Analysis & Commentary

Carbon risk: Background, conceptual definition and measuring method — Taking A-share listed companies as an example

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Abstract: Carbon risk has become the focal point of academic inquiry in the context of intensifying climate change and pursuing dual-carbon targets. This paper synthesizes domestic and international literature to clarify the concept of carbon risk, providing illustrative cases for various definitions. A key observation is the absence of a standardized approach within academia for measuring carbon risk. Notably, carbon emission data disclosed by Chinese enterprises are limited. In response, this study extends beyond traditional enterprise carbon emissions data and compiles current mainstream methodologies for assessing carbon risk. Using data from listed Chinese companies, this study examined the relevance and practicality of each metric. This study offers several recommendations for the future progress of carbon risk analyses in China and other emerging markets.

Key words: carbon risk; climate change; correlation analysis; information disclosure

1 Introduction

Since the Industrial Revolution, there has been a marked increase in greenhouse gas emissions, such as those of carbon dioxide, primarily due to human activities, which are the principal contributors to global warming. In 2022, global carbon dioxide emissions from energy combustion and industrial processes escalated by 0.9%, reaching an unprecedented high of 36.8 billion tons (International Energy Agency). The global annual mean land temperature now stands 1.67 °C above the 1850–1900 average, ranking as the fourth highest since 1850. The Global Mean Sea Level continued its upward trajectory in 2022, with Antarctic sea ice plunging to a record low of 1.92 million km^2 on February 25, 2022, approximately 1.0 million km^2 below the long-term (1981–2010) average (World Meteorological Organization, State of the Global Climate Report (2022)).

Climate change is impacting nations worldwide, hindering economic progress, affecting quality of life, and imposing significant burdens on individuals, communities, and countries. This trend is likely to intensify in the future. Increasing greenhouse gas emissions from human activities are fueling this change, with levels reaching all-time highs. In the absence of mitigative action, the

global average surface temperatures are expected to continue to rise throughout the 21st century, potentially exceeding 3 °C within this century, with even higher increases in certain regions. These repercussions affect the world's poorest and most vulnerable populations disproportionately.

Climate change is a global issue that transcends national borders and necessitates coordinated efforts at all levels and international collaboration to assist nations in transitioning to low-carbon economies. In a landmark move, 197 countries adopted the Paris Agreement at the 21st Conference of the Parties (COP21) in Paris on December 12, 2015. This agreement, which came into effect within a year, is committed to significantly reducing global greenhouse gas emissions and aims to limit the rise in global temperatures to 2 °C this century, with efforts to further constrain the temperature increases to 1.5 °C. On September 22, 2020, President Xi Jinping announced at the 75th session of the UN General Assembly China's aspiration to peak CO2 emissions by 2030 and achieve carbon neutrality by 2060, a goal known as the dual-carbon target. Currently, more than 70 countries have set net-zero targets, representing approximately 76% of global emissions.

In academic circles, the term "carbon risk" often refers to the socioeconomic production risks associated with global carbon emission reduction. In recent years, scholars have conducted extensive studies on carbon risk. Zhu and Zhao (2022) explored the relationship between carbon risk and corporate loan costs using bank loan data from listed Chinese companies. Lemma et al. (2019) examined the link between carbon risk, voluntary disclosure, and the corporate cost of capital. Bolton and Kacperczyk (2021) investigated investor concerns about carbon risk from three perspectives: carbon risk premium, pricing inefficiency, and transfer hypotheses. Carbon risk significantly affects the global economy, capital markets, bond markets, corporate operations, and production. This study defines carbon risk, examines its measurement methods, explores the differences between these methods, and assesses its impact on financial markets. It offers a comprehensive review of the relevant literature on carbon risk to aid researchers, government agencies, and investors interested in this area.

2 Concept of carbon risk

Risk is an omnipresent element in business decision making. Conventional risk metrics include political, business, macroeconomic, and external risks. Environmental risk pertains to the broader long-term risks that climate change poses to international businesses. Although the term is sometimes employed for specific environmental incidents such as oil spills (Romilly, 2007), it more broadly encompasses business risks associated with climate change or fossil fuel usage (Hoffmann and Busch, 2008). This includes the risk of asset devaluation owing to the diminishing value of fossil fuel reserves arising from climatic shifts or policy tightening (Ansar, 2013). Businesses utilizing fossil fuels face risks from carbon emission policies, fluctuating energy prices, and disposal of carbon waste, which can harm their operations.

Carbon risk, proposed by Labatt and White (2007), is categorized into regulatory, physical, and business risks. Regulatory risk involves the impact of carbon-related policies on financial performance. Physical risks are direct consequences of climate change and affect industries such as agriculture and energy. Business risks include legal, reputational, and competitive risks at the company level, such as lawsuits, brand perception changes, and competitive valuations in response to climate regulations. Lash and Wellington (2007) further divide carbon risk into regulatory,

product and technology, litigation, reputation, supply chain, and physical risks. These encompass a company's ability to produce eco-friendly products, handle rising supply chain costs, and face the direct impacts of climate change. Gasbarro et al. (2017) analyzed these risks from risk and opportunity perspectives, categorizing them into regulatory change, physical change, product and technology innovation, customer demand, reputation, financial impact, and operational efficiency risks. Further details are presented in Table 1.

Table 1 Types, definitions, and cases of carbon risk

Type	Concept	Case
Regulatory risk	Risks of current or future carbon-related policy implementation. Climate policies will affect different sectors at different times and in different ways. The power sector is one of the most vulnerable to such risks, and one of the first to feel the impact of limiting greenhouse gas emissions. In this sector, a company's generation assets, installed technology, fuel mix, and market position will influence the impact of carbon constraints it will feel.	California enacted regulations requiring a 30% reduction in greenhouse gas emissions from new vehicles from 2008 through 2016 and passed legislation to reduce total emissions to 1990 levels by 2020.
Physical risk	Direct impacts of climate change, such as droughts, floods, storms, and sea level rise. Particularly affected industries include agriculture, fishing, forestry, healthcare, tourism, water, real estate, and insurance. Similar weather developments could also negatively impact carbon-regulated industries such as electricity, oil, and gas producers.	In 2002, severe flooding across Europe caused $16 billion in direct losses, and insured losses from Hurricane Katrina in 2005 were estimated at $45 billion, higher than the combined insured losses from the four hurricanes that struck the southeastern United States in 2004.
Business risk	A range of risks at the firm level include legal, reputational, and competitive risks. Legal risk arises when lawsuits are filed against companies that contribute to climate change. Reputational risk evolves as a company's pattern of response to climate change alters the perception of brand value by customers, employees, suppliers, and investors. Competition risk may evolve as the pattern of a company's response to the climate regulatory framework changes.	In 2004, eight states and New York City filed unprecedented lawsuits against five United States electric utilities to reduce their carbon dioxide emissions. In a study analyzing the impact of climate change on brand value, The Carbon Trust, an independent consulting firm funded by the British government, found that the value of company brands may be at risk in certain industries due to negative perceptions of climate change.
Supply chain risk	Risks are passed on by companies up and down the supply chain. Suppliers receive carbon risk impacts, which can lead to higher component and energy costs, and suppliers pass on increasing carbon-related costs to customers.	The automotive manufacturing industry relies heavily on suppliers of steel, aluminum, glass, rubber, and plastics, all of which can be severely impacted by emissions regulations.
Product and technology risk	The company's ability and risk to produce climate-friendly products and services and to capitalize on new market opportunities.	Integrated Gasification Combined Cycle technology, although currently more expensive than conventional methods used in coal-to-carbon plants, reduces overall carbon emissions by capturing and storing carbon dioxide at higher efficiencies, thereby reducing the overall cost of carbon emissions to the business.
Financial impact risk	Financial risk is incurred when rating agencies consider environmental and sustainability performance in their investment decisions.	Financial markets are beginning to incorporate climate change to determine risk premiums for companies, and many governments are introducing fiscal incentives to reduce greenhouse gases.
Operational efficiency risk	Climate change may adversely affect the company's operations.	Elevated water temperatures may affect the cleanliness of the utility's system (due to algae, mussels), which can affect system reliability. Companies can introduce process or energy efficiency improvements and cost savings while having the opportunity to benefit from government financial incentives.

Nguywen and Phan (2020) viewed carbon risk as a financial vulnerability in transitioning from a fossil-based economy to a low-carbon economy, using the 2005 Kyoto Protocol as a reference. Grgen et al. (2019) defined this as the impact on firm value due to the uncertain shift from a brown to a green economy. Therefore, measuring carbon risk encompasses emissions and strategic and operational risks during this transition.

Regarding "carbon risk awareness," corporate environmental awareness is seen as a multidimensional structure that includes knowledge, values, attitudes, willingness to act, and actual behavior (Zsoka, 2008). Jung et al. (2018) defined carbon risk awareness as a company's ability to proactively identify and assess the potential consequences of carbon-related issues. This awareness is crucial for effective carbon risk management and for aligning social and corporate financial objectives (Luo and Tang, 2021).

The signing of the United Nations Framework Convention on Climate Change, Kyoto Protocol, and Paris Agreement requires the parties to report the degree of independent contribution and carbon emission reduction targets, China's commitment to 2030 carbon peaking and 2060 carbon neutrality, and the parties to develop a series of energy-saving and emission reduction policies that suit their national conditions. In this context, the main reasons for the intensification of corporate carbon risk are as follows. (1) High-carbon emission enterprises will be subject to strict environmental policy restrictions on their production and operation in the context of global energy saving and emission reduction, their operating revenues will decline, and they are likely to be subject to serious regulatory risks and economic penalties. (2) Since 2011, Beijing, Tianjin, Shanghai, and other locations have conducted pilot studies on carbon emissions trading. At the end of 2017, China launched a carbon emissions trading program. On July 16, 2021, the national carbon emissions trading market opened. Enterprises wanting to realize normal production and operation in the context of increasingly severe environmental regulations can trade carbon emission rights in the carbon emissions trading market. In the case of tight carbon emissions, the price of carbon emission rights increases, and enterprises face higher carbon trading costs. (3) Carbon dioxide emissions are related to fossil fuel usage. Owing to limitations on the use of fossil energy, enterprises may be unable to fully digest the existing fossil energy inventory and suffer from the risk of a decline in fossil energy-related assets. (4) Firms engage in green technology innovation in the context of energy efficiency and emissions reduction, and fossil energy-dependent firms are more likely to face the impacts of technology risks associated with low-cost renewable energy sources (Bolton and Kacperczyk, 2021).

3 Evaluation indicators of carbon risk

Measuring the magnitude of corporate carbon risk is a complex task with no uniform method. A prevalent approach involves constructing indices using carbon emission data disclosed by companies. However, due to the limited self-disclosure of such data, scholars are increasingly utilizing alternative indicators for measurement. Some methods for measuring carbon risk indicators and the relevant literature is listed in Table 2.

Table 2 Carbon risk evaluation indicators and literature

Indicators of carbon risk	Definition	Literatures
Carbon emission	Total carbon emissions of an enterprise in a given period	Ding et al. (2023) used corporate carbon-emission data to study the impact of corporate carbon emission behavior on financial distress. The results show that the more carbon emissions, the higher the risk of financial distress.
Carbon intensity	Corporate carbon emissions/corporate sales revenue	Phan et al. (2022) used carbon emissions and carbon intensity to study the impact of carbon risk on corporate investment. Carbon risk inhibits corporate investment and reduces investment efficiency. Zhu and Hou (2022) used CEI to measure carbon risk. The study shows that carbon risk has a significant negative effect on the level of corporate dividend payment.
Carbon allowance	Price of carbon emission allowances	Oestreich and Tsiakas (2015): An empirical study using data on EU carbon emission allowances shows that firms receiving free carbon allowances will earn higher cashflows and returns and demonstrates the existence of a carbon premium in stock returns.
Sectoral carbon emissions	Carbon emissions of the industry	Wu and Tian (2022) defined carbon risk according to the carbon emissions of the issuer's industry to solve the small sample problem, the impact of carbon risk on bond financing cost is investigated, and the results show that the credit spread of high carbon risk bonds is larger and there is a carbon premium.
Textual analysis	Frequency of words related to carbon risk in corporate annual or social responsibility reports	Luo et al. (2018) used textual analysis to measure carbon risk disclosure. The study concludes that corporate carbon intensity is significantly and positively related to the degree of carbon risk disclosure.
Environmental penalties for carbon violations	Penalties for carbon emission violations and their types by companies	Zhou et al. (2018) measured carbon risk using data on firms' carbon pollution violations and corresponding penalty types.
Policy effect	Impact of carbon emission reduction related policies on enterprises	Nguyen and Phan (2020) used the Australian Kyoto Protocol as a quasi-natural experiment to measure corporate carbon risk. The results show that an increase in carbon risk reduces a firm's financial leverage.
CDP questionnaire	Score of carbon-related indicators in the questionnaire	Jung et al. (2018) used firms' willingness to respond to CDP information requests as a measure of carbon risk awareness. The study shows that carbon risk awareness can mitigate the rising cost of debt caused by carbon risk.
ESG evaluation indicators	Carbon-related indicator scores in the evaluation system	Dumrose and Hock (2023) used MSCI's ESG evaluation metrics to measure carbon risk. The study shows that carbon risk leads to higher credit spreads and that good carbon management can reduce credit spreads.

3.1 Carbon emission levels or changes in carbon emissions

Environmental regulatory policies tend to target businesses with high carbon emissions. These emission levels indicate a firm's long-term carbon exposure under the regulatory frameworks. Bolton and Kacperczyk (2023) suggest that firms with lower emissions are more likely to commit to emission reductions, whereas those with higher emissions face greater challenges in achieving net-zero targets. Bolton and Kacperczyk (2021) consider that emission changes reflect a firm's short-term carbon risk under regulations, indicating shifts in carbon risk exposure. Corporate carbon emissions are typically categorized into direct emissions from production (Scope 1); indirect emissions from energy consumption (Scope 2); and other indirect emissions related to materials, products, waste, and outsourced activities (Scope 3). Zhu and Hou (2022) highlight the importance of firm-level data for accurately assessing the impact of carbon risk on financial policies.

3.2 Carbon emission intensity

Carbon Emission Intensity (CEI) refers to the amount of carbon dioxide emissions per unit of GDP and reflects energy utilization quality and emission efficiency. It typically declines with technological progress and economic growth. Hoffmann and Busch (2008) defined it at the micro level, relating it to a company's physical carbon performance and dependency on carbon in its operations and financial budget. Absolute carbon emissions are expressed as greenhouse gas emissions, whereas relative carbon emissions are expressed as absolute carbon emissions normalized by activity measures such as revenue. Relative carbon emissions are referred to in the literature as 'carbon intensity' and have been interpreted as indicating the extent to which a company's business model is dependent on greenhouse gas emissions. Jung et al. (2018) argued that relative emissions allow for a comparison of the relative carbon performance and risk exposure of companies of different sizes and industries. On March 15, 2023, Ministry of Ecology and Environment of China used this concept to allocate carbon emission quotas, emphasizing efficiency over absolute emission reductions. Chapple et al. (2013) used corporate carbon emissions relative to sales revenue to study the capital market impact of carbon risk.

3.3 Carbon allowance

Pindyck (2008) discussed the social cost of carbon, underpinning carbon taxes or trading. Oestreich and Tsiakas (2015) argued that the price of carbon allowances reflects the damage caused by carbon dioxide emissions, with future price uncertainty increasing the carbon risk for emitting companies.

3.4 Carbon emission of the industry

Massari et al. (2016) provided the variability of carbon risk across firms and industries; industry-level data are often used when firm-level data are scarce. Delis et al. (2018) argued that carbon-intensive industries are at risk of financial and operational distress from stranded fossil fuels. Nguyen and Phan (2020) and Wu and Tian (2022) advocated this method owing to the challenges in obtaining microlevel data.

3.5 Textual analysis

In recent years, content analysis has been used in climate change research. Content analysis allows researchers to systematically sift through large amounts of data with relative ease (Affairs, 1996). This technique allows us to discover and characterize the focus of individual, group, institutional, and societal concerns (Weber, 1990). The most basic concept in text analytics is word frequency statistics, based on the assumption that the most frequently mentioned words reflect the greatest concern (Stemler, 2001). Engle et al. (2018) calculate the correlation between the monthly textual content of the Wall Street Journal and fixed climate change terms to construct an index for climate risk news innovation. Social responsibility reporting is also known as sustainability reporting and environmental reporting, and is a type of corporate non-financial reporting that originated in corporate environmental reporting. Lock and Seele (2016) found that standardization and content are the most important factors in reporting credibility, external influences are

secondary at best, and voluntary standardization positively affects the credibility of CSR reports. Hossan and Masum (2022) and Jaworska (2018) studied climate change-related issues by analyzing CSR reports and providing literature support and reference values for our study of carbon risk and how it is measured.

3.6 Environmental penalties for corporate carbon emissions violations

The most important component of the carbon risk faced by firms is regulatory risk, where governments limit corporate carbon emissions through a series of laws and regulations and impose financial penalties on firms that violate emissions. Although the impact of climate policy goes beyond direct regulatory costs, climate change regulations have the greatest impact on firms, particularly in energy-intensive industries (Kim et al., 2015). Matsumura et al. (2014) argued that the market value penalty associated with carbon emissions first reflects the relationship between the level of carbon emissions and a firm's climate change-related risk profile. This risk is determined by a combination of climate change regulations, uncertainty about new regulatory compliance, and uncertainty about physical climate parameters, such as severe weather. Neither penalties for environmental violations nor the imposition of harsher penalties were associated with improved environmental performance. In contrast, penalties for environmental violations predict further deterioration in environmental performance (Shevchenko, 2020). Therefore, we can infer that firms are exposed to higher environmental risks because of environmental administrative penalties.

3.7 Assessment of policy effects

The Kyoto Protocol is an international agreement in which participating countries commit to reducing carbon emissions to meet their national emission-reduction targets. Nguyen and Phan (2020) used a major carbon regulatory policy, the Kyoto Protocol, as an exogenous shock to the carbon risk faced by high-carbon-emitting firms. The Kyoto Protocol increases the carbon risk for firms by potentially discouraging them from engaging in carbon-intensive activities while encouraging them to voluntarily switch to cleaner technologies.

As the Chinese government strengthens carbon regulations to decarbonize the economy and promote green development, firms must urgently transform and upgrade their governance to achieve these goals (Shu et al., 2023). In addition, China's low-carbon city pilot policy is used as an exogenous shock to carbon risk to analyze the relationship between carbon policy risk and corporate capital structure. The CBRC officially released the China Green Credit Guidelines in February 2012. These guidelines require commercial banks to adequately identify and consider environmental risks when providing and denying loans to companies with substandard environmental and social performance (Zhu and Zhao, 2022). Therefore, with the implementation of policies related to carbon emission reduction, high-carbon-emitting companies will face more serious impacts, greater operational risks, and more severe regulatory risks.

3.8 CDP questionnaire

With the rapid development of low-carbon industries, the Carbon Disclosure Project (CDP) has received increasing attention and support from Chinese and global companies. The CDP is the

world's largest environmental information platform that encourages and assists companies and cities to disclose their impacts on climate change, water resources, and forests through questionnaires. The questionnaire included items on corporate governance, risk opportunities, business strategies, and goal-setting. Currently, the Climate Questionnaire has the highest number of responses, and more than 18,700 companies worldwide are expected to participate in the CDP's environmental disclosure program in FY2022. In China (including Hong Kong, Macao, and Taiwan), over 2,700 companies participate in CDP climate change-related environmental information disclosure; however, listed companies account for only 14%. Based on the Carbon Disclosure Project Climate Questionnaire of 2015, Gasbarro et al. (2017) researched and analyzed the contextual drivers of multinational enterprises' responses to climate change. Jung et al. (2018) defined carbon risk awareness as a company's ability to proactively identify the main risks posed by the carbon-related issues it faces, carefully consider their potential consequences, and measure corporate carbon risk awareness based on the CDP questionnaire. The importance of carbon risk awareness is also emphasized in the rationale of the CDP, which argues that raising corporate awareness of carbon and climate change risks through measurement and disclosure is critical (Jung et al., 2014). Firms that are aware of carbon risks are more likely to integrate these risks into a formal risk management system and address them before they become a bigger problem (Subramaniam et al., 2015). The greater the willingness to respond to CDP surveys, the greater the CDP questionnaire disclosures, and the higher the CDP program scores, the more carbon risk aware the company is, and the more likely it is to consider climate change risks in the strategies it develops, and the less carbon risk it will face in the future.

3.9 ESG evaluation indicators

In recent years, responsible investments have become standard in international capital markets. Environmental, Social & Governance (ESG) performance has also become the focus of an increasing number of domestic and foreign investors and asset management companies; the essence of ESG is to harmonize economic, social, and environmental benefits at the same time. The MSCI, S&P Dow Jones, Hang Seng, FTSE Russell, and other large financial institutions have rated the ESG performance of listed companies. The index system of the MSCI ESG rating model mainly consists of three pillars: 10 themes, 35 ESG Key Issues, and hundreds of indicators. Dumrose and Hock (2023) used three ESG rating indicators as the basis and calculated the Carbon Emissions score based on the Carbon Emissions Exposure and Carbon Emissions Management scores to comprehensively measure the company's carbon risk. Gorgen et al. (2008) selected 785 ESG variables to measure a stock's carbon risk, of which 363 were descriptive of environmental issues and 131 higher-level environmental variables were directly related to carbon and climate transition issues. In summary, the selection of an appropriate ESG evaluation system can capture issues related to carbon and climate and thus measure the carbon risk faced by companies.

4 Carbon risk of listed Chinese companies

4.1 Disclosure of carbon information in China

International research on carbon information disclosure began in the 1980s, whereas China's

research on carbon information disclosure lagged behind that of the international community by nearly 20 years. To date, research on carbon information disclosure in China has made some progress; however, it is still in its infancy. Carbon information disclosure belongs to the voluntary disclosure category. In recent years, due to the intensification of the climate crisis, the standardization of carbon information disclosure has received attention from governments and various parties. As of September 2024, over 2200 listed companies had disclosed their 2023 social responsibility reports; however, only 40% of companies had formed an ESG framework. In 2023, 3000 Chinese companies participated in the CDP projects; however, the proportion of listed companies was relatively small, and the participation rate was still relatively low compared to that of foreign companies.

On May 27, 2024, the Ministry of Finance issued the "Basic Standards for Corporate Sustainable Disclosure," gradually building a unified system of sustainable disclosure standards, and gradually transitioning from voluntary disclosure to mandatory disclosure by listed companies by 2030. This shows that China's current carbon information disclosure is still in its infancy, with relatively few mandatory disclosures and low willingness of companies to disclose. The applicability of different carbon risk measurement indicators varies because of the different types of information disclosed by enterprises. In the next section, we use data from Chinese A-share listed companies to verify the accuracy of carbon risk indicators under different conditions.

4.2 Data sources

This study utilizes data from Chinese A-share listed companies on the Shanghai and Shenzhen stock exchanges. The data were sourced from the CSMAR database, annual reports, corporate social responsibility reports, carbon disclosure projects, and Institute of Public and Environmental Affairs (IPE). The financial and insurance industries are excluded because of their unique financial statement characteristics, and stocks labeled ST or PT during the sample period are omitted. In addition, the variables were trimmed by 1% to mitigate the impact of outliers.

Based on the carbon risk evaluation index discussed earlier, carbon emissions were measured using the annual total carbon emissions of a company with data sourced from the CSMAR database and the IPE. CEI was calculated as the carbon emission level divided by business revenue, using data from the CSMAR database. Carbon emission quotas drawn from the “Implementation Plan for Setting and Allocating Total National Carbon Emission Trading Quotas for 2021 and 2022” by the Ministry of Ecology and Environment are not publicly available; hence, their applicability in this study is not discussed. Industry Carbon Emissions (ICEs) are measured using industry-level carbon emissions from the CSMAR database. Text Analysis (TA) was conducted using the frequency of carbon risk-related words in CSR reports, and the data were sourced from these reports. Carbon Emission Environmental Penalty (CEP) is evaluated based on whether a company received administrative penalties for carbon emission violations during the accounting year, using data from publicly disclosed annual reports. Policy effects (Policy) consider the impact of the Paris Agreement on carbon-intensive firms using the approach of Wang and Sun (2021) to categorize the experimental group (carbon-intensive firms) based on their industries’ carbon emissions and energy consumption levels. The CDP questionnaire analysis utilized the responses and scores of Chinese firms from the official CDP website. Finally, ESG Evaluation Indicators (ESG) employ key

environmental indicator scores from the Running Spirit Global ESG ratings in the CSMAR database.

4.3 Differences in indicators of carbon risk

Table 3 presents the Pearson correlation coefficients between carbon risk indicators. These coefficients indicate strong correlations between most indicators. The highest correlation was observed between carbon emission levels and intensity, confirming the effectiveness of these measures in assessing carbon risk. This study also categorizes business income into quintiles (20%, 40%, 60%, and 80%) and examines the correlation coefficients between carbon emission levels and intensity within these groups, as shown in Table 4. There was a positive but not significant correlation in the lowest quintile (below 20%), a high and significant correlation in the middle quintiles (20%–80%), and a weaker but still significant correlation in the highest quintile (above 80%). This suggests that the difference between carbon intensity and emission levels is more pronounced at lower business income levels.

Table 3 Correlation coefficient matrix

	CE	***CEI***	***ICE***	***TA***	***CEP***	***Policy***	***CDPR***	***CDPS***	***ESG***
CE	1								
CEI	0.761***	1							
ICE	0.457***	0.520***	1						
TA	0.118**	0.099*	0.133***	1					
CEP	0.212***	0.165**	0.099***	0.042	1				
Policy	0.369***	0.347***	0.378***	0.061***	0.161***	1			
CDPR	0.078	-0.042	-0.207***	0.010	-0.064**	-0.076***	1		
CDPS	-0.056	-0.011	0.096***	-0.099***	0.052	0.019	-0.876***	1	
ESG	0.133**	0.042	0.116***	0.434***	0.091*	0.155***	0.114***	-0.220***	1

Table 4 Matrix of correlation coefficients between carbon emission and CEI

	20%	**40%**	**60%**	**80%**	**100%**
Pearson Correlation Coefficient	0.495	0.987***	0.955***	0.984***	0.816***

To assess the company's carbon risk, ICEs were measured based on the total carbon emissions level of the industry in which a company operates. In this study, companies were classified into carbon-intensive and low-carbon-intensive group to conduct a correlation analysis. Table 5 presents the results. As Table 5 illustrates, for carbon-intensive enterprises, there is a strong and significant correlation at the 1% significance level between carbon emissions level, carbon emissions intensity, and ICEs level. Conversely, for low-carbon-intensive enterprises, the correlation between industrial carbon emission levels and other indicators is weak.

Table 5 Matrix of correlation coefficients of carbon risk indicators for carbon-intensive firms

	Carbon-intensive enterprises				Low-carbon intensive enterprises			
	CE	***CEI***	***ICE***	***CEP***	***CE***	***CEI***	***ICE***	***CEP***
CE	1				1			
CEI	0.767***	1			0.661***	1		
ICE	0.406***	0.541***	1		0.168**	0.101	1	
CEP	0.289**	0.367***	0.030	1	-0.047	-0.041	-0.006	1

This study also observed a correlation between environmental penalties for carbon emissions violations and other indicators in carbon-intensive enterprises. However, this correlation is neither direct nor significant for low-carbon-intensive enterprises. This could be attributed to the fact that high-carbon-emitting companies are more likely to be penalized for carbon emission violations by relevant authorities, whereas low-carbon-emitting companies, owing to their inherently lower emissions, have a comparatively lower likelihood of facing such penalties.

According to the "China Listed Companies ESG Action Report (2022–2023)" produced jointly by Daily Economic News and the International Research Institute of Green Finance of the Central University of Finance and Economics, there has been an increasing trend in the number of A-share listed companies publishing independent ESG or social responsibility reports. By 2022, 1,455 companies in the A-share sector disclosed such reports, resulting in a 28.65% disclosure rate. Among the 19 industries, the top 5 for ESG/social responsibility report disclosure include finance (87.50%); culture, sports, and entertainment (55.56%); mining (54.43%); electric power, heat, gas, and water production and supply (53.79%); and transportation, warehousing, and postal services (50.89%).

The 2021 A-share Listed Companies ESG Disclosure Report by the Association of Chinese Listed Companies (ACLC) indicates that although listed companies are diversifying their social responsibility disclosures, there is no unified standardization. These reports vary significantly, with most using subjective qualitative descriptions and lacking specific quantitative analyses, particularly regarding environmental content.

Given that social responsibility report disclosure is not currently mandatory and lacks standardization with significant industry differences, the method of using these reports for TA to measure carbon risk has a weak correlation with other indicators. The report also suggests that the ESG disclosure structure of A-share listed companies requires further optimization, particularly in the environmental (E) dimension, where there is a tendency for qualitative rather than quantitative disclosures. For instance, 48.46% of the companies qualitatively disclosed compliance with the three waste (wastewater, exhaust gas, and solid waste) emissions. Consequently, the correlation between the E key indicator score and other indicators in the ESG evaluation index was also weak.

This study further analyzes the correlation between the indicators in the cultural, sports, entertainment, and mining industries; the results are displayed in Table 6. Table 6 shows that the correlation among text analytics, ESG measures, and other indicators is significantly stronger in specific industries, particularly in those with a higher quality of social responsibility and ESG report disclosure.

Table 6 Matrix of correlation coefficients of carbon risk indicators by sector

	Culture, sports, and recreation industry				Mining industry			
	CE	***CEI***	***TA***	***ESG***	***CE***	***CEI***	***TA***	***ESG***
CE	1				1			
CEI	0.974***	1			0.510***	1		
TA	0.969***	0.922***	1		0.714***	0.662***	1	
ESG	0.516	0.502	0.657***	1	0.518***	0.133	0.539***	1

According to the China Corporate CDP Disclosure Report 2022, major global markets are either implementing or planning to introduce mandatory environmental information disclosure requirements, whereas China's mainland remains in a “mandatory + voluntary disclosure” phase. This difference in market policy environments results in distinct variance between the proportion of CDP disclosures by Chinese listed companies and the global average. Only 23% of Chinese companies use qualitative or quantitative climate scenario analyses to identify climate risks and opportunities. This type of analysis, which is crucial for effectively identifying and analyzing climate change risks and opportunities, involves constructing models for climate and environmental risk transfers to evaluate how these risks impact companies. However, scenario analysis presents substantial challenges in terms of data completeness, granularity, and expertise. In 2021, of the Chinese companies that responded to the CDP’s Climate Change Questionnaire, only 52 were listed. Thus, the number of Chinese listed companies independently responding to CDP questionnaires or investors’ invitations is relatively low, and their assessment methodologies require further professional enhancement. Currently, the application of the CDP questionnaire for measuring corporate carbon risk in China is not feasible, owing to its nascent stage of development and associated challenges.

5 Conclusion and recommendation

5.1 Conclusion

The world is confronting the challenge of climate change, with carbon emissions from human activities being the primary cause of global warming since the mid-twentieth century. As the largest carbon emitter globally, China faces substantial risks related to corporate carbon emissions, which significantly affect companies’ operational and financial activities. Carbon risk, a vital aspect of climate risk, typically includes regulatory, physical, and business risks along with various uncertainties in the process of corporate green transition. Currently, no uniform method exists for measuring the magnitude of corporate carbon risk. Mainstream methods measure carbon emission levels, intensity, and ICEs based on corporate emissions; textual analysis based on company reports; CDP questionnaires; ESG evaluations based on third-party organization scores; and policy effects during the transition.

Although there is some correlation among these carbon risk indicators, their applicability varies. Carbon risk intensity shows greater differentiation from other indicators for companies with lower operating incomes. Carbon-intensive enterprises are more likely to face administrative penalties owing to higher emissions, making ICE indicators and environmental penalty methods for

carbon emission violations more relevant. The current non-mandatory nature and lack of uniform standards for social responsibility and ESG report disclosures make TA using these reports ineffective for measuring carbon risk. However, in industries with higher-quality disclosures such as culture, sports, and entertainment, the relevance and applicability of TA and ESG indices improve. The participation of listed Chinese companies in the CDP questionnaire was significantly lower than that of foreign companies, rendering this method unsuitable for assessing corporate carbon risk in China.

5.2 Suggestions

Carbon disclosure in China remains underdeveloped, with only a small number of enterprises voluntarily disclosing their carbon emissions annually, and the carbon trading market is still in its early stages. Although the quality and volume of ESG report disclosures are improving annually, overall disclosure remains relatively low, with uniform standards yet to be established. The disclosed reports are mainly descriptive, lack quantitative data, and have a few negative indicators. The content varies significantly between companies, hindering horizontal comparisons. Currently, most ESG rating agencies focus only on listed companies, neglecting non-listed entities, and the ratings provided by different agencies vary greatly, failing to meet investors' needs for comprehensive market coverage (Wang and Zhang, 2022) Furthermore, the participation of listed Chinese companies in CDP disclosure is below the global average. With major global markets moving towards mandatory environmental information disclosure, China should enhance carbon disclosure awareness among market participants, bolster the carbon disclosure infrastructure, improve the ESG evaluation index system, establish unified standards, and encourage greater enterprise participation in CDP projects to align with global carbon disclosure practices.

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