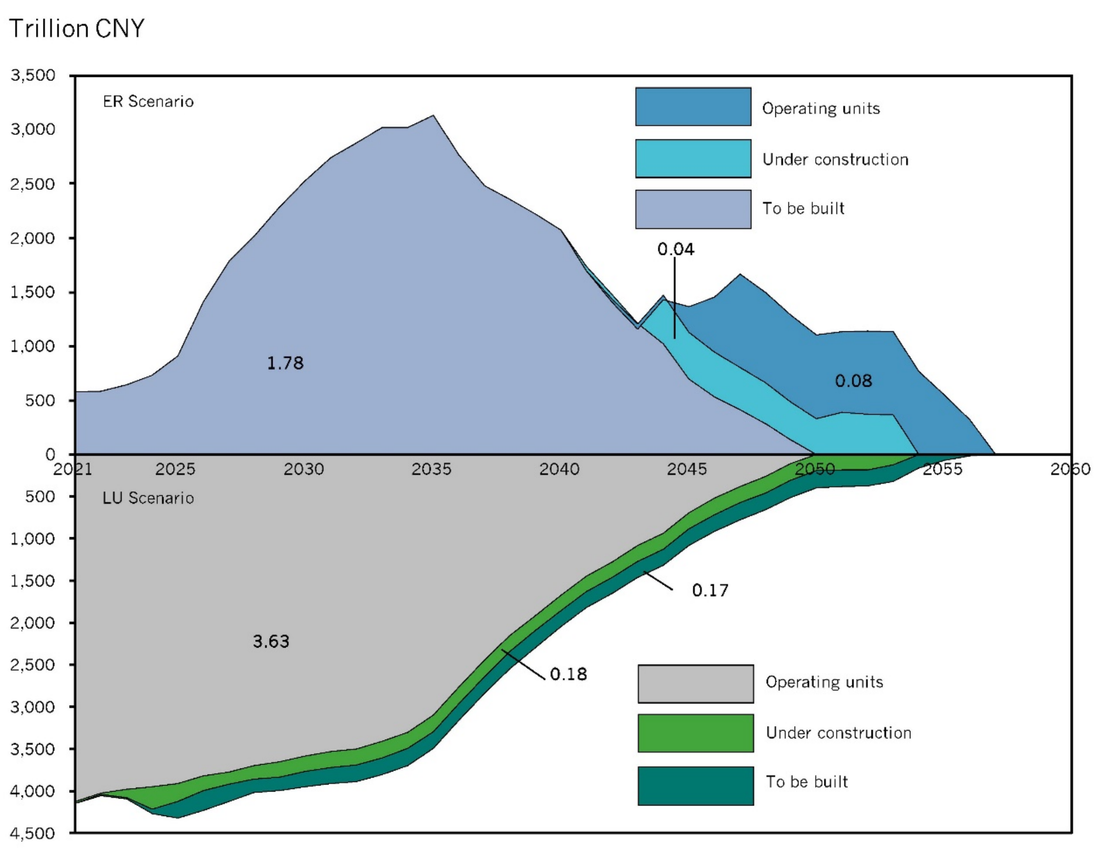
The concept of stranded assets has gradually developed, mainly referring to infrastructure investments that cannot earn economic returns due to climate policies and market regulation. This study adds to this definition that the decline in expected returns due to policies such as flexibility improvement is also a stranded asset. The low-carbon transition measures in the coal power industry, influenced by carbon emission constraints, will cause a decline in the profitability of coal power companies, resulting in a decline in the asset value of coal-fired generating units and other facilities. This has a negative impact on the asset quality of enterprises and financial institutions, and may even lead to a macroeconomic crisis.

China faces trillions of stranded assets as a result of the coal power transition. With a large number of newly-built units invested and constructed, early retirement and flexible operation will make China's cumulative scale of stranded assets reach 1.90 trillion and 3.98 trillion CNY, respectively. The asset loss of operating units accounts for the main part of the stranded asset risk of coal power. Under the LU scenario, the full-load operating hours of below-1,000MW units are required to reduce by 50%–60%. Further, fixed O&M costs should be considered. All these will lead to a net cash flow reduction of China's most coal power units, resulting in a higher stranded asset risk. It's required to restrict or not to add new coal power, so as to reduce the stranded asset scale. Under the scenario of ER and LU, stopping adding new coal power will reduce stranded assets by 119.212 billion and 350.283 billion CNY, respectively.

From the perspective of future annual stranded assets, 2030-2040 is the period with the highest coal power stranded asset risk under the ER scenario. In 2035 the stranded asset risk will reach to the peak, with a net cash flow loss of 313.2 billion CNY. While under the LU scenario, the generation of stranded assets is mainly concentrated in the recent 15 years, that is, coal power units may face a comprehensive net cash flow loss. The difference is related to the age structure of China's coal power units. The average age of China's coal power units is about 12 years, while there exists a large number of units that have been operating for less than 10 years in Xinjiang, Qinghai, Ningxia. Especially in 2015, the administrative changes in China's coal power approval procedures led to a significant rebound in the newly installed coal power production capacity, with an annual newly installed capacity of 80GW (IEA, 2020). These units will be decommissioned early in 2035, resulting in high losses of coal power assets. Flexible operation will affect most units' operating hours, and with the expiration of the service period of coal power units, the scale of asset losses will be gradually reduced.

The new coal power mainly includes two parts: the under-construction units and the proposed ones. Positively related to the total installed capacity, the stranded asset risk is respectively 75.946 billion and 43.266 billion CNY for the under-construction units and the proposed ones, under early-retirement scenario. While under the LU scenario, the stranded asset scale is almost the same, with 167.954 billion CNY for the under-construction units and 182.329 billion CNY for the proposed ones, yet the total amount of units differs greatly. The small scale of the proposed units (average installed capacity: 315.88MW) leads to the difference. And there exists more obvious coal power asset loss under the LU scenario.

Figure 3. Annual stranded assets under ER scenario and LU scenario



Early retirement and flexible operation have quite different impact on the cash inflow of different-size units. Under the ER scenario, the larger the unit scale, the higher the stranded asset risk. The existing installed capacity of the 600–1,000MW units is 403.51GW, only 3.78% higher than the 300–600GW units (388.80GW), while the former's stranded asset is 49.38% higher. On the contrary, the smaller units have the higher stranded asset risk under LU scenario, of which the cash inflow is more affected. It's worth noting that the stranded assets of units below 100MW under the ER scenario are negative. That is, such units are in a loss state as a whole under the BAU scenario, and the early retirement will shorten the unit-loss duration.

Table 3.
Stranded assets of units in different capacity (100 million CNY)

	Capacity (GW)	ER scenario	LU scenario
<100MW	25	-764	1,507
100–200MW	44	343	1,694
200–300MW	34	357	866
300–600MW	389	6,054	17,351
600–1,000MW	404	9,044	18,363
≥1,000MW	147	3,933	0
Total	1,043	18,967	39,781

The differences in coal power unit structure lead to differences in stranded asset in different provinces, under ER and LU scenarios. Among all provinces, Shandong and Inner Mongolia have both the largest coal power installed capacity and the highest stranded asset risk. Flexible operation will double the stranded asset size, from the perspective of the whole country. It is the same to many provinces such as Shandong and Inner Mongolia, of which the stranded asset reaches 437.4 billion and 473.4 billion CNY respectively, in the LU scenarios. Moreover, due to the construction of a series of UHV transmission lines such as "West Inner Mongolia-Northern Shanxi-Southern Tianjin" and "Shaanxi Power Transmission", the related provinces including Inner Mongolia, Shanxi, Shaanxi, Anhui., have larger new coal power installed capacity, and higher stranded asset risk, compared to other provinces. It's supposed to concern the differences of asset loss in different regions, so as to avoid the regional economic problems as far as possible.

Table 4

Stranded assets cause by operating units in different provinces (100 million CNY)

	ER scenario	LU scenario
Nationwide	17,774	36,278
Shandong	1,739	4,375
Inner Mongolia	1,725	4,734
Jiangsu	1,926	2,406
Guangdong	1,693	2,258
Henan	1,222	2,201
Xinjiang	152	2,380
Shanxi	1,176	2,885
Anhui	1,119	2,073
Hebei	1,139	2,334
Shaanxi	936	2,215
Zhejiang	1,110	1,126

Stranded asset measurements have long focused on early retirement units. When coal power locks are equal in emissions, increasing the flexibility generates a higher scale of stranded assets than early retirement, and has a greater impact on coal power companies and regional economies. Therefore, attention needs to be paid to the flexibility operation on the impairment of coal power assets. Low-carbon transition of China's coal power needs to achieve manageable stranded assets risk under carbon budget constraints. Through the combination of multiple transition measures, we can realize the complementarity of stranded assets in terms of spatial and temporal staggering, trying to avoid the sharp escalation of stranded assets in the short term. Considering the key role of coal power in grid supply stability in the future, it has a comparative advantage to adopt flexibility operation for larger units. The stranded asset loss per unit of installed capacity of technologically advanced units is gradually reduced. Meanwhile early retirement measures give priority to units that are technologically backward, smaller capacity and longer service life, especially those below 100MW.

Stranded coal power assets will directly cause a reduction in the revenue of coal power-related enterprises, which in turn will affect their ability to repay loans and even harm local financial stability and economic development. Considering the spatial distribution of stranded assets, we need to pay more attention to the differences in coal power regional transition pathways. develop locally appropriate coal power transition strategies, and try to avoid coal power transition exacerbating inter-regional imbalances. It is better to develop a locally tailored coal power transition strategy to try to avoid coal power transition exacerbating inter-regional economic imbalances. The orderly and gradual phase down of coal power units with backward technology can be moderately promoted in Shandong and Inner Mongolia because of the large total installed coal power capacity and the high proportion of small units in this province. A large number of small units can be transformed into energy-saving units, flexible units or standby units. Jiangsu, Guangdong and Zhejiang provinces have obvious advantages in converting their conventional coal power units to flexible resources.

4. Credit risk of coal power's low-carbon transition

Over 70% of the initial construction investment in the coal power industry comes from bank loans. The current remaining loan amount of coal power units is highly correlated with the size and age of the units, and the distribution of plants with large remaining loans is relatively concentrated. The remaining loans for coal power plants are more than 80 billion CNY in several provinces, such as Xinjiang, Inner Mongolia, Shandong, Anhui, Jiangsu, Henan, and Guangdong. These provinces are with large installed coal power capacity and relatively young units, while the total amount of remaining loans was relatively low in the central and southwestern regions. In 2019, the year-end loan balance of financial institutions nationwide was 153.11 trillion CNY. The study found that total coal power credit accounted for only 0.8% of total credit nationwide, but the ratio was higher in several provinces, with the highest being close to 8%. The ratios of coal power of Ningxia, Xinjiang and Inner Mongolia account for as much as 8.91%, 8.21% and 6.25%. When the coal power sector is retired early or when market prices fluctuate, such areas lead to a higher risk of bad loans to banks, and the transition needs to focus on the stability of the economic and financial system (Figure 4).

Low-carbon transition will bring about an industry-wide situation of rising costs, falling profits and expanding financial losses in coal power. Then, the decline in the value of coal power assets will be transmitted as credit default risk. According to the KMV model and coal unit-level cost database accounting, the expected default rate in BAU scenario is about 14.82%, while the coal power credit default probability will increase to 17.09% under ER scenario. If the coal power adopts flexibility modifications according to the policy guidance, LU scenario and CCS scenario will result in a significantly higher credit default probability of 36.67% and 40.39%, respectively. (Figure 5). Losses from credit defaults will also increase as the probability rises. Credit default losses of BAU scenario are only 214.2 billion CNY, while the credit default losses of ER, LU and CCS scenarios are 280.7, 573.5 and 687.0 billion CNY, respectively. Therefore, the low-carbon transition will not only cause a significant increase in the probability of credit default, but will also result in high credit losses in China. In fact, the actual default rate of coal power projects will not be so high. Because the groups of coal power projects often carry out internal capital allocation. However, the substantial increase of the expected default rate in this paper shows that the credit risk of coal power projects is a problem worthy of attention.

Figure 4. The percentage of remaining loans for coal power units by province in 2019

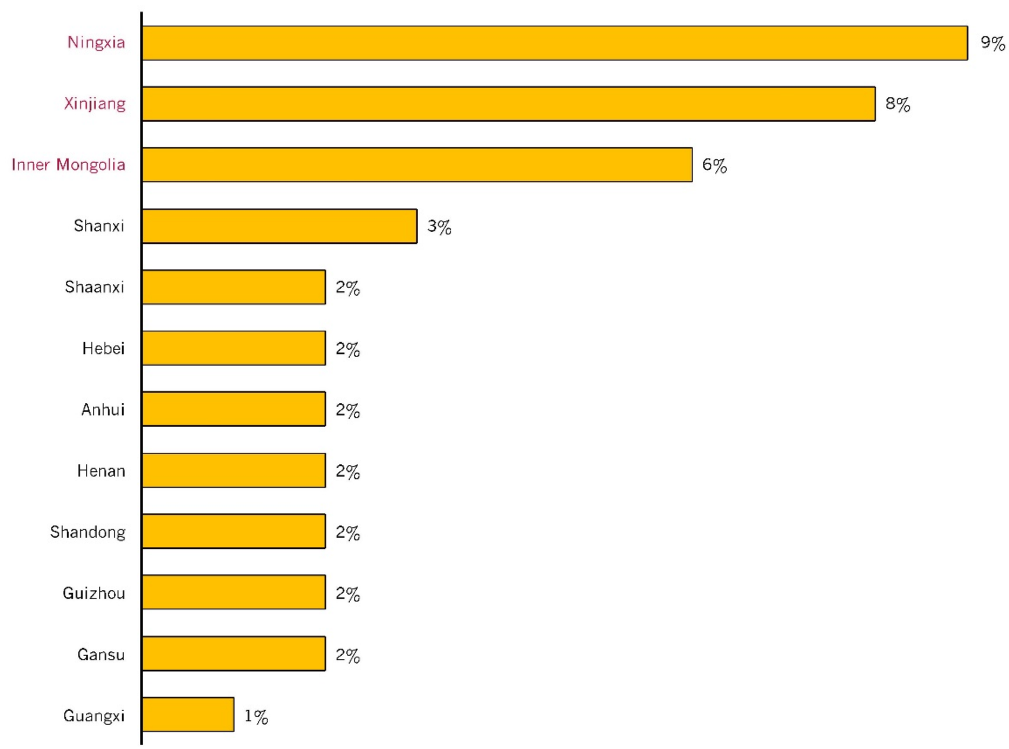
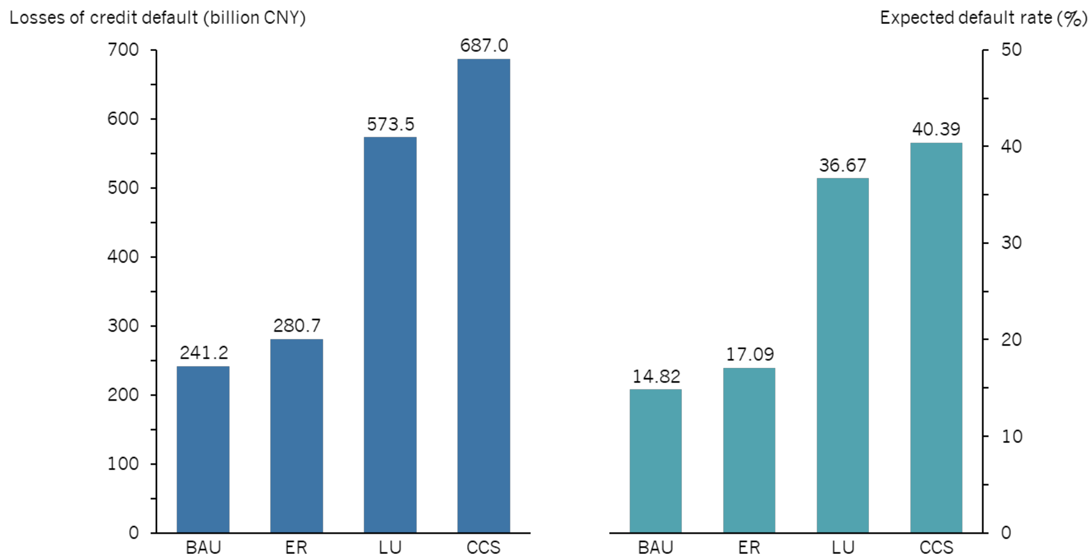
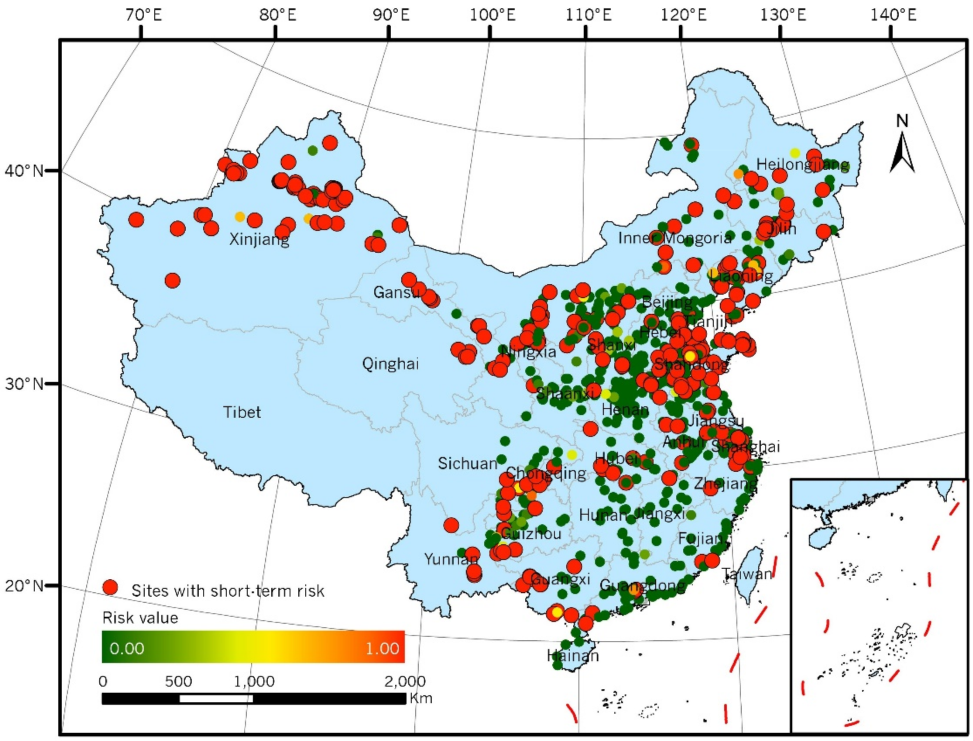


Figure 5. Credit default losses and probabilities under different transition scenarios



When the default distance is less than 0, the value of the firm's assets is severely below the amount of liabilities to be repaid. At this point, the credit risk present in the market is often beyond the tolerance of financial institutions. We find the power plants with default distance less than zero in order to more accurately identify the occurrence of credit default risk. There are 199 plants (17.5% of plants nationwide) with default distances less than 0, meaning that predictable credit defaults will occur in the short term (Figure 6). The units in default in the short term are spread across multiple provinces, which shows that coal power credit defaults will become a common problem in China. Under three transition scenarios, the number of these plants will increase to 405, 424, and 361 nationwide. The losses of credit defaults reached 129.6, 169.6, 504.3, and 622.5 billion CNY, respectively. We will further identify the severity of coal power credit defaults in different regions.

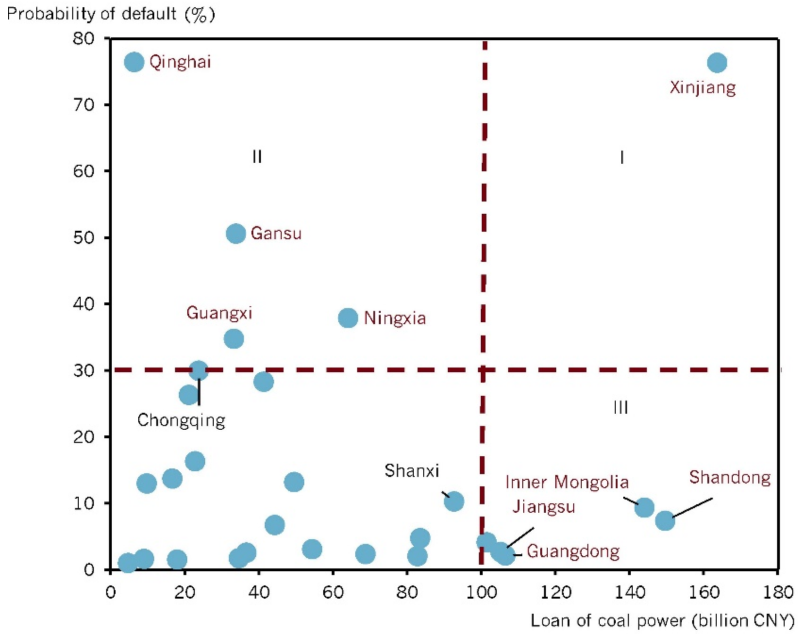
Figure 6. Plant-level Credit Risk Map of China in BAU Scenario



Regional credit default pressure varies greatly. The probability of default for coal power reaches 50% in Qinghai, Xinjiang, Gansu, and Yunnan provinces under BAU scenario, much higher than in other regions. In contrast, Shanxi, Inner Mongolia, and Shandong, which have some of the highest installed coal power units in China, have average default probabilities of about 10.17%, 9.29%, and 7.31%.

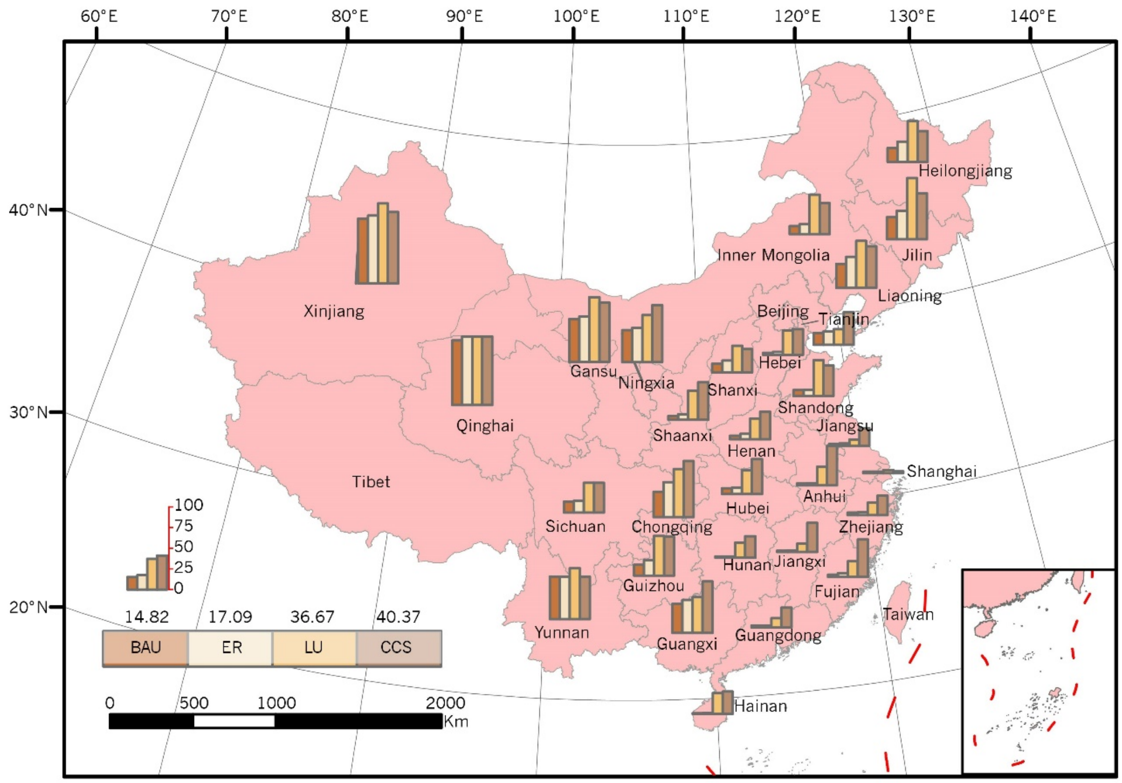
To more clearly demonstrate the regional differences, we divide the Chinese provinces into four categories (Figure 7). We classify provinces with 30% credit default rate and 100 billion yuan credit balance as thresholds. The top 10 provinces with installed capacity have better characteristics under this classification standard. Category I has higher default losses and default risk than other regions, such as Xinjiang. Xinjiang is expected to default on losses of up to 866.6 billion CNY, accounting for more than one-third of the national default losses. This is due to its more coal plants and worse profitability. Category II, with higher default risk but lower residual loan amounts, may need to be alert to the possibility of concentrated credit outbreaks in coal power companies. Category III is with lower default risk but higher residual loan amounts. The focus needs to be on being alert to regional defaults that may be triggered by the low-carbon transition. The remaining provinces are all of low credit risk.

Figure 7. provincial differences of credit default coal power under BAU scenario



Nationwide, the risk of default on coal power credit shows a decreasing trend from northwest to southwest. The response of coal power credit defaults to the transition pathways differs across provinces. Shanxi, Inner Mongolia, and Shandong are very typical provinces with elevated risk of substantial credit defaults under the LU scenario, raising it to 31.32%, 46.41%, and 42.36%, respectively, while under the CCS scenario it reaches 27.7%–36.5% and 36.44%. Therefore, phasedown of coal use is a process that should be decided in a comprehensive manner in terms of multiple dimensions such as asset value, financial risk, and carbon emission reduction. A classified transition strategy should be adopted according to the regional credit risk differences (Figure 8).

Figure 8. provincial changes of credit default coal power under different scenarios



5. Conclusions and policy recommendation

5.1 Conclusions

According to the constraints of China's carbon neutralization target on coal-fired plants, several coal power transition scenarios are designed, including BAU scenario, Early Retirement scenario, Low Utilization scenario, and CCS retrofitting scenario. Based on the unit-level financial framework, we quantitatively measured the asset losses under different transition pathways, and then assessed the default risk of coal power credit using KMV model. The main findings are as follows.

(1) Operating coal power units are the main cause of stranded assets under low-carbon transition. The total stranded assets under the ER and LU scenario are 1.90 trillion and 3.98 trillion CNY, respectively. The annual stranded coal assets vary significantly between different

transition scenarios, with the ER stranding pressure mainly concentrated between 2030 and 2040, and the LU scenario concentrated between 2021 and 2035. The spatial distribution of coal stranded assets is extremely uneven, with 10 major coal provinces such as Shandong, Inner Mongolia and Jiangsu accounting for 67% and 70% of the stranded assets nationwide.

(2) The expected value of the national coal power credit default rate is about 14.82% under the benchmark scenario, while the coal power credit default probability will increase to 17.09% under the early retirement scenario, which will lead to a significantly higher credit default probability of 36.67% if the coal power flexibility operation is increased according to the existing policy guidance. Typical provinces such as Gansu, Guangxi, Guizhou and Jilin, despite the overall low level of residual coal power loans, have a higher credit default ratio under the impact of coal power transition than other regions, which will also have a negative impact on bank asset quality, and need to pay attention to credit risks in such regions to prevent secondary financial risks in the transition process.

5.2 Policy Implications

From the financial perspective of the coal power industry itself, early retirement has the lowest asset losses and credit risks, but the losses don’t take into account the power supply security and the grid system cost. The development of renewables and the transition of power system is a medium-to-long-term process. To ensure the safe supply of power, coal power needs to play the role of flexible resources. It should be considered that the more realistic choice of the coal power industry is to strengthen the transition and upgrading, so as to meet the requirements of safe supply and carbon reduction, which means that the number and frequency of credit defaults in the coal power industry may rise sharply and erupt intensively. Bank loans accounts most of the funds, which may affect the quality of bank assets and even cause systemic financial risks locally. To this end, we put forward the following suggestions:

Firstly, speed up the power market reform: The risk of stranded asset and credit default exists in the low carbon transition. Coal power enterprises are currently experiencing operating losses and a lack of enthusiasm for transition. As a result, through market-oriented electricity price reform, the profitability of coal power can be improved, thereby improving the robustness of low-carbon transition and reducing the risks that transition may face. The proportion of renewable power generation will continue to increase, putting higher demands on the flexibility and stability of the power system. A power market system needs to be established gradually with complete trading varieties and functions avoiding financial risks of the coal power industry and enhance its ability to cope with the low-carbon transition.

The auxiliary service compensation policy must be improved, because flexibility operations of coal power will result in higher coal consumption, higher operation and maintenance costs, higher equipment aging rate during low-load operation. These will lead to more serious stranded asset risk and credit default. Renewable power plants should share the peak shaving cost pressure for coal power units. Market-based mechanism means can be adopted to enhance the financial situation of coal power enterprises, such as improving the power balance mechanism and price formation mechanism of electricity.

Secondly, consider the uneven spatial distribution of asset losses and credit defaults. Provinces response quite different to different transition pathways, which is mainly related to the coal power capacity, tariff, profitability, etc.. Thus, the regional economic impact of low-carbon transition in such regions should be specially considered. Priority will be given to retiring or upgrading coal power units in Shandong, Inner Mongolia and Shanxi provinces that have been in service for a long time, have low efficiency and poor profitability. At the same time, it is an inevitable choice in China's national context for coal power to take up the task of a flexible generators. From a long-term perspective, based on the key role of coal power in renewable energy consumption and power system supply stability, some units will adopt CCUS technology, especially units in the eastern coastal region. Zhejiang, Jiangsu and Guangdong can find units with more advanced technology and greater comparative advantage of flexibility operation. This will give full play to the advantages of closer proximity to the load, advanced technology and short operating life. Provide reliable transition solutions for regions with high dependence on coal and coal power, such as Inner Mongolia, Shanxi, Xinjiang. These provinces can also establish early warning mechanisms for key coal power projects to enhance their risk management capabilities. Supporting transition policies should be designed in order to minimize economic losses and to prevent systemic financial risks in the transition process.

Thirdly, strengthen the risk management of coal power transition. Relevant enterprises should strengthen the monitoring of the long-term financial status. Measures could be taken about the supervision mechanism of value changes of coal power related stocks, bonds and assets. Identify potential credit risks and establish a list of risky assets. It is necessary for the financial system to incorporate risk management into the decision-making framework for capital allocation, financial product/service development and supply chain management, thus give full play to the risk management function of the financial system.

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