A New Approach to Assess Climate Change Risk in Coal-Power Generation Sector

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Abstract. We propose a novel approach to identify and evaluate climate change risk in coal-power generation firms. This approach includes 92 indicators to assess climate change exposure from green transition, physical, ESG (Environmental, Social, and Governance), and financial dimensions. Based on these comprehensive risk exposure metrics, we calculate climate change risk exposure indices and categorize them into low, medium, and high levels. We implement this approach in the coal-power generation firms in China and obtain a series of insightful findings. For example, state-owned firms exhibit lower ESG risk and lower levels of technology risk. Firms in the eastern regions face lower risks related to fire, earthquake, and flooding but are more susceptible to hurricane risks. Shandong, Jiangsu, Shaanxi, Beijing, and Zhejiang demonstrate the highest overall transition risk. Guangxi, Yunnan, Sichuan, Hubei, and Hebei are exposed to the highest overall physical risk. Zhejiang, Inner Mongolia, Jiangsu, Shandong, Liaoning, and Anhui have the highest ESG risk. Firms in Inner Mongolia, Heilongjiang, Liaoning, Jilin, and Shandong are exposed to high financial risk, etc. Our findings generate practical implications for corporate managers to evaluate and integrate climate change risk into business strategies and policymakers to promote sustainable growth in the economy.

Keywords: climate change; transition risk; physical risk; ESG risk; financial risk

1 INTRODUCTION

The disasters caused by climate change, such as extreme temperatures, floods, rising sea levels, etc., significantly affect ecological balance and economic development [1]. Assessing the climate change risk is one of the critical strategies to respond to the impact of global climate change. Corporations, being significant contributors to carbon emissions, play a major role in the dynamics of climate change. Thus, it is crucial to identify and evaluate climate change risk on corporations. In this study, we introduce a novel approach to evaluate the impact of climate change on corporate risk exposure. Our approach composes a comprehensive metric with 97 indicators to assess climate change risk, particularly represented by carbon risk, from four

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dimensions: corporate green transition, physical impacts, ESG (Environmental, Social, and Governance) factors, and financial performance.

To empirically assess our approach, we use the coal-power generation firms in China, a sector known for its high carbon intensity. As one of the largest carbon emitters in the emerging economy, China has elevated energy conservation and environmental protection to a national strategy and has proposed its carbon peak and neutrality targets, with a series of supporting policies being developed, piloted, and implemented. In particular, the national carbon emissions trading market launched online trading on 16 July 2022. The power generation industry was the first to be included, with 2,225 coal-power firms taking the lead due to their high share of carbon emissions and the reliable and complete monitoring, reporting, and verification system (MRV system). According to the Ministry of Ecology and Environment of China, coal-powered generators emit approximately 4 billion tons of carbon dioxide annually. Such evaluations become imperative for these sectors, encouraging them to implement measures that effectively control their carbon emissions. Consequently, using these sectors as a focal point for assessing climate change risk is not only relevant but also essential.

The effect of climate change on corporate risk profile has been examined by prior literature using different approaches. For instance, using the Analytical Hierarchy Process (AHP) Algorithm, Pan [2] constructs a carbon risk system with indicators including market risk, credit risk, operational risk, and project risk. Zhu et al. [3] include external factors such as law and policy strength, macroeconomic fluctuation, energy price fluctuation, climate change, green and low-carbon development levels, and internal factors such as credit risk, operational risk, and market volatility. Zhang et al. [4] construct carbon asset management indicators, including carbon fund turnover ratio, carbon emission rate, carbon turnover ratio, carbon technology transformation efficiency, and fixed carbon asset profitability. However, there are several limitations in the literature. First, prior studies that evaluate firm risk are primarily based on financial performance and macroeconomic environment and rarely include carbon risk in the evaluation system. Second, most research focuses on certain risks rather than a comprehensive risk matrix when assessing corporate climate risk. Firms are gradually facing the requirement and regulation on reducing carbon emissions. It is crucial to establish a comprehensive risk matrix to evaluate the risk exposure to climate risk [5,6,7,8,9,10].

In this paper, we complement existing studies by constructing a systematic metric including 97 indicators to measure the climate risk, consisting of corporate green transition risk, physical risk, ESG risk, and financial risk. The rest of this paper is organized as follows: Section II presents climate change risk evaluation metrics. Sections III and IV empirically analyze the climate change risks for coal-power generation firms using the abovementioned metrics. Section V proposes policy recommendations.

2 CLIMATE CHANGE RISK EVALUATION METRICS

We utilize the Analytic Hierarchy Process (AHP) method to compose the climate change risk evaluation metrics. This multi-criterion decision-making approach breaks down complex problems into simple, manageable components and performs a hierarchical analysis. We consider four dimensions in our metric: physical risk, transition risk, Environmental, Social,

and Governance (ESG) risk, and entity financial risk. We elaborate on the details of evaluation metrics for each type of risk as follows.

2.1Transition Risk

The Task Force on Climate-related Financial Disclosures (TCFD) recognizes that the transition to a low-carbon economy requires a multi-faceted approach that addresses both mitigation and adaptation requirements related to climate change [11]. It includes a shift in policy and legal frameworks, technological advancements, and changes in market preferences and norms.[1] Based on this, we construct the transition-related metrics from the following four dimensions: policy risk, carbon market risk, low-carbon preference risk, and technology risk (more details are shown in Table A1 in the Appendix).

Specifically, the policy risk encompasses a list of carbon reduction policies and regulations that could raise the cost of carbon emissions, impose greater reporting obligations, and increase firms' exposure to legal action. Examples of such policies include the inclusion of carbon neutrality tasks in China's 14th Five-Year Plan, the formulation of carbon neutrality roadmaps, and the implementation of subsidy policies for low-carbon projects. Carbon market risk refers to the impact of carbon emissions trading on participants, including risks related to market liquidity, carbon prices (carbon quota price, CCER price), exchange rate, and interest rate. Further, climate change affects not only firms but also all of society. It raises social awareness of carbon emissions and shifts consumer preference toward low-carbon products, thus decreasing the value of fossil fuel assets and increasing the low-carbon preference risk. In addition, to comply with carbon-reduction policies and regulations, high-carbon emitters are likely to increase investment in low-carbon technology developments and green innovations. It will increase firms' technology risk for the uncertainties in developing low-carbon technologies and for the updates of existing technologies. In practice, we score firms on a scale of three, two, and one, from highest to lowest risk.

2.2Physical Risk

Physical risk is associated with adverse socio-economic impacts due to extreme weather events or other climate hazards and covers certain economic activities and geographical areas [12]. Its effects are long-term, irreversible, and uncertain. There are two main types of physical risks, namely acute and chronic physical risks. Acute physical risks are driven by specific weather events or "hazards," such as heatwaves, droughts, floods, wildfires, and storms. Chronic physical risks are driven by longer-term shifts in climate patterns, including temperature rise, sea level rise, the spread of tropical pests, diseases to temperate zones, and biodiversity loss.

The physical risk could be translated into real economic impacts and create knock-on effects, such as damage to fixed assets, business interruptions, and reduced profits. It will further increase future cash flow uncertainty and economic losses. For instance, in recent years,

[1] Climate Risks and Opportunities Defined | US EPA (see the detailed content at https://www.epa.gov/climateleadership/climate-risks-and-opportunities-defined#:~:text=Source%3A%20Recommendations%20of%20the%20Task%20Force%20on%20Climate-related,greenhouse%20gas%20emissions%20and%20transition%20to%20renewable%20energy.)

Florida has experienced a growing impact of extreme flooding events. The average annual losses attributed to storm surge damage on residential real estate are $2 billion. These losses are projected to escalate to approximately $2.5 to $3 billion by 2030 and further increase to $3 to $4.5 billion by 2050, provided that no adaptation and mitigation measures are implemented to address the challenges posed by these floods [13]. In this study, we estimate firms' physical risk from vulnerability and severity. Risk vulnerability refers to the frequency and severity of economic losses caused by events, including direct economic losses due to damage to physical assets (for example, buildings, plant facilities, or transportation facilities) and indirect economic losses from enterprise shutdowns and production reduction due to disasters.

Based on information publicly available from the National Bureau of Statistics and the Ministry of Emergency Management of China, we identify five natural disasters that frequently occur and have significant impacts in China, including hurricanes, fires, earthquakes, droughts, and floods. Further, to provide a comprehensive assessment of physical risk, we evaluate each risk in terms of vulnerability and severity (more details are shown in Table A2 in the Appendix).

In practice, we set thresholds to estimate the vulnerability and severity of risks (more details are shown in Table A2 in the Appendix). Specifically, we divide regions into high, medium, and low vulnerability regions based on the mean value over the past seven years, with high vulnerability at the top third and low vulnerability at the bottom third. Then, we assign scores of three, two, and one for high-, medium-, and low-vulnerability regions, respectively. When estimating the severity of risks, we use the same methodology. The overall physical risk rating is the sum of the vulnerability and severity scores for each dimension.

2.3ESG Risk

ESG, integrating firms' non-financial performance into their overall assessments, has become increasingly important in recent years. More and more investors are incorporating ESG into their investment decision-making process, making it a dominant theme in business. The previous literature has documented that firms with stronger ESG performance tend to have better financial performance [14], higher credit quality [15], greater risk resilience [16], and lower default likelihood [17]. Based on this, we incorporate ESG risk into our metric to comprehensively assess firms' climate change risk. In particular, for corporate environmental performance, the indicators include corporate carbon emissions, low-carbon propaganda, low-carbon technologies and design, and R&D expenditure. To evaluate corporate social performance, we consider supplier relations, customer relations, labor management, community relations, product quality, and corporate charitable donations. In terms of corporate governance, firms with higher levels of governance usually take climate change risk into account in their decision-making and pay attention to climate change risk management. Therefore, we evaluate corporate governance performance in three dimensions: low-carbon organizational structure, carbon risk management, and investor relations (more details are shown in Table A3 in the Appendix).

Thresholds are established for continuous variables based on industry average, including carbon emissions, R&D expenditures, and charitable donations. We assign a score of one for firms with strong ESG performance and zero for those with weak performance. For the remaining indicators, a binary approach is used, with firms conducting ESG activities scoring one and

those not conducting ESG activities scoring zero. We also set up a score deduction mechanism for negative events. After calculating firms' overall ESG score, we divide the score by the total score set for the indicator to make ESG ratings fall within the range of zero to one. To evaluate firms' ESG risk, we set the ESG risk score to one minus the ESG performance score.

2.4Financial Risk

Financial risk reflects firms' fundamentals, such as solvency, profitability, operating capabilities, and cash flows. It is decomposed into five attributes: micro-economic risk, regional risk, corporate governance risk, operating risk, and financial risk. For each of the five attributes, we set a battery of sub-indices. For instance, to evaluate firms' micro-economic risk, the indicators include GDP growth rates, urban registered unemployment rates, inflation rates, value added in the secondary sector, and total imports and exports of goods (more details are shown in Table A4 in the Appendix).

For quantitative variables at the macro level, we set the upper three and bottom three values over the past 18 years (2003-2020) as a benchmark in setting the threshold. Specifically, if a factor value is above the up-three value, it is assigned three points, indicating a high risk. In contrast, if the factor value is below the lower three values, one point is set, indicating a low risk. A score of two is assigned for firms valued in the middle third, representing a medium risk.

For firm-level quantitative variables, we adopt a two-step approach. First, we estimate the mean value for each indicator, covering 18 years from 2003 to 2020. Second, we sort the averages in descending order and divide them into three groups to identify the thresholds. The resulting thresholds are then used to score firms as three for high risk, two for medium risk, and one for low risk. For firm-level qualitative variables, we set up dummy variables, with a score of one for high risk and zero for low risk. This approach provides a comprehensive and objective financial risk assessment, enabling investors to make well-informed investment decisions.

3 COAL-POWER GENERATION FIRMS

3.1Sample Selection

We select Chinese coal-power generation firms included in the national carbon trading market as our research objectives. Due to data availability, we only keep A-share listed firms.[2] Carbon assets play a critical role for coal-power generators, particularly for small and medium-sized enterprises, as they can serve as new collateral for financing. This, in turn, helps alleviate some of the financing constraints faced by these firms, enabling them to access the necessary funds for their operations and low-carbon transition endeavors.

[2] China A-share listed firms are the major party in terms of CSR information disclosure; Several new rules and regulations have been introduced to create incentives for improving CSR practices and to promote more standardization of information among listed companies in China. Various regulatory bodies have formulated a series of voluntary or mandatory basis [24]. Simultaneously, Chinese listed companies regularly disclose operating results data and company fundamentals data, which facilitate our analysis of corporate operation and credit status related to carbon asset risks.

We gather data from several sources through direct extraction and manual collection. Specifically, our financial data is sourced from the China Stock Market & Accounting Research Database (CSMAR), Wind database, and Chinese statistical yearbooks. We manually collect carbon-related policies from government websites and ESG information from firms' websites, annual reports, and social responsibility reports. The data is then transformed into a panel format before merging all the datasets.

3.2Descriptive Statistics

Our sample consists of 1,317 state-owned enterprises (59.87%), 831 private enterprises (37.72%), 46 foreign-funded enterprises (2.09%), and seven collectively owned enterprises (0.32%); the rest of the enterprises make up 1.07% of the sample. Further, the coal-power generation firms concentrate in Shandong and Jiangsu provinces, with 338 firms located in Shandong province and 216 in Jiangsu province. Other firms are located mainly in Inner Mongolia (168), Zhejiang (141), and Henan province (121). Moreover, we find that the coal-power generation enterprises are mainly located in China's northern and eastern coastal regions.

4 THE EFFECT OF CARBON EMISSION ON CORPORATE RISK PROFILE

In this section, we first report the descriptive statistics of key variables in our analyses. Then, we discuss the detailed effects of climate change on green transition risk, physical risk, ESG risk, and financial risk, respectively.

4.1The Descriptive Statistics of Variables

Table I reports the descriptive statistics of variables. The transition risk faced by firms among provinces shows little variation, as indicated by a low standard deviation of 0.33. In particular, among the sub-indices pertaining to transition risk, technology risk stands out with the highest mean value, reaching 2.62. Regarding physical risk indices, drought risk has the highest standard deviation (0.87), followed by that of hurricane risk (0.76). These indicate that, regarding physical risk, the hurricane and drought risks have the highest inter-firm heterogeneity. For ESG risk, social risk has the highest mean value (0.52), indicating that coal-power generation firms are exposed to high social risk compared with the other two dimensions. Further, the coal-power generation firms should pay more attention to regional economic, corporate financial, and corporate governance risks, with a mean value of 2.47, 2.30, and 2.29, respectively.

TABLE1.TTHE DESCRIPTIVE STATISTICS OF VARIABLES

Variable	#Obs.	Mean	SD	Min	P25	Median	P75	Max
Transition Risk	2,193	2.07	0.33	1.18	1.85	2.10	2.43	2.52
Policy Risk	2,193	2.10	0.85	1	1	2	3	3
Carbon Market Risk	2,193	1.40	0	1.40	1.40	1.40	1.40	1.40
Low Carbon Preference Risk	2,193	2.16	0.45	1.33	2.00	2.33	2.67	2.67
Technology Risk	2,193	2.62	0.60	1	2.33	3	3	3

Physical Risk	2,193	1.71	0.22	1.10	1.60	1.80	1.80	2.30
Hurricane Risk	2,193	2.12	0.76	1	1.50	2	3	3
Fire Risk	2,193	1.15	0.53	1	1	1	1	3
Earthquake Risk	2,193	1.71	0.66	1	1	1.50	2	3
Drought Risk	2,193	1.95	0.87	1	1	2	3	3
Flooding Risk	2,193	1.62	0.83	1	1	1	2.50	3
ESG Risk	840	0.38	0.15	0.13	0.28	0.38	0.50	0.94
Environment Risk	840	0.40	0.22	0	0.20	0.40	0.60	0.90
Social Risk	840	0.52	0.20	0.14	0.36	0.43	0.71	1
Governance Risk	840	0.12	0.18	0	0	0	0.25	1
Financial Risk	559	1.96	0.20	1.37	1.81	1.99	2.09	2.66
Macroeconomic Risk	2,191	1.29	0	1.29	1.29	1.29	1.29	1.29
Regional Economic Risk	2,191	2.47	0.46	1.50	2	2.50	3	3
Corporate Governance Risk	559	2.29	0.4	1	2	2.33	2.67	3
Corporate Operating Risk	559	1.47	0.71	1	1	1	2	3
Corporate Financial Risk	559	2.30	0.60	1.25	1.75	2.38	2.88	3

This table presents the descriptive statistics for the variables used in our climate change risk assessment index system for Chinese coal-power generation firms participating in the carbon-emission trading market. The number of observations (#Obs.), mean value (Mean), standard deviation (SD), minimum (Min), first quartile (P25), median (Median), third quartile (P75), and maximum (Max) are reported in sequence.

We further split the full sample into two groups according to their state ownership and geographical distribution, respectively. We find that state-owned firms suffer less ESG risk. It may be attributed to the fact that, as an agile tool of the government, state-owned firms are tasked with a dual objective of achieving social welfare and economic development [18] and thus are ESG-oriented by design. Additionally, state-owned coal-power generators demonstrate lower levels of technology risk, primarily attributable to the strong support and encouragement provided by government policies and financial assistance in the realm of low-carbon transformation. State-owned enterprises (SOEs) enjoy the advantage of government backing, facilitating their access to financial and technical resources for the implementation of low-carbon initiatives. Furthermore, due to their unique industrial nature, state-owned firms bear heavier responsibilities for energy conservation and emission reduction, and they exhibit a strong sense of responsibility, driving them to be more proactive in undertaking green technology innovation [19]. As a result, state-owned coal-power generators experience a reduced technology risk, enabling them to navigate the transition towards low-carbon practices with enhanced efficiency and effectiveness. Regarding financial risk, state-owned coal-power generation firms are exposed to higher corporate governance and financial risks, which is in line with the findings in [20].

Further, as shown in Table II, a comparison between firms in the mid-western regions and those in the eastern regions reveals that coal-power generation firms in the eastern regions face lower risks related to fire, earthquake, and flooding but are more susceptible to hurricane risks.[3] Indeed, the geographical proximity of the eastern region to the coastline makes it more susceptible to marine meteorological events, such as hurricanes. In contrast, the mid-western

[3] We categorize regions located in Beijing, Tianjin, Liaoning, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangxi, Guangdong, and Hainan as the east regions, while considering other regions as midwestern regions.

area, being farther away from the coastline, experiences lower exposure to such risks. Furthermore, the eastern region often benefits from a milder climate than the western region, reducing risks of natural disasters such as fires, earthquakes, and floods.

In addition, firms located in the eastern regions face higher policy and low-carbon preference risks. The higher policy risk in the east is due to the more extensive implementation of carbon-related policies in these areas compared to the relatively limited policies in the mid-western region. Moreover, the higher risk of low-carbon preference in the eastern regions can be linked to the significant presence of banks that have joined the Equator Principles (diff = 0.93, p-value < 0.01). These environmentally conscious banks are more likely to incorporate carbon-related factors into their leading practices and risk assessment procedures. As a result, when providing loans or financial services to businesses, these banks tend to treat climate change as one of the evaluation criteria. Therefore, firms with high carbon emissions are likely to experience higher external financing costs [21]. Furthermore, according to the Baidu search index for low-carbon-related terms, residents in the eastern regions have a higher low-carbon preference. Therefore, firms in these regions are exposed to higher low-carbon preference risk (diff = 1.01, p-value < 0.01).

Notably, firms in the mid-western region demonstrate lower levels of corporate governance and financial risks compared to their counterparts in the East. This observation can be attributed to two key factors. First, the mid-western region's relatively lower level of development, as evidenced by higher regional economic risk [22], leads to the adoption of simplified and manageable governance structures [23]. As a result, this approach helps in mitigating corporate governance risks. Another significant influence on the lower financial risks in the mid-western region is the government's implementation of supportive policies and measures. The authorities in this region strategically introduce various policies to promote economic development. These measures provide crucial support and safeguards for firms' smooth operation and growth, effectively reducing the probability of encountering financial risk.

TABLE2.TTHE EFFECT OF CARBON RISK ON CORPORATE RISK PROFILE

Risk	Non-SOE	Mean	SOE	Mean	t-test	Non-East	Mean	East	Mean	t-test
Transition Risk	901	2.18	1,292	1.99	0.18***	1,108	1.91	1,085	2.23	-0.33***
Policy Risk	901	2.22	1,292	2.01	0.21***	1,108	1.70	1,085	2.50	-0.80***
Carbon Market Risk	901	1.40	1,292	1.40	0.00	1,108	1.40	1,085	1.40	0.00
Low Carbon Preference Risk	901	2.23	1,292	2.11	0.12***	1,108	1.91	1,085	2.41	-0.49***
Technology Risk	901	2.86	1,292	2.45	0.40***	1,108	2.61	1,085	2.62	-0.01
Physical Risk	901	1.72	1,292	1.71	0.01	1,108	1.74	1,085	1.68	0.05**
Hurricane Risk	901	2.24	1,292	2.04	0.20***	1,108	1.60	1,085	2.65	-1.04***

Fire Risk	901	1.14	1,292	1.17	-0.03***	1,108	1.30	1,085	1.00	0.30***
Earthquake Risk	901	1.69	1,292	1.72	-0.03***	1,108	1.84	1,085	1.57	0.28***
Drought Risk	901	1.98	1,292	1.93	0.04***	1,108	1.97	1,085	1.93	0.05
Flooding Risk	901	1.54	1,292	1.67	-0.14***	1,108	1.96	1,085	1.27	0.69***
ESG Risk	168	0.45	672	0.37	0.08***	418	0.39	422	0.38	0.01
Environment Risk	168	0.50	672	0.38	0.12***	418	0.40	422	0.41	-0.01
Social Risk	168	0.55	672	0.51	0.04**	418	0.53	422	0.51	0.02
Governance Risk	168	0.20	672	0.10	0.10***	418	0.12	422	0.12	0.01
Financial Risk	112	1.89	447	1.98	-0.08***	265	1.97	294	1.95	0.02
Macroeconomic Risk	901	1.29	1,290	1.29	0.00***	1,106	1.29	1,085	1.29	0.00
Regional Economic Risk	901	2.44	1,290	2.49	-0.05***	1,106	2.62	1,085	2.31	0.31***
Corporate Governance Risk	112	1.92	447	2.38	-0.47***	265	2.24	294	2.33	-0.09**
Corporate Operating Risk	112	1.88	447	1.37	0.50***	265	1.47	294	1.48	0.00
Corporate Financial Risk	112	1.99	447	2.38	-0.39***	265	2.18	294	2.41	-0.22***

This table reports the results of the univariate analysis for variables in our climate change risk assessment index system. Columns (2) to (6) show the univariate analysis results for private firms (i.e., Non-SOE) and state-owned firms (i.e., SOE). Columns (7) to (11) show the univariate analysis results for non-eastern and eastern firms. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

4.2Green Transition Risk Analysis

The carbon output emitted by coal-power firms is substantial, with over 2,000 coal-power generation sectors emitting over 4 billion tons of carbon dioxide annually. Therefore, coal-power generation firms are likely to experience greater scrutiny from regulators. The risk associated with carbon reduction policies would affect coal-power generation firms' profitability, asset value, and motivation to conduct green transition, increasing operational unpredictability. Furthermore, coal-power generation firms are exposed to reputational risk. For example, if a coal-power producer discharges illegally, this behavior will affect its reputation, leading to lower market competitiveness, reduced investments, and loss of business. Moreover, climate change affects both firms and the whole society, raising social awareness of carbon emissions and shifting consumer preference toward low-carbon products. Thus, coal-power generation tied with high carbon emissions may lose customers who prefer low-carbon products and services. In addition, developing and adopting low-carbon technologies could also bring unforeseen challenges and risks, including investment risks, commercialization failures, and difficulties in scaling up green innovations. These challenges could influence coal-power generation firms' profitability, production, and operations.

We calculate the mean value of each risk index for firms in each province, we observe the highest overall transition risk among firms located in Shandong, Jiangsu, Shaanxi, Beijing, and Zhejiang. Firms located in Zhejiang, Shanghai, Shandong, Shaanxi, and Ningxia face the highest policy risk, while those in Guizhou, Guangxi, Gansu, Fujian, and Chongqing exhibit low policy risk. This empirical evidence sheds light on the regional variations in policy risk and its impact on coal-power generation firms. Moreover, we find that firms operating in Yunnan, Sichuan, Shandong, Jiangsu, and Chongqing are more exposed to the impact of low-carbon preference risk due to the low-carbon preferences of society. For example, commercial banks in these regions are actively involved in the Equator Principles and the Principles for Responsible Banking. Regarding technology risk, the evidence shows that firms in Shaanxi, Guizhou, Sichuan, Henan, and Yunnan face higher levels of technical risk. In contrast, firms located in Shanghai, Qinghai, Anhui, Hainan, and Hunan exhibit lower technical risk.

4.3Physical Risk Analysis

The physical risk depends on geographical location. For instance, coal-power generation firms are vulnerable to water resources due to the high dependence on water for thermoelectric cooling. With global climate change, the distribution of water resources will change, thus exposing these coal-power producers to greater risk. In addition, earthquakes, floods, and fires could also damage power generation equipment and buildings, negatively impacting the production and operation of coal-power producers.

We calculate the mean value of each risk index for firms in each province, coal-power generators located in Zhejiang, Jiangxi, Jiangsu, Hainan, and Guangxi are exposed to high hurricane risk, and those in Inner Mongolia are most exposed to fire risk. Moreover, firms in Yunnan, Sichuan, Xinjiang, Qinghai, Jilin, Chongqing, and Hubei should take earthquake risks into account in their operations, as earthquakes can damage transport routes, resulting in fuel shortages (e.g., coal). Furthermore, coal-power producers in Yunnan, Shandong, Liaoning, and Inner Mongolia are at high risk of drought. For coal-power producers in Sichuan, Shaanxi, Jiangxi, Hunan, and Hubei, flooding risk is a physical risk of concern. Firms located in these regions should include consideration of flood damage to power stations and transport routes. To sum up, firms located in Guangxi, Yunnan, Sichuan, Hubei, and Hebei are exposed to the highest overall physical risk.

4.4ESG Risk Analysis

ESG has received increasing attention recently, with investors and lenders incorporating it into their investment decision-making process. Moreover, local governments have enforced a battery of new policies and regulations to honor the commitment to sustainability. This will increase the operating and financing costs of coal-power generation firms. It, in turn, reduces their ability to conduct ESG-related activities, such as carbon reduction and green innovation. Furthermore, coal-power generation firms with high ESG risk are more vulnerable to reputational damage and stakeholder litigation, leading to reduced market competitiveness and profitability.

We calculate the mean value of each risk index for firms in each province, and we find that firms in Zhejiang, Inner Mongolia, Jiangsu, Shandong, Liaoning, and Anhui have the highest

ESG risk. We also break down the overall ESG risks into environmental, social, and corporate governance risks. The findings show that coal-power generation firms located in Zhejiang, Jiangsu, Henan, Liaoning, Inner Mongolia, and Hubei are exposed to high environmental risks. Therefore, investors and firm managers in these regions need to consider more how environmental performance and climate change affect firms' financial performance and policies to make accurate firm valuations. Further, we find that coal-power generation firms in Shandong, Jiangsu, Anhui, Guangdong, Zhejiang, and Heilongjiang are exposed to both high social and governance risks.

4.5Financial Analysis

Financial performance is used to estimate coal-power producers' fundamental information, providing insights into firms' financial status and repayment capability. Due to the limited data, we use the financial performance of the listed parent firm as a proxy for coal-power generation firms. After calculating the mean value of each risk index for firms in each province, we find that firms in Inner Mongolia, Heilongjiang, Liaoning, Jilin, and Shandong are exposed to high financial risk. For regional economic risk, firms located in Xinjiang, Tianjin, Qinghai, Ningxia, and Liaoning, mainly in non-eastern regions, are at high risk. It highlights the need for them to be aware of the impact of regional economic risk on their production and operations. In addition, we find that coal-power generation firms with high governance risk are concentrated in Guangdong, Inner Mongolia, Zhejiang, and Liaoning, and those with high operating risk are mainly located in Zhejiang, Inner Mongolia, Shandong, Jiangsu, Anhui, and Liaoning. Investors and financial analysts should consider governance and operating risks to make accurate firm valuations when evaluating these firms. Furthermore, coal-power generation firms in Shandong, Hebei, Guangdong, Henan, and Shanxi are exposed to high financial risk relative to those in other regions.

5 CONCLUSIONS

In this paper, we present a novel approach for the identification and assessment of climate change risk in coal-power generation companies. Our approach incorporates a set of 92 indicators that evaluate climate change exposure across various dimensions, including the green transition, physical factors, ESG (Environmental, Social, and Governance) considerations, and financial aspects. By utilizing these comprehensive metrics, we compute climate change risk exposure indices and classify them into three levels: low, medium, and high. To demonstrate the applicability of our approach, we apply it to coal-power generation firms in China and derive several noteworthy findings. For instance, state-owned firms exhibit lower ESG risk and lower levels of technology risk. Firms located in eastern regions are less exposed to risks associated with fire, earthquake, and flooding, but are more susceptible to hurricane risks. Shandong, Jiangsu, Shaanxi, Beijing, and Zhejiang demonstrate the highest overall transition risk. Guangxi, Yunnan, Sichuan, Hubei, and Hebei face the highest overall physical risk. Zhejiang, Inner Mongolia, Jiangsu, Shandong, Liaoning, and Anhui have the highest ESG risk. Companies in Inner Mongolia, Heilongjiang, Liaoning, Jilin, and Shandong are exposed to high financial risk, among others. These findings offer valuable insights for corporate managers,

enabling them to evaluate and integrate climate change risk into their business strategies. Furthermore, policymakers can utilize these findings to foster sustainable economic growth.

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APPENDIX A1 TRANSITION RISK EVALUATION INDICATORS

Level 1 Indicator	Level 2 Indicator	Level 3 Indicator	Definition
Transition Risk	*Policy Risk*	*"Carbon Neutrality" Related Tasks and Policies in the 14th Five-Year Plan*	This indicator reflects the level of awareness and importance given to carbon neutrality in the region where the firm is located. It is measured based on the inclusion of carbon neutrality targets in the 14th Five-Year Plans of the 31 provinces, municipalities, and autonomous regions.
		Carbon Neutrality Policy	This indicator reflects the level of commitment to carbon neutrality in a particular region where the firm is located. It is measured based on the implementation of carbon neutrality governance pathways by the 31 provinces, municipalities, and autonomous regions.
		Subsidy Policies for Carbon Emission Reduction	This indicator reflects the level of support for the development of green and environmentally friendly enterprises in the region where the firm is located. It is measured based on the implementation of policies related to low-carbon environmental protection or green fund management measures by the 31 provinces, municipalities, and autonomous regions in recent years.

	Carbon Market Risk	*Carbon Market Liquidity Risk*	*Carbon Quota Trading Activity*	This indicator reflects the liquidity of carbon assets in the carbon market. It is the ratio of the 2021 carbon quota trading volume in each pilot carbon market and the national carbon market to the total carbon quota of that carbon market in 2021.
		Carbon Price Risk	*CCER Trading Activity*	This indicator reflects the liquidity of carbon assets in the carbon market. It is the 2021 CCER trading volume ratio in each pilot carbon market to the total registered emission reduction volume of CCER nationwide.
			Carbon Quota Price Volatility	This indicator reflects the volatility of carbon quota assets in various carbon markets in 2021. It includes short-term price volatility, medium-term price volatility, and long-term price volatility.
			CCER Price Volatility	This indicator reflects the volatility of CCER assets in various carbon markets in 2021. It includes short-term price volatility, medium-term price volatility, and long-term price volatility.
		Foreign Exchange Risk	*Volatility of RMB Exchange Rate against Euro*	This indicator reflects the volatility of exchange rates in international carbon asset trading. It includes short-term exchange rate volatility, medium-term exchange rate volatility, and long-term exchange rate volatility.
		Interest Rate Risk	*Volatility of Benchmark Lending Rate*	This indicator reflects the level of interest rates. It includes a one-year benchmark lending rate, a five-year benchmark lending rate, and a benchmark lending rate for loans longer than five years.

	Low Carbon Preference Risk		*Proportion of Sustainable Development Private Firms*	This indicator reflects the proportion of the Top 100 Sustainable Development Private Enterprises in the region where the firm is located.
			Banks that Have Joined the Equator Principles & Responsible Banking Principles	This indicator reflects the level of low-carbon preference among banks in the region where the firm is located. It is measured by the presence of banks that have adopted the Equator Principles and the Principles for Responsible Banking in a region where the firm is located.
			Low-Carbon Related Baidu Index	This indicator reflects the level of low-carbon preference among the general public in the region. The criterion is based on the daily average of the Low-Carbon Baidu Index in 2021.
	Technology Risk	*Low-Carbon Technology Research and Development Risks*	*R&D Investment in Low-Carbon Technologies*	The investment-output ratio of low-carbon technology research and development (R&D) funding
			Low-Carbon Technology Output	The number of patent applications for low-carbon technologies
		Commercialization Risk	*Number of Citations of Low-Carbon Technology Patents*	The number of citations of low-carbon technologies

APPENDIX A2 PHYSICAL RISK EVALUATION INDICATORS

Level 1 Indicator	Level 2 Indicator	Level 3 Indicator	Definition
Physical Risk	*Hurricane Risk*	*Vulnerability* and *Severity*	*Vulnerability* refers to the average annual frequency of specific physical risks occurring in each province over the past seven years. *Severity* refers to the ratio of direct economic losses caused by specific physical risks to the GDP in a region where the firm is located.
	Fire Risk		
	Earthquake Risk		
	Drought Risk		
	Flooding Risk		

APPENDIX A3 ESG RISK EVALUATION INDICATORS

Level 1 Indicator	Level 2 Indicator	Level 3 Indicator	Definition
ESG Risk	*E (Environment) Risk*	*Carbon Emissions*	The amount of carbon emissions generated per unit of sales revenue.
		Low-carbon Propaganda	There are three sub-indicators for qualitative scoring. These sub-indicators include: *Presence of Low-carbon Promotion on Firm's Website*: This sub-indicator assesses whether the firm's website contains information or promotions related to low-carbon initiatives. *Inclusion of Low-carbon Information in Annual Risk Analysis*: This sub-indicator evaluates whether the firm's annual risk analysis includes discussions or considerations of low-carbon issues. *Support for Low-carbon Public Activities*: This sub-indicator examines whether the firm supports or participates in public activities related to low-carbon initiatives.
		Low-carbon Technology and Design	Under this indicator, three sub-indicators are used for quantitative scoring. These include the number of low-carbon-related patent applications, the number of low-carbon-related patents granted, and the number of citations received by low-carbon-related patents.
		R&D Expenditure	R&D expenditure divided by sales revenue
	S (Social) Risk	*Supplier Relations*	There are three sub-indicators for qualitative scoring. These sub-indicators include: *Existence of Environmental Policies for Suppliers*: This criterion assesses whether a firm has environmental policies specifically for its suppliers. *Use of Environmental Criteria to Screen New Suppliers*: This criterion evaluates whether a firm utilizes environmental standards or criteria when selecting new suppliers. *Actions Taken to Address Environmental Impacts in the Supply Chain*: This criterion examines whether a firm takes proactive measures to address environmental impacts within its supply chain.
		Labour Management	*Minimum Wage Standards for Low-carbon Positions*: This sub-indicator evaluates whether the firm has set minimum wage standards specifically for employees in low-carbon positions. *Communication Channels for Employees in Low-carbon Positions*: This sub-indicator assesses whether the firm has established effective communication channels for

			employees in low-carbon positions. *Provision or Support of Low-carbon-related Employee Training*: This sub-indicator examines whether the firm provides or supports training programs specifically focused on low-carbon-related skills and knowledge for employees.
		Community Relations	*Provision of Financial Support for Community Low-carbon Awareness Campaigns*: This sub-indicator evaluates whether the firm provides financial resources to support community initiatives to raise awareness about low-carbon practices.
		Product Quality	This indicator consists of two sub-indicators to qualitatively evaluate the product aspect. They include: *Low-carbon Certification*: This sub-indicator assesses whether the product has obtained a low-carbon label or other relevant certifications. *Energy Efficiency*: This sub-indicator assesses whether the product meets energy efficiency standards.
		Charitable Donations	*Participation in Charitable Donations or Poverty Alleviation Activities*: This sub-indicator assesses whether the firm has engaged in charitable activities or initiatives. *The Proportion of Charitable Donations to Sales Revenue*: This sub-indicator evaluates the proportion of the firm's charitable donations relative to its sales revenue.
	G (Governance) Risk	*Low-carbon Organizational Structure*	*Firm's Carbon Neutrality Goals and Pathways*: This sub-indicator assesses whether the firm has set clear goals and developed pathways to achieve them. *Development of Transition Policies*: This sub-indicator evaluates whether the firm has formulated policies to guide its low-carbon transformation. *Establishment of Low-carbon Governance System*: This sub-indicator examines whether the firm has established a governance system specifically focused on low-carbon initiatives. *Creation of Low-carbon Department or Dedicated Personnel*: This sub-indicator assesses whether the firm has established a separate low-carbon department or assigned dedicated personnel responsible for driving low-carbon transformation efforts.

		Carbon Risk Management	*Integration of Carbon Risk into Risk Management*: This sub-indicator assesses whether the firm incorporates carbon risk into its overall risk management framework. *Carbon Risk Knowledge among Risk Management Department Employees*: This sub-indicator examines whether the employees within the risk management department possess adequate knowledge and understanding of carbon risk.
		Investor Relations	This indicator comprises two sub-indicators to assess a firm's performance in investor relations qualitatively: *Alignment with Investor Low-carbon Preferences*: This sub-indicator evaluates whether the firm meets the low-carbon preferences of investors. *Engagement with Investor Low-carbon Recommendations*: This sub-indicator assesses the firm's responsiveness to investor recommendations related to low-carbon issues.

APPENDIX A4 FINANCIAL RISK EVALUATION INDICATORS

Level 1 Indicator	**Level 2 Indicator**	**Level 3 Indicator**	**Definition**
Entity Credit Risk	*Macroeconomic Risk*	*GDP Growth Rate*	GDP in the current year minus GDP in the last year, divided by GDP in the last year.
		Registered Urban Unemployment Rate	The ratio of registered unemployed individuals to the total number of employed individuals and registered unemployed individuals.
		The Rate of Inflation	The Consumer Price Index (CPI)

		Added Value of Secondary Industry	The added value in the production process of the industrial sector (including mining, manufacturing, water supply, electricity, steam, hot water, and gas) and the construction industry refers to the additional value created during the production process.
		Total Import and Export of Goods	The actual value of goods imported into and exported from China.
		Total Primary Energy Production (Standard Coal)	The sum of all energy generated within the national borders during a specific period. Primary energy includes fossil fuels (such as coal, oil, and natural gas), nuclear energy, and renewable energy sources (such as hydroelectric, wind, solar, biomass, etc.).
		Total Energy Consumption (Standard Coal)	The sum of all energy consumed within the national borders during a specific period. Primary energy includes fossil fuels (such as coal, oil, and natural gas), nuclear energy, and renewable energy sources (such as hydroelectric, wind, solar, biomass, etc.).

	Regional Economic Risk	*Population Density*	The number of people residing in a region where the firm is located per square kilometer.
		Regional GDP Growth Rate	GDP of the region in the present minus GDP of the region in the last year, divided by previous GDP.
	Corporate Governance Risk	Corporate Ownership Property	A dummy variable that equals one if this firm is in state-owned status, and zero otherwise.
		Separating Extent of Ownership and Controlling Right	The difference between control rights and ownership rights.
		Board Size	The total number of members on the firm's board of directors.
	Corporate Operation Risk	Market Share	The ratio of sales revenue of the firm to the total sales revenue of total firms in the same industry.
	Corporate Financial Risk	Audit Conclusion	A dummy variable that equals one if the firm's audit opinion for the year is non-standard, and zero otherwise.
		Total Asset Turnover	Operating income divided by the end-of-period total assets.
		Cash Ratio of Operating Income	Cash received from sales of goods and services divided by operating income.

		Operating Cash Flow to Current Liabilities Ratio	Operating cash flow divided by current liabilities.
		Ratio of Operating Cash Flow to Total Debt	Operating cash flow divided by total liabilities.
		Cash Ratio	Cash and cash equivalents at the end of the period divided by current liabilities.
		Current Ratio	Current assets divided by current liabilities.
		Interest Coverage Multiple	(Net profit + income tax expense + financial expenses) divided by financial expenses.

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