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Determinants of Corporate Fossil Energy Assets Impairment and Measurement of Stranded Assets Risk

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Abstract: Climate change and transition risks have become major issues concerning the sustainable development of human society today. And the stranded fossil energy assets generated in this context are gradually becoming an important factor affecting corporate development and the stability of financial markets. Based on the data of China's A-share listed companies in the high-carbon industry from 1998 to 2021, a two-way fixed-effects model is used to study the determinants of corporate fossil energy asset impairment. Furthermore, a "two-stage estimation approach" is used to measure the risk of stranding corporate fossil energy assets The results show that: (1) climate transition risks are a significant cause of stranded corporate fossil energy assets; (2) the stranded risk of Chinese companies' fossil energy assets has been oscillating upward over the past two decades; (3) the stranded risk has increased significantly after the "double carbon" target. Based on the above conclusions, this paper puts forward relevant suggestions from both government and enterprise perspectives.

Keywords: fossil energy assets impairment; stranded assets risk measurement; high-carbon enterprises

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1. Introduction

Energy is an important cornerstone of industrial economic development. Since the reform and opening, China's economy has been developing rapidly, and the level of urbanization has continued to rise, with a concomitant increase in energy demand. In this process, the waste of energy resources and environmental pollution have become increasingly serious. The risk of stranded assets may have a short-to-medium-term impact that exceeds previous expectations, as extreme weather disasters become more frequent and market participants' understanding of climate change continues to evolve. Due to the importance of fossil energy in industrial production and economic development, a large-scale asset stranding will affect many stakeholders, including energy-consuming companies in upstream and downstream industries, financial markets, government agencies and the public [1,2]. In the proliferation of traditional fossil energy asset stranding risks, market investor expectations, financial institution support and government policy intervention all play an important role in transmission. Therefore, investor risk decision-making and corporate climate risk management will be crucial in preventing and resolving financial market risks and even systemic risks arising from stranded fossil energy assets [3–5].

Risks related to fossil energy assets have raised a wide range of concerns in the community [6,7]. On one hand, climate events triggered by carbon emissions and the corresponding transition risks from tightening environmental regulations could lead to a significant revaluation of financial assets [8–10]. On the other hand, for companies exposed to carbon risk, especially fossil fuel-intensive companies, such as those in the materials, energy or utilities sectors, future cash flows are highly volatile due to uncertainty in carbon control regulations, the company's level of policy compliance and managers' perceptions of the importance of carbon reduction [11–14]. Given the ongoing and widespread impacts of climate change, it is critical to assess the associated financial risks due to climate change.

The research contribution of this paper is that it extends the study of measuring and quantifying asset stranding risk from the perspective of individual firms. Combining the firm's micro-financial data and external macro-transformational risk factors, the asset stranding risk faced by the firm is measured and analyzed. Most of the current literature uses carbon emission data to measure stranded asset risk. However, carbon emissions reflect a firm's historical business model, from which it is difficult to distinguish the attempts and efforts made by the firm in green transformation. And there is the problem of selection bias brought about by the firm's self-reported data, as well as the inability to accurately capture the degree of asset stranding led by physical risks and alternative energy development. Therefore, this paper adopts a two-way fixed-effects model to study the determinants of corporate fossil energy asset impairment, and a "two-stage estimation approach" is used to measure the risk of stranding corporate fossil energy assets. Moreover, in terms of climate risk metrics, most of the existing literature uses direct data based on carbon emissions for metrics. In this paper, we utilize big data and text analysis methods to construct a comprehensive carbon risk index.

The remainder of the paper is organized as follows: the second part is the literature review, the third part is the characterization of stranded corporate fossil energy assets, the fourth part is the empirical analysis and the fifth part is the conclusions and countermeasure recommendations.

2. Literature Review and Research Hypotheses

Since Krause introduced the concept of "unburnable carbon," scholars have proposed the notions of "carbon bubble" and "stranded asset" based on this concept. "Stranded asset" reflects the unburnable fossil fuel assets that are caused by climate change [15–17]. At the same time, scholars have identified the policy, economic and social factors that cause stranded assets, expanding the scope of application of the concept. Concerns about stranded assets due to climate change risks originate from the evolution of the concept of "non-combustible carbon" under the carbon budget measurement framework system. Fossil fuels that cannot be burned in order to achieve a given climate goal are classed as non-combustible carbon [18–20]. The Financial Stability Oversight Council estimates that 33% of current global oil reserves, 50% of natural gas reserves and 80% of coal reserves will become unburnable carbon due to the carbon budget being constrained by climate change goals. On the other hand, the Carbon Tracker Initiative has found that in order to keep the global average temperature increase to 20 °C, around 60% of the listed companies in the period of 2000–2050 will become non-combustible. In this period, non-combustible carbon has been and will continue to be referred to as a polluting asset, an environmentally unsustainable asset or an unusable fossil fuel.

Concerns about unburnable carbon have sparked not only a divestment movement in developed countries but also a major discussion about the risks of investing in fossil fuel assets [21,22]. Investors are aware of the potential for "early obsolescence" not only of the fossil fuel-based infrastructure but also of the impaired stranding of large amounts of capital associated with fossil fuel extraction, processing, transportation and power generation. At the same time, studies have found that a high proportion (50–80%) of fossil fuel reserves will become unavailable, driven by the climate change goal of keeping the rise of the global average temperature within a certain range [23,24], and this will make companies that rely heavily on fossil fuels as a factor of production potentially overvalued, which is a phenomenon known as a "carbon bubble." The concept of a carbon bubble has increased investor awareness of the sudden shifts in the expected future prices of fossil fuels as a result of climate policy, and it could not only result in a loss of value in the fossil fuel industry market but also contribute to the instability of the financial market [25,26].

In this context, the discussion of stranded assets is gradually moving beyond "non-combustible carbon" and "carbon bubbles" to more investment and financial concepts, such as "stranded assets" and "stranded capital," and such concepts are now being used more widely. Broadly speaking, stranded assets are "assets that have suffered unexpected or premature write-downs, depreciations, or conversions to liabilities," and this is the "meta" definition of stranded assets. As research has progressed, the concept of stranded assets has been explored in more detail. In the energy context, human factors related to climate risk have become the main cause of stranded assets, and the scope of the stranded asset concept has been gradually refined to specific features, such as causes and economic consequences. Indeed, the Generation Foundation and Carbon Tracker Initiative consider stranded assets as assets with economic consequences, such as loss of economic returns and asset devaluation due to changes in regulation, markets, environmental risks, social norms and technology.

Based on the above research, this paper proposes two research hypotheses:

H1: *Climate transition risks lead to stranded corporate fossil energy assets.*

H2: *The risk of stranded corporate fossil energy assets still exists.*

3. The Characteristics of Corporate Fossil Energy Assets Stranded

Risks related to fossil energy assets have raised a wide range of concerns in the community. On the one hand, climate events triggered by carbon emissions and the corresponding physical risks and transition risks from tightening environmental regulations could lead to a significant revaluation of a company's financial assets. On the other hand, for companies exposed to carbon risk, especially companies that are fossil-fuel-intensive (such as those in the materials, energy or utilities sectors), future cash flows are extremely volatile due to uncertainty regarding carbon control regulations, the company's level of policy compliance and managers' perceptions of the importance of carbon reduction.

Given the persistent and widespread impacts of climate change, it is crucial to assess the financial risks associated with it. Climate change will undermine the stability of the financial system through two main channels: direct asset depreciation losses and indirect declines in capital gains [27–29]. Battiston further suggested two main types of climate risks: physical risks and transition risks. Of these, transition risk is considered to be the most important climate risk. Transformation risk is the financial risk arising from stranded assets due to policy changes, technological advances, shifting market preferences and changing environmental norms during the rapid transition to low carbon. Transformation risk is long-term in nature, and it typically occurs in industries with high levels of potential asset stranding, particularly in fossil energy-related industries. High-carbon intensity industries, typically fossil fuel production, metal smelting and chemicals, are highly exposed to stranded assets. Investors are therefore increasingly concerned about the measurement and disclosure of climate-related matters in corporate financial statements. Although there is no single explicit standard for climate-related matters in IFRS, climate risks and other climate-related matters may affect the fossil energy assets of many high-carbon companies through capital markets, energy supply and demand, and industrial policy regulation.

As is shown in Figure 1, climate transition risks consist of three main types: governmental environmental policies, expected changes in consumer behavior and environmental technology. From the governmental perspective, the goal is mainly to limit carbon emissions; from the technological leavening perspective, it is mainly to develop new energy sources; and from a consumer perspective, it is mainly about reducing fossil energy consumption. Ultimately, all of these contexts can lead to problems with fossil fuel demand and companies having asset stranding problems.

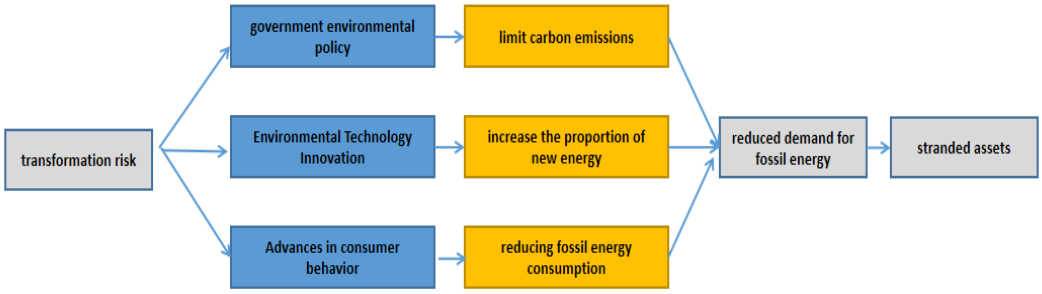

Figure 1. Pathway of stranded assets due to transition risk.

Climate-related risks can have a profound impact on the accrual of impairment losses on fossil energy assets [30]. Referring to the study of the Working Group on Climate-Related Financial Disclosures under the G20 Financial Stability Board, this paper analyzes three categories of transition risks—governmental environmental policies, expected changes in consumer behavior and expected changes in environmental technologies—under the framework of financial analysis. The specific ways in which the three types of risk affect the cash output units and the estimation of future cash flows attributable to the enterprise's assets are as follows:

(1) The impact of expected changes in consumer behavior on cash flow estimates. A firm's expectations of revenue streams and revenue growth are likely to change as a result of changes in consumer behavior preferences. If a business believes that climate-related events will affect consumer behavior, resulting in changes in the future sales volume or the sales price of its goods, it must estimate future cash flows based on its best estimate of changes in consumer behavior due to climate-related events. For example, as consumers become more environmentally conscious, there is a decreasing demand for goods that generate high-carbon emissions and an increasing demand for environmentally friendly goods, which can lead to changes in a company's projected future revenue distribution and related cash flows. In addition, a company's suppliers may make changes in their business strategies in response to changes in social expectations, which may result in changes in the company's cost-related cash outflows.

(2) The impact of anticipated changes in government actions on cash flow estimates. Companies also need to consider the cost of complying with new policies or regulations issued by the government and the growing cost of insurance when estimating future cash flows, rather than simply waiting until the relevant policies and regulations start to be implemented to include their impact in the estimation of future cash flows. As long as a company's best estimate is that a government's legislative or regulatory action will have an impact on future cash flows, the expected change should be included in the cash flow estimate, even if the exact nature or form of the government action is not yet clear.

(3) The impact of expected environmental technology innovations on cash flow estimates. As environmental technology innovation advances, the demand for fossil fuels is expected to decrease once new energy and new energy-efficiency technologies become widely used. The imbalance between supply and demand in the fossil fuel market and the decline in market prices are considered to be important indicators of asset impairment, and companies will need to reassess the future cash flows of high-carbon assets and affect the impairment of related assets when making in-use value measurements.

Accordingly, this paper analyzes the main characteristics of fossil energy assets stranded under the impact of climate risk at the corporate financial level:

(1) The valuation of fossil energy-related inventories is affected. Climate-related risks may result in the obsolescence of a company's inventory of fossil energy-related finished goods, a decrease in sales prices or an increase in the cost of completion of semi-finished goods inventory. If the cost of the inventory is not recoverable, then a provision for inventory impairment is required to write down the carrying value to its net realizable value in accordance with ASU No. 8 Impairment of Assets.

(2) Impairment charges for fossil energy-related assets are affected. According to the above-mentioned accounting standards, enterprises should assess whether an asset has an indication of impairment at the end of each reporting period, estimate its recoverable amount if there is an indication of impairment and provide for asset impairment when the recoverable amount is lower than the carrying amount. If high-carbon enterprises do not consider the impact of significant climate risks when conducting asset impairment tests, then the carrying value of many asset items may be overestimated. First, climate-related events may affect the determination of whether there is an indication of impairment of an asset, and certain climate risks are likely to indicate an indication of impairment of an asset. Second, climate-related events may affect the estimation of future cash flows from the asset or the cash-generating unit to which the asset is attributed and thus directly affect the calculation of value in the use of the asset in the recoverable amount measurement.

4. Empirical Analysis

Based on relevant studies and analyses of the impact of climate transition risk on the value of corporate assets [31–34], this paper mainly analyzes the causes and determinants of corporate fossil energy stranded asset risk and removes the confounding factors that are not related to the transition risk.

4.1. Determinants of Impairment of Corporate Fossil Energy Assets

4.1.1. Model Construction

This paper expects to strip out the risk of asset value loss due to transition risk from many risk factors and complex value transmission and identify how climate risk factors are reflected in asset value changes of high-carbon enterprises by building a fixed-effects regression model.

$$SA_{it} = \beta_0 + \beta_1 CRI_{jt} + \beta_2 \ln GDP_{jt} + \lambda \sum Controls_{it} + Ind + Year + \varepsilon_{it} \tag{1}$$

where SA_{it} is the proportion of expected asset impairment of high-carbon firm i in year t, and CRI_{jt} is the macro transition risk indicator of the provincial administrative region to which the firm belongs in period t. The indicator is based on the frequency of words about transition risk in the government work report of the provincial administrative region where the firm is located in the year (transition risk-related words as a proportion of the total words in the report) in which it was constructed [35,36].

In this paper, we need to consider expanding the word frequency statistics and constructing proxy variables for transition risk such as environmental technological innovation and social environmental norms. The textual analysis based on authoritative guiding documents such as government work reports not only includes the climate policies planned by the government but also takes into account the expectations and judgments of the market and industrial technology sectors on the future climate situation. To avoid the subjectivity and randomness of the transition risk-related terms selected in this paper, a series of low-frequency terms, such as renewable resources, mineral resources, PM2.5 and so on, are added to the original transition risk to construct the independent variable CRI2 for robustness testing.

4.1.2. Variable Selection

(1) Explained variable. SA is the percentage of impairment of total high-carbon assets. In order to obtain the impairment status of fossil energy-related assets of enterprises, this paper first cross-integrates the CSMAR database, annual reports and financial notes of enterprises; then, it screens high-carbon assets related to fossil energy based on the inventory impairment allowances and asset impairment charges disclosed by enterprises, including fixed assets, inventories, intangible assets involving high-carbon and high-energy consumption, and goodwill. The percentage of impaired high-carbon assets of the enter-

prise is obtained by dividing the sum of the net book value of high-carbon assets by linear summation:

$$SA = \frac{(stock + fa + cip + ua + ia + br)}{(STOCK + FA + CIP + UA + IA + BR)} \quad (2)$$

where stock is the ending amount of the provision for decline in value of high-carbon inventories, and STOCK is the ending amount of the net book value of high-carbon inventories of the enterprise. Similarly, fa and FA are, respectively, the end of period provision for impairment and net book value of high-carbon fixed assets; cip and CIP are the closing amounts of the provision for impairment and net book value of high-carbon construction in progress (construction materials); ua and UA are the impairment allowances and net book value of high-carbon related right-to-use assets; ia and IA are the impairment allowances for high-carbon-related intangible assets; and br and BR are the impairment allowances and net book value of goodwill of high-carbon-related enterprises at the end of the period.

(2) Explanatory variable. CRI is the transition risk index. Through the government work reports of each provincial administrative region, CRI is obtained by word separation and word frequency statistics.

(3) Control variables. They consist of a set of factors affecting the impairment of corporate assets, including macroeconomic factors, the nature of ownership, firm size, profitability, TobinQ, gearing, total asset turnover, the turnaround motive in the surplus management motive, the big wash motive, the profit smoothing motive and the management change motive. As is shown in Table 1, we have described each variable in detail.

Table 1. Description of relevant variables.

Variable Types	Variable Abbreviation	Variable Measurement
Explained variable	*SA*	See Equation (2) for details
Explanatory variables	*CRI*	Transformational risks in climate risk, mainly including government climate policies, public perceptions and innovations in environmental technologies
Control variables	ln*GDP*	Logarithmic removal of heteroskedasticity effects on GDP by region
	ln*Size*	Logarithmic removal of heteroskedasticity effects on asset totals
	State	If the company is fully privately capitalized or a foreign-controlled foreign enterprise, it is equal to 1; and otherwise it is 0
	Roa	Ratio of net profit to total assets at the end of the period
	TobinQ	Ratio of enterprise market capitalization to total assets
	Lev	total liabilities to total assets
	Turnover	Ratio of net sales to total assets at the end of the period
	Losses	If the company had a loss in the previous year and is profitable in the current year, it is equal to 1; otherwise, it is 0
	Bath	When the difference between the listed company's operating profit before impairment in the year of impairment and the operating profit before impairment in the previous year divided by the value of total assets at the beginning of the year is less than the median of all negative values of the variable, the value of Bath takes 1; otherwise, it is zero
	Smooth	When the difference between the listed company's pre-impairment operating profit in the year of impairment and the previous year's pre-impairment operating profit divided by the value of total assets at he beginning of the year is higher than the median of all the positive values of the variable, it is considered that the listed company has an incentive to smooth earnings, and Smooth is taken to be 1. Otherwise, it is taken to be 0

4.1.3. Samples and Data

This paper uses the balanced panel data of Chinese A-share listed companies from 1998 to 2021 as the initial sample. Six high-energy-consuming and high-emission industries related to the upstream and downstream of fossil fuel extraction, processing and power generation were identified: (1) petroleum, coal and other fuel processing industries; (2) chemical raw material and chemical product manufacturing industries; (3) non-metallic mineral product industries; (4) ferrous metal smelting and rolling processing industries; (5) non-ferrous metal smelting and rolling processing industries; (6) electricity, heat, and gas and water production and supply industry (National Economic Classification; major category). The missing data were excluded, and the effect of extreme values and outliers was eliminated using the upper and lower 1% tailing process; the final total sample size was 15,279.

The main sources of corporate-level data in this paper are shown below: (a) company asset impairment data come from the CSMAR database, annual reports, notes to financial statements, audit reports and social responsibility reports disclosed by listed companies in Shanghai and Shenzhen; (b) data on other company characteristics come from Tianyan search corporate credit reports, the CSMAR database and company annual reports. The macroeconomic data GDP is obtained from the statistical yearbooks of 30 provincial-level administrative regions in China (excluding Hong Kong, Macao, Taiwan and Tibet), which are more comprehensive and reliable. The data processing of this paper was performed by Stata16.0 and Anaconda software 3 4.4.0.

4.1.4. Descriptive Statistics

Before the statistical test, this paper conducts descriptive statistics on each regression variable. As is shown in Table 2, the mean value of enterprise fossil energy asset impairment ratio is 0.041; the standard deviation is 0.049; the minimum value is −0.260 and the maximum value is 0.935. This indicates that there is a certain degree of high-carbon asset impairment risk in stone energy enterprises in general, while the data still have a large extreme value. The risk of high-carbon asset impairment is still high and may be caused by some enterprises that are about to be delisted or face bankruptcy and liquidation. The mean and standard deviation and extreme values of the transition risk factors CRI1 and CRI2 indicate that the range of data fluctuation is relatively small during the sample period, and the overall climate transition risk is relatively stable.

Table 2. Descriptive statistics of variables.

Variables	Obs	Mean	SD	Mix	Max
SA	15,279	0.041	0.049	−0.260	0.935
CRI1	15,279	0.014	0.004	0.000	0.029
CRI2	15,279	0.015	0.005	0.002	0.033
lnGDP	15,279	10.007	1.125	4.516	11.731
State	15,279	0.475	0.499	0.000	1.000
lnSize	15,279	22.211	1.384	14.937	28.636
Roa	15,185	0.043	0.133	−4.161	7.445
Lev	15,279	0.476	0.363	0.000	16.329
Turnover	15,279	0.279	0.359	0.000	4.441
TobinQ	15,279	1.782	1.871	0.684	122.190
Losses	15,279	0.162	0.368	0.000	1.000
Bath	15,279	0.380	0.485	0.000	1.000
Smooth	15,279	0.508	0.500	0.000	1.000

4.1.5. Correlation Analysis

Correlation analysis is a statistical method that does not consider the causal relationship between variables but only studies the direction of correlation and the degree of correlation between the analyzed variables. In order to determine whether the respective variables in the aforementioned model are significantly correlated with asset impairment of high-carbon enterprises, this paper analyzed their correlation using Pearson test, and the results are shown in Table 3.

Table 3. Correlation results.

	SA	*CRI1*	*CRI2*	*lnGDP*	*State*	*lnSize*	*Roa*	*Lev*	*Turnover*	*TobinQ*	*Losses*	*Bath*	*Smooth*
SA	1												
CRI1	0.056	1											
	(0.000)												
CRI2	0.056	0.999	1										
	(0.000)	(0.000)											
lnGDP	0.019	0.506	0.503	1									
	(0.022)	(0.000)	(0.000)										
State	0.070	−0.221	−0.221	−0.408	1								
	(0.000)	(0.000)	(0.000)	(0.000)									
lnSize	0.264	0.218	0.218	0.168	0.155	1							
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)								
Roa	−0.087	0.021	0.021	0.040	−0.047	0.061	1						
	(0.000)	(0.010)	(0.009)	(0.000)	(0.000)	(0.000)							
Lev	0.068	−0.031	−0.032	−0.073	0.157	0.107	−0.387	1					
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)						
Turnover	−0.036	0.005	0.005	0.051	−0.222	0.135	0.123	−0.009	1				
	(0.000)	(0.525)	(0.532)	(0.000)	(0.000)	(0.000)	(0.000)	(0.269)					
TobinQ	−0.028	0.059	0.060	0.063	−0.023	−0.253	−0.023	0.048	−0.057	1			
	(0.001)	(0.000)	(0.000)	(0.000)	(0.005)	(0.000)	(0.004)	(0.000)	(0.000)				
Losses	−0.038	0.048	0.047	0.063	−0.242	0.207	0.084	0.037	0.654	−0.059	1		
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)			
Bath	0.005	0.127	0.127	0.224	−0.237	0.196	0.040	−0.025	0.322	−0.031	0.461	1	
	(0.553)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.000)		
Smooth	−0.044	0.044	0.044	0.093	−0.244	0.025	0.065	−0.038	0.245	0.030	0.390	0.271	1
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	

Note: The *p*-value corresponding to the correlation coefficient test is shown in parentheses.

As can be seen from Table 3, there is a highly significant positive correlation between the expected percentage of impairment (SA) of corporate fossil energy-related assets and the transition risk (CRI) at the 1% level, which indicates that the percentage of impairment of corporate fossil energy assets is strongly influenced by climate risk factors, i.e., the higher the climate risk is, the higher the percentage of impairment of corporate fossil energy assets is. This is consistent with the general concern and scientific proof of climate change in modern society.

In terms of macroeconomic factors, SA is significantly and positively correlated with lnGDP at the 5% level, indicating that the more developed the economy is, the greater the risk that fossil energy companies may face in terms of market competition and policy pressure is, which will lead to an increase in their asset impairment risk.

Regarding the firm-level control variables, first, SA is significantly and positively correlated with the state at the 1% level, suggesting that state-owned fossil energy firms may have differences related to their business practices, management systems and risk control mechanisms compared to private firms, leading them to be more likely to face asset impairment problems. In addition, state-owned fossil energy enterprises are more influenced by policies and regulations, which may also lead to higher asset impairment. SA has a significant positive relationship with lnSize at the 1% level, which implies that the increase in the size of fossil energy enterprises may bring more environmental and social responsibility risks, such as large-scale carbon emissions and resource consumption, and this may increase the impairment of enterprise assets. SA has a significant positive relationship with indicators reflecting corporate performance and is significantly negatively correlated at the 1% level, which indicates that the percentage of fossil energy asset impairment is closely related to corporate performance, i.e., the worse the corporate performance is, the higher the percentage of fossil energy asset impairment is. This may be due to the fact that firms with poor performance have more difficulty maintaining the value of their fossil energy assets and that they are more vulnerable to industry competition and market risks. SA is significantly and positively correlated with Lev, an indicator reflecting firms' solvency, at the 1% level, which indicates that the higher the firm's overall leverage and the poorer its solvency are, the higher the firm's asset impairment expectation is; this is probably due to the fact that firms with weaker solvency are usually exposed to debt stress and liquidity risk, thus putting their assets at an increased risk of impairment. For firm operating capacity, its correlation coefficient with SA is significantly negative at the 1% level. This relationship may reflect the fact that firms with a high turnover are more able to manage their assets effectively and avoid tying up excessive resources over time while also being able to update their technology and equipment in a timely manner to adapt to market changes and improve efficiency. As a result, these firms are more likely to reduce their reliance on fossil fuels and lower their carbon emissions. There is a significant negative relationship between the Tobin's Q of fossil energy companies and their asset impairment ratios at the 1% level, suggesting that fossil energy companies that fail to effectively manage their asset and liability structures or lock their assets into specific business areas over time may end up with higher asset impairment ratios.

For each of the three surplus management motives, the motives of loss reversal and profit smoothing are significantly negative at the 1% level, indicating that they may reduce their asset impairment charges through management adjustments or accounting treatments when companies attempt to take measures to improve their financial position and either turn a loss into a profit or else smooth their profits. In contrast, there is no significant linear correlation between the "clean-up" management motive and the stranded assets.

4.1.6. Regression Results

To reveal the effect of the core explanatory variable CRI on the impairment of corporate fossil energy assets under a multivariate combination, this paper investigates the model using fixed effects based on corporate panel data and controlling for the effects of industry fixed effects and time fixed effects.

As per the regression results shown in Table 4, this paper focuses on the impact of transition risk on the impairment of corporate fossil energy assets. It was found that the regression coefficients of CRI1 and CRI2 on SA are both significantly positive at the 1% level, and when the transition risk factor increases, the expected impairment of fossil energy assets will also increase. In other words, under the combined effect of governmental climate action, public environmental awareness and technological changes on environmental protection, high-carbon companies will expect depreciation in the value of fossil energy-related assets, impairment of future cash flows and an increase in the proportion of corresponding asset impairment.

To avoid potential endogeneity and reverse causality problems, the first-order lagged terms of CRI1 and CRI2 are introduced as explanatory variables. The regression coefficients of $CRI1_{t-1}$ and $CRI2_{t-1}$ on SA are both significantly positive at the 1% level, which is more consistent with the results of original model. It is noteworthy that the regression coefficients of $CRI1_{t-1}$ and $CRI2_{t-1}$ on SA are larger compared to those of CRI1 and CRI2 on SA, which implies that there may be some lags in firms' perceptions and decisions on external transition risks, and this is also consistent with the empirical fact of risk information transmission.

In fact, since the transition risk in climate risk is determined by a combination of environmental policy factors external to the enterprise, public perceptions in society and industrial technology factors, and since it is also not related to the internal decisions and the management of individual fossil energy enterprises, the transition risk can be considered exogenous. In addition, individual fossil energy companies' impairment decisions and risk management are unlikely to affect the changes in overall climate factors in the short term, and there is thus no theoretical issue of reverse causality.

Transition risk has become an important economic and social risk for fossil energy companies that can materially damage the value of their assets. It also demonstrates the need for fossil energy companies to focus more on environmental sustainability issues to take measures to mitigate the impact of transition risks on their business operations and financial position, as well as to reduce the risk of the impairment of fossil energy assets through corresponding risk management measures. These measures center on reducing dependence on fossil energy, increasing investments in renewable energy and other clean technologies, and developing appropriate adaptive strategies. In addition, the regression results also suggest that investors and stakeholders need to pay more attention to corporate as well as environmental, social and governance (ESG), as climate change is a global, cross-sectoral challenge, and corporate climate risk management capabilities will play an important role in future market competition.

Table 4. Regression results.

	(1) *SA*	(2) *SA*	(3) *SA*	(4) *SA*
CRI1	69.606 ***			
	(23.553)			
CRI2		64.557 ***		
		(21.945)		
$CRI1_{t-1}$			91.300 ***	
			(20.366)	
$CRI2_{t-1}$				95.179 ***
				(21.456)
Roa	−2.186 **	−2.186 **	−2.177 **	−2.178 **
	(0.936)	(0.936)	(0.936)	(0.935)
Lev	0.996 ***	0.997 ***	0.999 ***	1.000 ***
	(0.355)	(0.355)	(0.355)	(0.355)
Turnover	0.354 *	0.355 *	0.341 *	0.346 *
	(0.181)	(0.181)	(0.180)	(0.180)
State	0.961 ***	0.961 ***	0.965 ***	0.967 ***
	(0.122)	(0.122)	(0.122)	(0.123)
Losses	−0.147	−0.148	−0.151	−0.159
	(0.224)	(0.224)	(0.224)	(0.224)
Bath	−0.134	−0.134	−0.140	−0.139
	(0.213)	(0.213)	(0.213)	(0.213)
Smooth	−0.648 ***	−0.647 ***	−0.643 ***	−0.641 ***
	(0.146)	(0.146)	(0.146)	(0.146)
TobinQ	−0.143 ***	−0.143 ***	−0.144 ***	−0.144 ***
	(0.045)	(0.045)	(0.045)	(0.045)
Constant	4.823 ***	4.783 ***	4.784 ***	4.526 ***
	(1.033)	(1.032)	(1.003)	(0.971)
Industry fixed effects	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes
N	15,279	15,279	15,279	15,279
R^2	0.249	0.243	0.258	0.252

Note: Robustness standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.2. Measurement and Analysis of Stranded Risk of Corporate Fossil Energy Assets

Based on the analysis of the determinants of fossil energy asset impairment, it can be seen that the impairment testing and impairment strategy of enterprises for high-carbon assets are not only attributed to the transition risk, but also other macroeconomic, market factors and enterprises' own operations. In this paper, we focus most on the impairment of fossil energy assets due to the transition risk, so we need to divorce the effect of the transition risk on the impairment of high-carbon assets from many factors.

This paper draws on the "two-stage approach". Combined with the previous definition of stranded risk of fossil energy assets, this paper uses the depreciation of assets due to transition risk as a measure of stranded risk of high-carbon assets. Specifically, the estimated coefficient α of transition risk in the regression results of Equation (1) measures the stranded risk of fossil energy assets faced by the firm in the current period, involving the following equation (Equation (3)):

$$SR_i = \beta_1 \times \frac{\Delta CRI_{i,(t,t-1)}}{CRI_{i,t-1}} \times SA \tag{3}$$

where SR_i denotes the stranded risk of fossil energy assets faced by enterprises in the current period; β_1 is the estimated coefficient of transition risk in the regression results of Equation (2) and SA is the proportion of high-carbon assets impaired by enterprises.

Table 5 illustrates the time trends of the impairment ratio (SA) and stranded risk (SR) of corporate fossil energy assets, and it can be seen that there is an overall upward trend of the impairment ratio (SA) of corporate fossil energy assets from 3.09% to 5.93%, with an overall increase of 52.05% during the sample period, which shows that the global energy market and economic environment has changed dramatically. The overall domestic situation is relatively stable, but the supply and demand in the Chinese energy market is still subject to continuous impact and influence, which may lead to damage of the value of enterprises' fossil energy assets. In addition, as international and domestic issues such as environmental protection and energy transition continue to heat up, they can also have an impact on the fossil energy market and devalue corporate fossil energy assets.

Table 5. Corporate fossil energy asset impairment (SA) ratio and stranded risk (SR) time trend.

Year	***1998***	***1999***	***2000***	***2001***	***2002***	***2003***	***2004***	***2005***	***2006***	***2007***	***2008***	***2009***
SA (%)	3.09	3.06	3.71	4.77	3.88	4.51	3.52	5.03	4.21	4.38	4.80	3.44
SR (%)	1.00	1.77	2.21	4.29	2.14	3.64	0.56	5.62	5.86	4.9	9.46	−0.12
Year	***2010***	***2011***	***2012***	***2013***	***2014***	***2015***	***2016***	***2017***	***2018***	***2019***	***2020***	***2021***
SA (%)	3.68	3.73	3.67	3.84	3.85	3.96	4.40	3.88	4.38	4.39	4.57	5.93
SR (%)	2.62	2.82	1.05	7.93	8.09	3.22	9.24	4.95	5.31	9.38	5.38	19.88

The risk of stranded fossil energy assets (SR) is more volatile, oscillating from 1% in 2008 to 19.88% in 2021. Whereas stranded assets are an unavoidable business risk in economic development, it was only around the year 2000 that people gradually realized that environmental factors such as climate change and the different attitudes of governments and society toward the consequences of climate change could also lead to stranded assets. Against the backdrop of an international consensus to address climate change and a clear goal of carbon neutrality set by each country, the issue of climate-related stranded assets is gaining attention from financial and governmental organizations.

Stage 1: 1998–2004. Since the 21st century, as China's economic development has continued to grow, people have become increasingly aware of the importance of environmental protection and have attached great importance to a series of environmental problems caused by climate change. During this period, energy companies have made great efforts to improve the efficiency of resource utilization, and the risk of stranded assets has continued to decrease.

Stage 2: 2005–2008. A series of eco-environmental and atmospheric governance policies enacted by the central government and responded to by local governments have led to a surge in China's short-term climate constraints, and the financial crisis of 2008 hit small and medium-sized enterprises (SMEs) hard, with a heightened risk of stranded fossil energy assets.

Stage 3: 2009–2020. In 2010, China introduced the Action Plan for Prevention and Control of Air Pollution to address air pollution in general by improving the comprehensive treatment of pollution sources, adjusting and optimizing the industrial structure, accelerating the green technological transformation of enterprises and increasing the supply of clean energy. In 2014, plummeting international energy prices and a vocal fossil energy divestment campaign abroad similarly drove down domestic fossil energy assets and the risk of stranding rose. At the end of 2020, China announced that it would strive to achieve "carbon peak" by 2030 and "carbon neutrality" by 2060, posing new requirements and challenges for promoting the energy revolution in the new era, leading to a significant increase in the risk of stranded fossil energy assets of Chinese companies.

Stage 4: 2021–present. In 2021, the official opening of China's carbon trading market will create a forcing mechanism for the energy business sector, increasing the risk of stranded assets.

Overall, the risk of stranded fossil energy assets fluctuates with the introduction of environmental policies and changes in the climate risk expectations of energy companies, market investors and the public. And there is a phenomenon of a "pullback" in the expectation of stranded asset risk. To some extent, it demonstrates the sensitivity of the public and the market and confirms that there is a lagging effect in the actual policy effects of some of the environmental policies and an overreaction of the relevant markets in the short term.

5. Conclusions and Policy Implications

Based on the data of China's A-share listed companies in the high-carbon industry from 1998 to 2021, we use a two-way fixed-effects model and a "two-stage estimation approach" to study the determinants of corporate fossil energy asset impairment and measure the stranded asset risk. We have come to some conclusions.

First, in the context of climate change, the key determinants of stranded corporate fossil energy assets are transition risks arising from government environmental policies, environmental technology innovations and social norms, which have a significant impact on corporate asset values and cash flow estimates; second, in the past two decades, with the increasing environmental awareness of the community, clean energy development and climate policies, the stranded risk of corporate fossil energy assets has shown an oscillating upward trend and a significant increase after the double carbon target; third, the risk of stranded corporate fossil energy assets will show signs of "pullback" after a "big year" for climate change, reflecting over-interpretation and expected adjustments by capital markets and companies to policy changes, environmental campaigns or clean technology trends.

Based on the above conclusions, some policy suggestions have been proposed from both government and enterprise perspectives.

As for government, first, a third-party forensic system should be introduced. An oversight mechanism for climate risk disclosure centered on investor needs should be established as soon as possible. Second, the government should broaden the financing channels of fossil energy enterprises and promote green financial innovation and market standardization. Finally, governments should provide businesses with effective tools to scientifically identify climate risks and systematically disclose them to stakeholders. For example, they should prioritize the different types of risks to improve efficiency, analyze the likelihood of climate risks occurring and the severity of their impact on business operations, and derive risk assessment results, which will provide an important basis for investors in the capital market to assess the risks of corporate transformation, organizational leadership and low-carbon transformation practices, and ultimately form a scientific and efficient climate risk pricing system in the financial market.

As for enterprises, first of all, they should coordinate their future production and operation plans, and the decision-making level of enterprises should form an integrated construction of climate policy interpretation, exit strategy for high-carbon assets, trading of high-carbon assets, related financial and tax management, legal compliance and information system. Subordinate departments strictly implement GHG monitoring, reporting, verification and GHG emission reduction and compliance in the region where the enterprise is located. Moreover, traditional fossil energy companies should actively advance investments in low-carbon assets. At last, enterprises should consider the asset recovery value from the perspective of the full life cycle of assets. For new technologies and new projects requiring large-scale investment, it is necessary to adopt multi-level investment methods such as pilots, pilot tests, etc., and to scientifically assess the R&D cycle of new technologies and new products, the speed of iteration and the timing of market entry, so as to guard against the potential risk of impairment that exists in the rapid iteration of technologies and to avoid stranding of R&D assets brought about by the unprofitable large-scale R&D investment in the early stage.

There are also shortcomings in this paper. China has a large number of enterprises directly or indirectly owning fossil energy-related assets, and this paper selected A-share listed companies in the fossil energy sector as the main object of analysis, whose financial indicators and operation and management data are public and reliable. However, large-scale enterprises with stranded assets and overcapacity in the relevant industries are not listed due to management and profitability issues, and their relevant data are not publicly disclosed. As a result, this paper is missing part of the valuable data information.

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