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Article

Technological innovation, financing constraints, and carbon reduction in energy companies—From the perspective of the corporate lifecycle

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Abstract: From the perspective of the corporate life cycle, this study investigates the transmission mechanism of 'technological innovation-financing constraints-carbon emission reduction' in energy companies using panel data and mediating models, focusing on listed energy companies from 2014 to 2020. It explores the stage characteristics of this mechanism during different life cycle phases and conducts heterogeneity tests across industries and regions. The results reveal that technological innovation positively influences carbon emission reduction in energy enterprises, demonstrating significant life cycle stage characteristics, specifically more pronounced in mature companies than in growing or declining companies. Financing constraints play a mediating role between technological innovation and carbon reduction, but this is only effective during the growth and maturity stages. Further research shows that the impact of technological innovation on carbon emission reduction and the mediating role of financing constraints exhibit heterogeneity across different stages of the life cycle, industries, and regions. The conclusions of this paper provide references for energy companies in planning rational emission reduction strategies and for government departments in policy-making.

Keywords: technological innovation; financing constraints; carbon emission reduction in energy enterprises; corporate life cycle

1. Introduction

In recent years, the greenhouse effect has led to a continuous rise in global temperatures, and the issue of climate change caused by excessive emissions of greenhouse gases, primarily CO_2, has increasingly garnered international attention. Addressing how to manage the environment and reduce and control the chain reaction caused by CO_2 emissions has become an urgent topic in global politics, energy, and environmental fields. China, being the largest emitter of CO_2 globally and one of the countries with high average energy consumption, has set ambitious goals to achieve peak carbon by 2030 and carbon neutrality by 2060. The realization of these 'dual carbon' goals is a challenging and long journey, requiring joint efforts from the government, public organizations, private sectors, individuals, and society as a whole. Currently, as China's industrialization is still in a key stage, and energy is a pillar of China's high-quality economic development, energy enterprises continue to play a significant role in the sustainable development of the national economy. Therefore, how to promote carbon emission reduction in energy enterprises has become a worthy research question. Numerous studies indicate that enhancing technological innovation capacity is key to addressing this issue. The systematic study of the relationship between technological innovation and carbon emission reduction largely originates from the view proposed by Poter that environmental regulation will promote technological innovation, thereby achieving a win-win situation for economic development and emission reduction. Many domestic and international scholars have focused on the impact of technological innovation on carbon reduction and conducted in-depth research, with varying conclusions. Some research results show that technological innovation has a positive effect on CO_2 emission reduction. Ooba et al. found that technological innovation can reduce corporate carbon footprints by improving energy utilization efficiency. Gu et al. (2022) believe that technological innovation can indirectly drive carbon reduction by reducing energy consumption and optimizing the energy consumption structure. Yin et al. (2020) argue that low-carbon technology promotes carbon reduction by reducing carbon intensity and energy usage intensity. However, other studies indicate that the role of technological innovation in carbon reduction has not been fully utilized and may even lead to an increase in carbon emissions. For example, Zhao et al. (2024) believe that technological progress does not have a significant effect on carbon reduction; Zhang and Xu (2013) think that the direction of the impact of technological progress on carbon emissions is uncertain. Other studies emphasize the negative externalities of technological innovation on the environment. Jaffe et al.(2002) believe that technological innovation increases carbon emissions through scale effects. Berkhout et al. (2020) analyzed that technological innovation has a bidirectional impact on carbon emissions, known as the ‘energy rebound’ effect, which was confirmed by Zhou and Lin (2007) using Chinese data samples.

In exploring the factors influencing corporate carbon emission reduction, apart from the use of high-emission energy, the financing constraints faced by enterprises themselves have also become one of the important reasons for the lack of enthusiasm in carbon emission reduction. High-quality technology can alleviate financing constraints to some extent. Corporate technological innovation is often manifested in the form of patents, with the number of patent grants and patent citations being important indicators of corporate technological innovation levels. Therefore, most research on the relationship between technological innovation and corporate financing focuses on the perspective of patents. Haeussler et al.’s (2014) study shows that the number of patents and patent citations increase the likelihood of obtaining venture capital; Meng and Li (2019) believe that patents have a significant financing signaling function, and patent quality has a significant impact on attracting venture capital; Zheng and Jia (2018), through their research on the relationship between corporate patents and external financing, also concluded that patent activities send positive signals to investors.

From current research, it can be seen that first, the impact of technological innovation on carbon reduction has not yet reached a consensus, and existing studies mostly analyze from a macro perspective. The effect and mechanism of technological innovation on micro-subjects’ carbon reduction still need further confirmation; second, the mechanism of action revealed by relevant studies shows that technological innovation can promote carbon reduction by improving energy utilization rates and optimizing energy consumption structures, but it overlooks the research on the path of technological innovation promoting carbon reduction by alleviating financing constraints, while the financing signaling function of technological innovation has been confirmed; third, most existing research places enterprises under the same cross-sectional stage without considering the stage characteristics of different life cycle developments. Based on this, the marginal contribution of this paper lies in, by empirical testing, it answers the following questions: At each stage of the enterprise life cycle, how does technological innovation affect carbon emission reduction in energy enterprises? Will technological innovation promote carbon emission reduction in energy enterprises by alleviating financing constraints? Is there a difference in the role played at different stages of the enterprise life cycle? The answers to these questions are beneficial for objectively evaluating the carbon reduction effect and path of corporate technological innovation at different life cycle stages, providing references for enterprises to plan emission reduction strategies and for government departments to make decisions.

2. Theoretical analysis and research hypothesis

2.1. Technological innovation, lifecycle, and carbon emission reduction in energy enterprises

Energy enterprises, primarily engaged in energy development, processing and conversion, storage, transportation, distribution, trade, and services, produce a significant amount of carbon emissions in every operational process. Technological innovation is a necessary factor for reducing carbon emissions in energy companies and is fundamental to achieving their green and low-carbon transformation goals. For traditional energy companies, reducing carbon emissions through low-carbon technology to transition from high to low carbon emission rates alleviates the ecological pressure from energy development and utilization. Technological innovation is the driving force behind low-carbon development in energy companies and helps promote carbon emission reduction. Specifically, technological innovation improves production technology and processes, enhancing production capacity, thereby increasing energy efficiency and reducing energy consumption and carbon emissions during production. Enhancing low-carbon technological innovation capabilities will shift the profit growth mode of high energy consumption and emissions towards cleaner and low-carbon production.

From the perspective of the corporate life cycle, companies at different stages exhibit significant differences in technological innovation capabilities and environmental and resource endowments. Based on Dickinson’s research, this paper divides the corporate life cycle into three stages: growth, maturity, and decline. Companies in the growth stage, being in a phase of rapid development, inevitably require technological innovation. At this stage, companies gradually clarify their technological innovation strategies and can carry out planned independent innovation activities. However, growth at this stage relies largely on leadership, product marketing, and business expansion rather than on technological innovation. Therefore, technological innovation is used mainly to improve energy efficiency and production capacity, with carbon reduction being a secondary economic outcome. In contrast, companies entering the maturity stage, with accumulated experience in innovation, possess high-quality innovative technical talents and more diversified information access channels, significantly enhancing their innovation capabilities and reducing the risks associated with technological innovation. At this stage, companies focus more on developing low-carbon technology to avoid environmental regulations, cultivate environmentally friendly corporate images, and promote sustainable development. Mature companies have more advantages in technological innovation than growing companies, and the positive impact of technological innovation on carbon reduction is more significant. In contrast, companies in the decline stage often face declining profits or even losses, almost stagnant business development, increased business risks, and limited internal and external financing channels, leading to tighter R&D funds. Organizational structures become rigid, responses to market changes are slow, and innovation consciousness is lacking. Despite having accumulated significant innovation experience earlier, companies in decline struggle to update equipment and modify process technology due to internal funding shortages and governance structure issues, leading to inefficient technological innovation. Thus, the impact of innovation activities on carbon reduction is minimal during the decline stage.

Based on the above analysis, hypothesis H1a is proposed: Technological innovation can promote carbon emission reduction in energy enterprises. H1b: The promoting effect of technological innovation on carbon emission reduction in energy enterprises is significantly influenced by the stage of the corporate life cycle, manifesting as mature companies > growing companies > declining companies.

2.2. The mediating effect of financing constraints

When companies obtain sufficient capital investment and alleviate financing constraints through the financing signaling function of technological innovation, the risks and costs associated with environmental investment decrease. In this scenario, compared to reducing production, companies can derive more benefits from pollution control, such as reducing high taxes due to high emissions through carbon reduction technology. Therefore, companies reduce emissions through environmental investment and pollution control, significantly lowering their emission intensity. Conversely, when companies face strict financing constraints, those with high financing constraints lack the motivation for long-term investment. This is due to the separation of ownership and management rights in companies; under severe financing constraints, trustees are prone to moral hazards of agency, often choosing short-term profits over environmental protection. Thus, they tend to adopt low-cost production methods and try to avoid additional costs from pollution control, thereby increasing the company's carbon emissions.

From the perspective of the corporate life cycle, companies at different stages have significantly different investment strategies due to their stage-specific strategic objectives and primary challenges. These strategies directly impact the intensity of the company's carbon emission reduction. Companies in the growth stage, with gradually improving innovation capabilities accompanying their growth, face reduced investment risks. However, at this stage, corporate fundraising is primarily for expanding production scale and achieving reproduction, with a large amount of capital being used for purchasing production equipment and raw materials, as well as factory expansion. Companies focus more on short-term economic benefits, limiting their investment in carbon reduction projects. Mature-stage companies, with large internal cash flows and easier access to external financing, tend to invest funds in green and low-carbon projects supported by national policies to bring long-term benefits and establish a good corporate image. Additionally, mature companies, having reached a certain scale with peak carbon emissions, are more likely to trigger government environmental regulation policies. To avoid government environmental penalties or taxes, compared to reducing production scale, companies are more inclined to allocate more funds to pollution treatment and low-carbon technology R&D, thereby promoting corporate carbon emission reduction. Companies in the decline stage, primarily aiming to quickly overcome barriers to decline and successfully transition, lack spare funds to invest in low-carbon projects, which require large investments, have slow effects, and carry high risks. Additionally, due to insufficient innovation capabilities and significant talent loss at this stage, financing constraints cannot play a mediating role.

Accordingly, hypothesis H3a is proposed: Financing constraints are a mediating variable between technological innovation and carbon emission reduction in energy enterprises, meaning that technological innovation can promote carbon emission reduction in energy enterprises by alleviating financing constraints. H3b: The mediating effect of financing constraints exhibits certain stage characteristics, manifesting as mature companies > growing companies, with the intermediary mechanism being ineffective in declining companies.

2.3. Technological innovation, lifecycle, and financing constraints

In imperfectly competitive markets, asymmetric information is a primary factor for enterprises facing financing constraints, significantly influencing investor behavior. A company’s technological and innovative capabilities are key indicators of core competitiveness and sustainable development, influencing investor investment decisions. The signal transmitted by technological innovation is positive: it implies improved production technology and iterations of green products. In the future, companies can gain advantages in production efficiency and costs with environmentally friendly products, enhancing market competitiveness. Hence, the implementation of technological innovation can convey a signal of promising development prospects, policy alignment, and low investment risks, making these companies more appealing to investors, leading to higher investment valuations and expectations, thereby alleviating financing constraints for the enterprise.

From the perspective of the corporate life cycle, companies at different stages exhibit significant differences in financing channels, the degree of financing constraints, and corporate credibility. Accordingly, the financing signaling function of corporate technological innovation also shows clear stage characteristics. In the growth stage, to maintain high-speed growth in corporate benefits, companies need to purchase large amounts of high-end equipment and raw materials, leading to strong capital demands. However, the overall situation of bank loans to these companies is not optimistic due to the limited financing function of technological innovation at this stage, as the level of technological innovation is relatively low and the number of patents meeting bank collateral standards is few and of low quality. Thus, technological innovation in growth-stage companies can play a certain role in financing. In contrast, mature-stage companies, with more stable and abundant funding sources, face less uncertainty in innovation activities than other life cycle companies. The innovation strength of these companies is stronger, reducing the risk expectations of external investors regarding R&D and innovation activities, making it easier to realize the financing signaling function of technological innovation. Therefore, mature-stage companies can exert a greater financing effect through technological innovation. In comparison, declining companies facing severe deterioration in business performance, outdated technology, low utilization efficiency, and greater risks in R&D face reduced trust from investors, making it difficult to fulfill the financing signaling function of technological innovation.

Based on the above analysis, hypothesis H2a is proposed: Technological innovation can alleviate financing constraints in enterprises. H2b: The mitigating effect of technological innovation on financing constraints is significantly influenced by the stage of the corporate life cycle, manifesting as mature companies > growing companies, with declining companies unable to play a role.

3. Results and discussion

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Variable description

3.1.1. Dependent variable

The dependent variable is Carbon Emission (CE). The carbon emission is calculated as the product of energy consumption and the energy carbon emission coefficient, as shown in **Table 1**. The unit of energy consumption is tons of standard coal, with the original data obtained from the “China Energy Statistical Yearbook” and then converted into tons of standard coal. Referring to the research by Chen and Chen (2021), the carbon emission of the industry in which a company operates is obtained from the energy consumption data in the statistical yearbook. Then, the proportion of a company’s total operating costs in the main business costs of the industry is calculated as a weight and multiplied by the industry’s carbon emission to obtain each company’s carbon emission, represented by the symbol CE. The calculation formula is as shown in Equation (1).

$$CE_{it} = \frac{total\ cost\ of\ business\ i\ in\ year\ t}{The\ main\ business\ cost\ of\ the\ industry} \times Industry\ carbon\ emissions \tag{1}$$

Table 1. Conversion table of the carbon emission coefficient of the energy source.

Energy categories	Carbon emission coefficient	Standard coal conversion coefficient
Total consumption of industrial coke (ten thousand tons)	0.885	0.9714
Total consumption of industrial coal (ten thousand tons)	0.7559	0.7143
Total consumption of industrial kerosene (ten thousand tons)	0.5714	1.4714
Total consumption of industrial fuel oil (ten tons)	0.6185	1.4286
Total consumption of industrial diesel oil (ten thousand tons)	0.5921	1.4571

Table 1. (*Continued*).

Energy categories	Carbon emission coefficient	Standard coal conversion coefficient
Total industrial crude oil consumption (ten million tons)	0.5857	1.4286
Total consumption of industrial gasoline (ten thousand tons)	0.5538	1.4714
Total industrial natural gas consumption (100 million cubic meters)	0.4483	13.3

3.1.2. Explanatory variable

Technological Innovation (TI). Many scholars use R&D expenditure as an indicator to measure the level of technological innovation (He and Zhang, 2012; Yin et al., 2015), but R&D expenses are not always "visible," thus unable to send signals to investors. The level of technological innovation in a company can be observed through patents, which are public information directly visible to stakeholders and whose development requires the company to expend funds, time, intellectual capital, and other related costs. Therefore, patents, which are "visible" and high-cost, are regarded as signals that reflect a company's technical capability and level of innovation. The number of citations a patent receives can also reflect the degree of innovation of that technology to some extent (Wang and Chen, 2022; Yin et al., 2022), sending positive signals to investors. Hence, the explanatory variable for technological innovation is measured by the number of times a patent is cited.

3.1.3. Division of life cycle

There are various standards for measuring the corporate life cycle, which can roughly be divided into three categories: single variable analysis method, comprehensive financial index method, and cash flow pattern method (Dickinson, 2011). The cash flow pattern method determines the growth rate, profitability, and operational risk of companies at different life cycle stages by combining the net amounts of operating, investing, and financing cash flows. This method is more objective and conforms more to reality (Tong et al., 2018). Therefore, this paper chooses the cash flow pattern method to measure the life cycle of enterprises, dividing the listed energy companies in the sample into three stages: growth, maturity, and decline. The detailed division method is shown in **Table 2**.

Table 2. Combination of cash flow characteristics of enterprises in different life-cycle stages.

cash flow	Start-up period	Growth period	Maturation period	Phase of decline				
	Start-up period	Growth period	Maturation period	Phase of decline	Phase of decline	Phase of decline	Elimination period	Elimination period
Net cash flow from operations	-	+	+	-	+	+	-	-
Net investment cash flow	-	-	-	-	+	+	+	+
Net financing cash flow	+	+	-	-	+	-	+	-

3.1.4. Mediating variable

Financing Constraints (SA). Scholars primarily use the WW index, KZ index, and SA index to measure the degree of financing constraints faced by enterprises. Due to the strong endogeneity of the WW and KZ indexes, this paper chooses to measure using the SA index established by Hadlock and Pierce (2010). The model is as shown in Equation (2): where Age represents the age of the enterprise, and Sale is measured by the total assets of the enterprise.

$$SA_{it} = -0.737 \times Sale_{it} + 0.043 \times Sale_{it}^2 - 0.04 \times Age_{it} \quad (2)$$

3.1.5. Control variables

In **Table 3**, referencing the research findings of Feng et al. (2021) and Pan and Wang (2022), this paper controls for several variables that may influence the level of corporate technological innovation and carbon emission reduction. These include: company size (SALE), asset-liability ratio (LEV), tangibility of assets (PPE), total asset turnover (AT), growth ability (GROWTH), and return on equity (ROE).

Table 3. Variable definition table.

Type of variable	Name	Symbol	Instruction
explained variable	Corporate carbon emissions	C	Using industry carbon emission data, calculate the logarithm of the weighted average of the company's total operating costs as a proportion of the industry's main operating costs.
explanatory variable	technical innovation	TI	The number of patents cited
Mediator variable	Financing constraints	SA	According to the formula of Hadlock and Pierce (2010)
controlled variable	enterprise scale	SALE	The log value of the enterprise's total assets
	asset-liability ratio	LEV	Total liabilities/total assets
	Tangible assets ratio	PPE	Tangible assets/total assets
	turnover of total capital	AT	Average operating income/total assets
	Growth ability	GROWTH	The rate of change of the current operating income compared with the previous period
	Return on equity	ROE	Average balance of net profit/shareholders' equity

3.2. Model construction

Based on the above research hypotheses, the following model is constructed in this paper:

$$CE_{it} = \alpha_0 + \alpha_1 TI_{it} + \sum \alpha_j control_{it} + \varepsilon_{it} \quad (3)$$

$$SA_{it} = \beta_0 + \beta_1 TI_{it} + \sum \beta_j control_{it} + \delta_{it} \quad (4)$$

$$CE_{it} = \theta_0 + \theta_1 TI_{it} + \theta_2 SA_{it} + \sum \theta_j control_{it} + \mu_{it} \quad (5)$$

In this, Model (3) is used to validate the hypothesis regarding the relationship between technological innovation and carbon emission reduction in energy enterprises, and Model (4) to verify the hypothesis concerning the relationship between technological innovation and corporate financing constraints. Models (3), (4), and (5) combined are based on the testing method of Wen and Ye (2014) to construct a mediating effect model, which is used to verify the mediating effect of financing constraints. Here, i and t represent the company and the period, respectively; C stands for the company's carbon emissions; TI is the level of corporate technological innovation; SA represents the level of financing constraints; control is a series of control variables; additionally, ε_{it}, δ_{it}, μ_{it} represent random disturbance terms.

3.3. Data source and descriptive statistics

The data required for this paper comes from the China Energy Statistical Yearbook, National Bureau of Statistics, Guotai An database, Wind database, and CNRDS database, as well as various provincial statistical yearbooks for the years 2014–2020. The calculation and analysis of the data were primarily conducted using Stata17 software.

The paper is based on the disclosed data of all A-share listed energy companies within the sample period, with the following data further excluded: first, data related to ST and ST* listed companies; second, data from companies listed on the GEM (Growth Enterprise Market) and the STAR Market; third, data from listed companies with incomplete disclosures. To avoid the influence of outliers, tail-trimming was performed on the variables, resulting in a final count of 6237 observations from 81 listed energy companies. **Table 4** presents the descriptive statistics of the data for this paper. Additionally, the paper conducted tests for correlation and variance inflation factors on the variables, and the results showed no multicollinearity among the variables selected for this study.

Table 4. Descriptive statistics table.

Variable	Sample number	Mean value	Standard deviation	Minimum value	Maximal value
C	567	2.666	1.417	0.192	6.314
TI	567	2.9	1.709	0.693	8.689
SA	567	−3.792	0.284	−4.596	−2.715
CGL	567	−0.283	0.895	−2.431	2.122
SALE	567	4.722	1.651	1.334	10.084
LEV	567	0.505	0.195	0.079	0.953
PPE	567	0.379	0.214	−0.369	0.917
AT	567	0.629	0.598	0.063	3.587
GROWTH	567	0.118	0.396	−0.586	2.139
ROE	567	0.004	0.253	−1.787	0.333

3.4. Technological innovation, lifecycle, and carbon emission reduction in energy enterprises: Test of H1

Using White's and Newey's correction to address possible heteroscedasticity and cross-sectional correlation issues among groups, Model (3) was used to verify the impact of technological innovation on carbon emissions of energy enterprises. The baseline regression results are shown in **Table 5**. Using a progressive regression method, the first column (1) does not include control variables. Technological innovation is significantly negatively correlated with carbon emissions of energy enterprises, indicating that technological innovation can promote carbon reduction in energy enterprises. In columns (2) to (7), control variables are added sequentially, and the conclusion remains robust; technological innovation still has a significant promoting effect on corporate carbon reduction, passing the 1% significance test. Thus, hypothesis H1a is validated.

Table 5. Benchmark regression results of technological innovation affecting carbon emission reduction of energy enterprises.

Variable	CE						
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
TI	−0.168***	−0.114***	−0.112***	−0.109***	−0.115***	−0.112***	−0.113***
	(−5.82)	(−6.56)	(−6.54)	(−6.4)	(−8.11)	(−7.96)	(−8.05)
SALE	-	0.848***	0.822***	0.839***	0.881***	0.895***	0.911***
	-	(29.59)	(27.41)	(27.82)	(34.94)	(35.41)	(35.01)
LEV	-	-	0.4***	1.595***	1.211***	1.081***	0.858***
	-	-	(2.73)	(4.03)	(3.68)	(3.3)	(2.53)
PPE	-	-	-	1.209***	0.817***	0.699**	0.609**
	-	-	-	(3.25)	(2.63)	(2.26)	(1.97)
AT	-	-	-	-	0.591***	0.638***	0.647***
	-	-	-	-	(14.74)	(15.18)	(15.42)
GROWTH	-	-	-	-	-	−0.112***	−0.106***
	-	-	-	-	-	(−3.39)	(−3.21)
ROE	-	-	-	-	-	-	−0.138**
	-	-	-	-	-	-	(−2.41)
Constant	3.153***	−1.007***	−1.09***	−2.242***	−2.453***	−2.433***	−2.366***
	36.3	(−6.72)	(−7.17)	(−5.82)	(−7.66)	(−7.68)	(−7.48)
N	567	567	567	567	567	567	567
within R^2	0.0653	0.6672	0.6723	0.6793	0.7791	0.7843	0.7869
Time fixed	YES	YES	YES	YES	YES	YES	YES
Enterprise fixed	YES	YES	YES	YES	YES	YES	YES

Note: In brackets is the *t* value misadjusted by the clustering robust standard; represents the level of 10%, 5% and 1% respectively, the same components.

3.5. Formatting of mathematics

The regression results of technological innovation and carbon emission reduction in energy enterprises at different life cycle stages are shown in **Table 6**, including both the results without control variables and those with control variables added. The results indicate that during the growth phase, the impact of technological innovation on carbon emissions of energy enterprises is negative, with the regression coefficient in CE column (2) being −0.112, and it passes the 1% significance test. This suggests that in the growth phase, technological innovation can significantly promote carbon emission reduction in energy enterprises, consistent with the theoretical analysis of this paper.

Table 6. Regression results of technological innovation in different life cycles affecting the carbon emission reduction of energy enterprises.

Variable	Growth period		Maturation period		Phase of decline	
	CE(1)	**CE(2)**	**CE(3)**	**CE(4)**	**CE(5)**	**CE(6)**
TI	−0.122***	−0.112***	−0.152***	−0.117***	−0.034	−0.079**
	(−2.17)	(−5.44)	(−3.53)	(−5.22)	(−0.60)	(−2.35)
SALE	-	1.018***	-	1.352***	-	0.967***
	-	(26.67)	-	(13.04)	-	(6.24)
LEV	-	1.217***	-	−4.058***	-	0.115
	-	(2.74)	-	(−3.41)	-	(0.14)
PPE	-	1.382***	-	−4.216***	-	−0.167
	-	(3.58)	-	(-3.69)	-	(-0.21)
AT	-	0.782***	-	0.711***	-	0.518***
	-	(7.93)	-	(6.9)	-	(7.63)
GROWTH	-	−0.002	-	−0.104	-	−0.035
	-	(0.06)	-	(−1.03)	-	(−0.44)
ROE	-	−0.405***	-	−0.017	-	−0.155
	-	(−4.21)	-	(−0.09)	-	(−1.51)
Constant	2.954***	−3.395***	3.418***	−0.556	2.147***	−1.681
	(15.18)	(−8.75)	(26.27)	(−0.46)	(13.48)	(−1.66)
N	271	271	191	191	105	105
within R^2	0.0745	0.8586	0.0975	0.7796	0.0065	0.6845
Time fixed	YES	YES	YES	YES	YES	YES
Enterprise fixed	YES	YES	YES	YES	YES	YES

In the maturity phase, technological innovation also has a negative impact on carbon emissions of energy enterprises, with the regression coefficient in CE column (4) being −0.117, and it too passes the 1% significance test. This indicates that during the maturity phase, technological innovation can significantly promote carbon reduction in energy enterprises, and compared to the growth phase, the positive impact of technological innovation on carbon reduction is greater. The carbon reduction power of technological innovation reaches its peak during this phase, not only because enterprises possess strong technological innovation capabilities at this stage but also because enterprises have formed the largest scale, and their carbon emission intensity has peaked. Pollution prevention and control also become a key focus for enterprises in addition to their core business activities.

In the decline phase, technological innovation has a negative impact on carbon emissions of energy enterprises, with the regression coefficient in CE column (6) being −0.079, which passes the 5% significance test. This indicates that at this stage, technological innovation can promote carbon emission reduction in energy enterprises, but compared to the growth and maturity phases, its carbon reduction intensity and significance are diminished. From the above analysis, it is clear that the promoting effect of technological innovation on carbon emission reduction in energy enterprises is significantly influenced by the life cycle stage, showing that mature companies > growing companies > declining companies. Hence, hypothesis H1b is validated.

3.6. The mediating effect of financing constraints: Testing Hypothesis H3

Table 7 presents the test results of the mediating effect of financing constraints for the full sample and at different life cycle stages, both with and without the inclusion of control variables in the regression results. Looking at the full sample test, the regression results in column CE(2) indicate that the coefficient sign for technological innovation remains unchanged and significant, with a financing constraint coefficient of −1.233, which is significantly negative at the 1% level. This suggests that the easing of financing constraints can facilitate carbon emission reduction in energy companies. The mediating effect of financing constraints between technological innovation and carbon emission reduction in energy companies is validated, confirming Hypothesis H3a. Technological innovation can promote carbon emission reduction in energy companies by alleviating financing constraints.

Table 7. Test results of the mediation effect of the whole sample and different life cycle financing constraints.

Variable	Full sample		Growth period		Maturation period		Phase of decline	
	CE(1)	CE(2)	CE(3)	CE(4)	CE(5)	CE(6)	CE(7)	CE(8)
TI (direct effect)	−0.121***	−0.093***	−0.187***	−0.107***	−0.086***	−0.076***	−0.005	−0.042
	(−4.40)	(−7.05)	(−3.74)	(−5.36)	(−2.19)	(−4.01)	(−0.09)	(−1.54)
SA	−2.534***	−1.233***	−1.541**	−0.585**	−2.741***	−2.019***	−0.325	−0.316
	(−8.29)	(−8.91)	(−2.40)	(−2.21)	(−6.02)	(−10.08)	(−0.54)	(−1.37)
SALE	-	0.851***	-	1.016***	-	0.909***	-	0.904***
	-	(36.94)	-	(26.88)	-	(17.08)	-	(21.26)
LEV	-	0.864***	-	1.190***	-	−0.911	-	0.526
	-	(2.78)	-	(2.71)	-	(−1.16)	-	(0.86)
PPE	-	0.603**	-	1.436***	-	−1.57**	-	0.264
	-	(2.12)	-	(3.75)	-	(−2.1)	-	(0.43)
AT	-	0.639***	-	0.787***	-	0.801***	-	0.663***
	-	(16.48)	-	(8.06)	-	(10.41)	-	(11.61)
GROWTH	-	−0.096***	-	0.010	-	−0.277***	-	−0.113
	-	(−3.07)	-	(0.23)	-	(−3.35)	-	(−1.52)
ROE	-	−0.119**	-	−0.413**	-	0.138	-	−0.063
	-	(−2.18)	-	(−4.34)	-	(0.93)	-	(−0.64)
Mediating effect	-	−0.019	-	−0.007	-	−0.067	-	-
Total effect	-	−0.112	-	−0.114	-	−0.143	-	-
Mediating effect/Total effect	-	16.9%	-	6.1%	-	46%	-	-
Constant	−6.591***	−6.811***	−2.613	−5.625***	−7.071***	−8.444***	1.087	−3.229***
	(−5.60)	(−11.28)	(−1.06)	(−5.21)	(−4.05)	(−7.21)	(0.46)	(−3.04)
N	567	567	271	271	191	191	105	105
within R^2	0.1816	0.8115	0.1015	0.8622	0.3151	0.8541	0.1062	0.7197
Time fixed	YES	YES	YES	YES	YES	YES	YES	YES
Enterprise fixed	YES	YES	YES	YES	YES	YES	YES	YES

Examining the results at different stages of the life cycle, during the growth stage, the regression results in column CE(4) show that the coefficient sign for technological innovation remains unchanged and significant, with a financing constraint coefficient of −0.585, significantly negative at the 1% level. This indicates that the alleviation of financing constraints can enhance carbon emission reduction in energy companies, thereby validating the effective mediation mechanism of financing constraints. During the maturity stage, the regression results in column CE(6) reveal that the coefficient sign for technological innovation remains unchanged and significant, with a financing constraint coefficient of −2.019, significantly negative at the 1% level. The easing of financing constraints can further enhance carbon emission reduction in energy companies compared to the growth stage, indicating a more significant mediating mechanism effect. However, during the decline stage, column CE(8) shows that neither technological innovation nor financing constraints passed the significance test, and technological innovation fails to function as a financing signal. Thus, the mediating mechanism of financing constraints is ineffective at this stage.

Furthermore, **Table 7** also provides the mediating effect, total effect, and the proportion of the mediating effect in the total effect within this mediation model. Comparing the mediating effects at different life cycle stages, the mediation effect value is 0.007 during the growth stage, accounting for 6.1% of the total effect. This indicates that during the growth stage, the promotion of carbon emission reduction in energy companies by technological innovation mainly relies on direct effects, with room for improvement in the mediating effect of financing constraints. In contrast, during the maturity stage, the mediation effect value is 0.067, accounting for 46% of the total effect. This suggests that the mediating role of financing constraints plays a crucial part in the impact of technological innovation on carbon emission reduction in energy companies during the maturity stage. Therefore, when devising carbon emission reduction schemes for companies in the maturity stage, this transmission path should be given more attention. Based on the above analysis, it is clear that the mediating effect of financing constraints exhibits certain stage characteristics, being more pronounced in mature stage companies than in growth stage companies, and ineffective in declining stage companies, thereby verifying Hypothesis H3b.

3.7. Technological innovation, lifecycle, and financing constraints: Test of H2

Table 8 presents the regression results of the impact of technological innovation on financing constraints of energy enterprises for the full sample and for different lifecycle stages, including both results without control variables and with control variables added. From the full sample test, column SA (2) shows that the regression coefficient between technological innovation and financing constraints is 0.016, which is significantly positive at the 1% level. This indicates that technological innovation can alleviate the financing constraints of energy enterprises, thus validating hypothesis H2a.

Table 8. Regression results of the full sample and different life cycle technological innovation affecting the financing constraints of energy enterprises.

Variable	Full sample		Growth period		Maturation period		Phase of decline	
	SA(1)	SA(2)	SA(3)	SA(4)	SA(5)	SA(6)	SA(7)	SA(8)
TI	0.018***	0.016***	0.011**	0.012**	0.033***	0.033***	0.01	0.01
	(4.57)	(4.02)	(2.12)	(2.12)	(4.56)	(4.56)	(1.13)	(1.13)
SA	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-
SALE	-	−0.032***	-	0.018*	-	0.063***	-	0.004
	-	(−4.33)	-	(1.84)	-	(4.01)	-	(0.19)
LEV	-	−0.019	-	−0.108	-	0.381	-	−0.137
	-	(−0.2)	-	(−0.92)	-	(1.52)	-	(−0.67)
PPE	-	0.029	-	0.062	-	0.304	-	−0.222
	-	(0.34)	-	(0.60)	-	(1.27)	-	(−1.08)
AT	-	−0.004	-	0.009	-	−0.034	-	0.018
	-	(−0.3)	-	(0.36)	-	(−1.2)	-	(1.02)
GROWTH	-	0.007	-	0.017	-	−0.026	-	0.001
	-	(0.71)	-	(1.35)	-	(−0.77)	-	(0.05)
ROE	-	0.004	-	−0.039	-	0.038	-	0.017
	-	(0.25)	-	(−1.51)	-	(0.65)	-	(0.59)
Constant	−3.844***	−3.687***	−3.833***	−3.893***	−4.479***	−4.479***	−3.731***	−3.731***
	(−317.97)	(−41.23)	(−128.98)	(−36.83)	(−18.66)	(−18.66)	(−17.03)	(−17.03)
N	567	567	271	271	191	191	105	105
within R^2	0.0413	0.0993	0.0086	0.0462	0.0415	0.0415	0.0878	0.0878
Time fixed	YES	YES	YES	YES	YES	YES	YES	YES
Enterprise fixed	YES	YES	YES	YES	YES	YES	YES	YES

Looking at the results from different stages of the lifecycle, during the growth phase, column SA (4) shows that the regression coefficient between technological innovation and financing constraints is 0.012, passing the 5% significance test. This suggests that technological innovation can alleviate the financing constraints faced by energy enterprises, which is particularly beneficial during this high-speed development phase when the need for capital is great and financing constraints are significant, making the financing signal function of technological innovation a much-needed relief. In the maturity phase, column SA (6) shows that the regression coefficient between technological innovation and financing constraints is 0.033, passing the 1% significance test. This indicates that technological innovation can alleviate the financing constraints of energy enterprises, and compared to growth-phase enterprises, the financing signal function of technological innovation is stronger and more significant. However, for mature enterprises with sufficient internal cash flow, the financing signal function of technological innovation is just an added bonus. In the decline phase, column SA (8) shows that the impact of technological innovation on financing constraints did not pass the significance test, meaning that declining energy enterprises cannot leverage the financing function of technological innovation, which is adding insult to injury for these companies. Based on the above analysis, the alleviating effect of technological innovation on financing constraints shows clear stage characteristics, manifesting as mature companies > growing companies, with declining companies unable to play a role, thus validating hypothesis H2b.

3.8. Robustness test

To validate the regression results of Hypotheses H1, H2, and H3, this study employed an alternative research method for robustness checks. Considering the carbon emission data, which serves as the dependent variable, exhibits a clear left-censored characteristic with zero as the boundary, and the financing constraint data shows a distinct right-censored characteristic with zero as the boundary, a Tobit regression analysis for censored dependent variables was conducted for the robustness check. The results, as shown in **Table 9**, indicate that both the regression coefficients and their significance levels have not undergone significant changes, thereby affirming the robustness of the findings in this paper. In addition, the alternative explanatory variables and explained variables were used, which also passed the robustness test.

Table 9. Test of robustness of hypothesis H1, H2, H3: Results of Tobit regression.

Variable	Full sample			Growth period			Maturation period			Phase of decline		
	CE(1)	**SA(2)**	**CE(3)**	**CE(7)**	**SA(8)**	**CE(6)**	**CE(10)**	**SA(11)**	**CE(12)**	**CE(13)**	**SA(14)**	**CE(15)**
TI	−0.117 ***	0.019 ***	−0.093 ***	−0.121 ***	0.010*	−0.113 ***	−0.135 ***	0.033 ***	−0.075 ***	−0.044	0.009	−0.046*
	(−8.58)	(4.83)	(−7.16)	(−6.36)	(1.94)	(−6.01)	(−5.88)	(4.64)	(−4.24)	(−1.59)	(1.18)	(−1.72)
SA	-	-	−1.231 ***	-	-	−0.663 ***	-	-	−2.027 ***	-	-	−0.387
	-	-	(−8.96)	-	-	(−3.16)	-	-	(−10.53)	-	-	(−1.44)
Constant	−2.183 ***	−3.756 ***	−6.817 ***	−3.062 ***	−3.878 ***	−5.642 ***	0.498	−4.477 ***	−8.444 ***	−2.052 ***	−3.731 ***	−3.451 ***
	(−6.79)	(−40.68)	(−11.40)	(−8.24)	(−37.66)	(−6.31)	(0.55)	(−19.60)	(−7.46)	(−3.47)	(−17.60)	(−3.06)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	567	567	567	271	271	271	191	191	191	105	105	105
rho	0.9212	0.9300	0.9184	0.9011	0.9235	0.9003	0.9443	0.8738	0.9684	0.7282	0.9395	0.7887
Log likelihood	−236.7532	437.416	−199.2008	−129.4849	211.9651	−124.5675	−124.959	117.2124	−83.4742	−40.8857	58.4879	−39.7641
Time fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Enterprise fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

3.9. Industry heterogeneity test

Due to the fundamental differences between traditional and new energy enterprises, this paper divides energy enterprises into these two categories for group testing. The test results are presented in **Table 9**:

(1) Full Sample and Maturity Phase Results: There is no significant difference in the regression results between traditional and new energy enterprises. This indicates that technological innovation can promote carbon reduction in both types of enterprises, and financing constraints play a significant mediating role in this process.

(2) Growth Phase Results: A notable difference in the heterogeneity test is that the financing signal function of technological innovation is not effectively exerted in new energy enterprises during their growth phase. This additional challenge for new energy enterprises in the growth phase may be due to traditional energy enterprises, typically large state-owned enterprises established early with significant scale, having abundant fixed asset value, and often receiving local government preferences and "implicit guarantees," which are beneficial for obtaining financing (Mei et al. 2022). In contrast, new energy enterprises, mainly in wind, solar, and nuclear power, are mostly established later and have yet to reach a significant scale. This leads to more uncertainty in profitability (Kong et al. 2021), insufficient collateral for financing, and lower financial market valuations, making them vulnerable to strict "credit discrimination" during the financing process.

(3) Decline Phase Results: A significant difference in the heterogeneity test is that technological innovation does not promote carbon reduction in traditional energy enterprises during their decline phase, which is unexpected. The reason might be that traditional energy enterprises are capital-intensive and primarily rely on primary energy sources like coal, oil, and natural gas. These industries, often heavily polluting, are subject to environmental restrictions by government departments. Traditional energy enterprises have a solid foundation and large scale, and the current national economy still relies on traditional energy sources. Moreover, these enterprises have high fixed costs and substantial sunk costs in case of production shutdowns. Therefore, if subjected to minor environmental regulations causing additional environmental costs, most enterprises can bear these costs and choose to expand production scale and technological innovation to offset the costs brought by pollution instead of exiting the traditional energy market. However, traditional energy enterprises in decline face severe environmental regulations, making it difficult for smaller and more polluting companies to bear high environmental costs, significantly encroaching on their R&D expenditures for technological innovation. For example, with the increase of winter smog, the State Council decided to fully implement ultra-low emissions and energy-saving transformations in coal-fired power plants, significantly reducing coal consumption and pollution emissions. Some local governments, competing for political purposes, even issued "military orders" to strictly control smog pollution expansion, implementing measures to restrict the development of high energy consumption and high pollution industries. Some regions even halted all high energy consumption projects, and some financial institutions stopped lending to coal, electricity, and similar projects.

3.10. Regional heterogeneity test

Considering the imbalanced regional development in China, the paper categorizes the samples into enterprises located in the eastern region and those in the central and western regions, according to the classification by the National Bureau of Statistics (2024). The regression results are presented in **Tables 10** and **11**:

Table 10. Test of industry heterogeneity: Traditional energy enterprises and new energy enterprises.

Table A: Traditional energy enterprises	**Full sample**			**Growth period**			**Maturation period**			**Phase of decline**		
	CE(1)	**SA(2)**	**CE(3)**	**CE(7)**	**SA(8)**	**CE(6)**	**CE(10)**	**SA(11)**	**CE(12)**	**CE(13)**	**SA(14)**	**CE(15)**
TI	−0.128***	0.021***	−0.101***	−0.095***	0.015**	−0.108***	−0.116***	0.024**	−0.077***	−0.018	0.016	−0.022
	(−6.18)	(3.19)	(−5.46)	(−4.59)	(1.97)	(−5.12)	(−2.86)	(2.02)	(−2.91)	(−0.31)	(0.53)	(−0.35)
SA	-	-	−1.522***	-	-	−0.763**	-	-	−2.272***	-	-	−0.062
	-	-	(−8.38)	-	-	(−2.19)	-	-	(−8.27)	-	-	(−0.2)
Constant	−1.983***	−3.507***	−7.277***	−3.255***	−3.781***	−6.593***	0.730	−4.373***	−8.971***	−0.818	−3.199	−1.128
	(−3.78)	(−21.71)	(−9.37)	(−6.99)	(−18.86)	(−4.83)	(0.56)	(−12.12)	(−5.48)	(−0.8)	(−6.06)	(−0.75)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	259	259	259	109	109	109	82	82	82	46	46	46
within R^2	0.7549	0.1233	0.8111	0.8723	0.1215	0.8867	0.5008	0.0303	0.8385	0.3781	0.0546	0.3976
Time fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Enterprise fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Table B: New energy enterprises	**Full sample**			**Growth period**			**Maturation period**			**Phase of decline**		
	CE(1)	**SA(2)**	**CE(3)**	**CE(4)**	**SA(5)**	**CE(6)**	**CE(7)**	**SA(8)**	**CE(9)**	**CE(10)**	**SA(11)**	**CE(12)**
TI	−0.11***	0.02***	−0.089***	−0.138***	0.005	−0.087**	−0.142***	0.038***	−0.082***	−0.065	0.012	−0.056*
	(-5.9)	(3.9)	(−4.87)	(−3.99)	(0.50)	(−2.53)	(−4.9)	(4.23)	(−3.24)	(−1.65)	(1.26)	(−1.8)
SA	-	-	−1.038***	-	-	−0.591	-	-	−1.803***	-	-	−0.177
	-	-	(−5.17)	-	-	(−1.30)	-	-	(−6.27)	-	-	(−0.62)
Constant	−2.301***	−3.959***	−6.408***	−3.467***	−3.824***	−6.542***	0.699***	−4.693***	−7.655***	−2.604*	−3.883	−3.179**
	(−5.56)	(−34.51)	(−7.23)	(−4.91)	(−20.04)	(−3.50)	(0.56)	(−13.27)	(−4.53)	(−1.81)	(15.35)	(−2.39)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	308	308	308	104	104	104	109	109	109	59	59	59
within R^2	0.8103	0.0755	0.8232	0.9118	0.1185	0.9228	0.8413	0.131	0.8883	0.8120	0.1732	0.7925
Time fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Enterprise fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

(1) Across All Samples and Stages of the Energy Enterprise Lifecycle: In the eastern region, the effect of technological innovation on carbon reduction is higher than in the central and western regions, and the same is true for the strength of the financing signal of technological innovation. This reflects that the innovation system and environment in the eastern region are superior to those in the central and western regions, facilitating the development of innovation activities and the enhancement of technological innovation levels. The central and western regions are relatively lagging in development, with less market competition, a weaker sense of enterprise innovation, insufficient attention to innovation activities, lack of R&D investment, inadequate

R&D resources, inability to access advanced technological development equipment, and a shortage of excellent R&D personnel, making it difficult for enterprises to complete R&D and innovation (Han et al., 2015). Moreover, due to the high degree of marketization and industry competitiveness in the eastern region, the cost of patent applications is higher, and their positive impact on market value is stronger.

(2) Impact on Growth Phase Enterprises: Regional differences have a certain impact on the regression results of enterprises in the growth phase. A significant difference is that technological innovation in the central and western regions does not promote carbon reduction in energy enterprises, nor does it realize the financing signal function, interrupting the mediating pathway of financing constraints. This may be due to the relative vulnerability of enterprises in the growth phase, compounded by the poor innovation environment and policy in the central and western regions, and a lower level of marketization, preventing these enterprises from engaging in high-quality technological innovation activities, thereby inhibiting the development of low-carbon technology and the financing function of technological innovation.

(3) Impact on Decline Phase Enterprises: Regional differences also affect the regression results of enterprises in the decline phase. In the eastern region, technological innovation in energy enterprises significantly promotes carbon reduction, while in the central and western regions, the regression results of technological innovation on carbon reduction do not pass the significance test. A possible reason is that declining energy enterprises in the eastern region can use existing and newly introduced talents to build emerging industries, thereby smoothly transitioning and upgrading the enterprises, making the carbon reduction effect of technological innovation evident. However, declining energy enterprises in the central and western regions face obstacles to transformation: first, there are fewer channels for receiving new information, leading to information closure and hindering product structure adjustment; second, there is a lack of high-tech talents, and compared to the eastern region, the central and western regions are less attractive for retaining talents, lacking intellectual support for enterprise transformation; third, there is a gap between the central and western regions and the eastern region in terms of hardware equipment and software facilities.

Table 11. Test of regional heterogeneity: Enterprises in eastern regions and enterprises in central and western regions.

Table A: Enterprises in the eastern region	-	**Full sample**		-	**Growth period**		-	**Maturation period**		-	**Phase of decline**	
	CE(1)	**SA(2)**	**CE(3)**	**CE(4)**	**SA(5)**	**CE(6)**	**CE(7)**	**SA(8)**	**CE(9)**	**CE(10)**	**SA(11)**	**CE(12)**
TI	−0.109 ***	0.024 ***	−0.077 ***	−0.099 ***	0.018 **	−0.090 ***	−0.134 ***	0.03 ***	−0.073 ***	−0.040	0.011	−0.043
	(−6.55)	(4.74)	(−5.1)	(−5.29)	2.46	(−4.92)	(−3.65)	(3.07)	(−2.62)	(−1.18)	(1.9)	(−1.31)
SA		-	−1.457 ***	-	-	−0.739* **		-	−2.388 ***	-	-	−0.431
		-	(−8.9)	-	-	(−3.06)		-	(−8.05)	-	-	(−1.56)
Constant	−2.368 ***	−3.681 ***	−7.685 ***	−3.465 ***	−3.963 ***	−6.376 ***	−0.274 ***	−4.274 ***	−11.052 ***	−0.924	−3.537 ***	−2.283*
	(−5.14)	(−26.72)	(−10.67)	(−6.74)	(−20.74)	(−6.00)	(−0.19)	(−11.96)	(−6.23)	(−1.02)	(−10.62)	(−1.72)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Table 11. (*Continued*).

Table A: Enterprises in the eastern region	-	**Full sample**		-	**Growth period**		-	**Maturation period**		-	**Phase of decline**	
	CE(1)	**SA(2)**	**CE(3)**	**CE(4)**	**SA(5)**	**CE(6)**	**CE(7)**	**SA(8)**	**CE(9)**	**CE(10)**	**SA(11)**	**CE(12)**
N	357	357	357	136	136	136	113	113	113	76	76	76
within R²	0.8139	0.0892	0.8462	0.9427	0.0254	0.9453	0.6679	0.1681	0.8471	0.7516	0.1795	0.8003
Time fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Enterprise fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Table B: Enterprises in the central and western regions		**Full sample**			**Growth period**			**Maturation period**			**Phase of decline**	
	CE(1)	**SA(2)**	**CE(3)**	**CE(4)**	**SA(5)**	**CE(6)**	**CE(7)**	**SA(8)**	**CE(9)**	**CE(10)**	**SA(11)**	**CE(12)**
TI	−0.073 ***	0.011*	−0.073 ***	−0.0487	0.002	−0.057 *	−0.083 ***	0.023 **	−0.064 **	−0.025	−0.003	−0.054
	(−3.39)	(1.72)	(−3.39)	(−1.63)	(0.19)	(−1.91)	(−3.05)	(2.31)	(−2.5)	(−0.27)	(−0.2)	(−1.06)
SA	-	-	−0.376*	-	-	−0.436	-	-	−1.218 ***	-	-	−0.313
	-	-	(−1.83)	-	-	(−1.53)	-	-	(−4.14)	-	-	(−0.69)
Constant	−2.508 ***	−3.849 ***	−4.04 ***	−3.338 ***	−4.08 ***	−5.201 **	−2.681 ***	−4.241 ***	−7.515 ***	1.804	−3.88 ***	−4.341 **
	(−7.26)	(−31.29)	(−4.48)	(−8.71)	(−24.67)	(−3.63)	(−3.76)	(−14.45)	(−5.19)	(0.81)	(−15.23)	(−2.33)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	210	210	210	77	77	77	78	78	78	29	29	29
within R²	0.741	0.124	0.7512	0.8117	0.0810	0.8286	0.7794	0.1035	0.8622	0.5934	0.7395	0.3424
Time fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Enterprise fixed	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

4. Conclusion and implications

4.1. Conclusion

This study, using a sample of 81 Chinese energy enterprises from 2014 to 2020, applies panel data and mediating models to investigate the impact of technological innovation on carbon emission reduction in energy enterprises from a lifecycle perspective, as well as the mediating role of financing constraints. It also conducts heterogeneity tests by industry and region. The conclusions are as follows:

1) Technological innovation positively promotes carbon emission reduction in energy enterprises, with the strength of this effect showing significant lifecycle stage characteristics: mature companies > growing companies > declining companies.
2) Technological innovation can alleviate corporate financing constraints, with its effectiveness showing clear lifecycle stage characteristics: mature companies > growing companies, with declining companies unable to play a role.
3) Financing constraints mediate between technological innovation and carbon emission reduction, meaning that technological innovation can promote carbon reduction in energy enterprises by alleviating financing constraints. The mediating effect of financing constraints shows certain stage characteristics, with

the mechanism being more effective in mature companies than in growing ones, and ineffective in declining companies.

4) Industry heterogeneity tests show that, compared to new energy enterprises, traditional energy enterprises have a more significant carbon reduction effect and stronger mediating role of financing constraints. For growing new energy enterprises, the mediating mechanism of financing constraints is disrupted, and for declining traditional energy enterprises, the carbon reduction effect of technological innovation is not significant.
5) Regional heterogeneity tests show that compared to central and western companies, eastern companies have a more significant carbon reduction effect of technological innovation and a stronger mediating role of financing constraints. For growing companies in the central and western regions, the carbon reduction effect of technological innovation is not significant, and the mediating mechanism of financing constraints is disrupted. For declining companies in these regions, the carbon reduction effect of technological innovation is also not significant.

4.2. Implications

1) Enhance Technological Innovation in Energy Enterprises:

In energy production, increase support for clean coal production technology, improving the overall clean level of energy enterprises and promoting the energy structure transformation.

In energy utilization, intensify support for energy-saving stoves, intelligent control, carbon capture, and storage technologies to continuously improve energy carbon efficiency and reduce carbon emission intensity.

Further, independently developed low-carbon technologies by energy enterprises are effective means to reduce carbon emissions. Hence, the government should continue to increase investment in energy utilization technology and low-carbon technology research and development, enhancing the proactiveness of enterprises in innovation and striving for breakthroughs in core low-carbon and key technologies.

2) Focus on Alleviating Financing Constraints to Enhance the Effectiveness of Technological Innovation in Carbon Reduction:

Fully utilize the signaling function of patents for capital financing of energy enterprises. Enterprises should improve the quality of patents and obtain external financing by pledging patents.

Policymakers should improve the patent information service environment, including construction of patent information service platforms, integration services, and patent information query and transaction services, to ensure effective patent information is timely conveyed to investors.

Finally, to ensure the originality, practicality, and novelty of patents, it’s necessary to raise the threshold for patent protection, fully leveraging the signaling function of patents to ensure a smooth pathway for alleviating financing constraints.

3) Implement Differentiated Carbon Reduction Policies for Different Lifecycle Stages of Energy Enterprises:

For enterprises in the growth phase, create a favorable innovation environment and provide innovation subsidies, helping them overcome development challenges and improve the level of technological innovation.

For mature enterprises, apply appropriate environmental regulations to inversely promote technological innovation and pollution control.

4) Develop Differentiated Carbon Reduction Policies for Traditional and New Energy Enterprises:

New energy enterprises face "credit discrimination," especially in the growth phase. Therefore, establish green credit channels to alleviate financing constraints and enhance the carbon reduction strength of technological innovation in new energy enterprises.

Traditional energy enterprises are more likely to be constrained by environmental regulations. Severe environmental regulations prevent declining traditional energy enterprises from transforming and upgrading. This necessitates differentiated environmental regulatory measures based on the enterprise's lifecycle stage.

5) Employ Region-Specific Carbon Reduction Policy Support:

In the eastern region, continue to leverage technological innovation for carbon reduction and unleash the potential for high-quality technological development.

In central and western regions, improve the enterprise innovation environment by establishing innovation funds, integrating production, education, and research platforms, and building a sustainable innovation ecosystem.

Establish and improve a talent mobility mechanism to attract and retain talents, thereby enhancing the level of technological innovation in enterprises.

Establish a transparent and efficient market mechanism to improve industry competitiveness, ensuring the effective functioning of the financing role of technological innovation and alleviating financing constraints.

For declining enterprises in central and western regions facing transformation challenges, the government can adjust directly through new technology introduction and re-employment labor skills training, or indirectly through financial means such as interest subsidies and setting up new industry funds, thereby promoting the transformation rate of innovative achievements and the development of new industries.

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