Evolutionary Game Analysis of Carbon Emission Pledge Financing in the Electricity Market Environment

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Abstract

This paper explores the integration of carbon finance, particularly focusing on carbon emission rights pledge financing, as a pivotal instrument in attaining carbon peak targets. This integration is crucial in the context of growth stabilization and structural adjustment. The study identifies key challenges hindering the development of carbon emission rights pledge financing, such as process discrepancies, limited bank engagement, and suboptimal risk management. Addressing these issues, we propose a novel model featuring government intervention. This model employs an evolutionary game approach involving key stakeholders: power companies, carbon emission exchanges, and banks. The objective is to navigate towards a Pareto optimal outcome for the pledging of carbon emission rights. Numerical analyses reveal that appropriate government sanctions can effectively streamline the pledging process. Results show a higher compliance rate from carbon emission exchanges under stringent regulations and increased bank participation under direct government incentives. The study advocates for the establishment of a robust public disclosure mechanism for carbon emission pledge financing and urges the government to enact unified trading regulations. This proposed method not only tackles existing impediments in carbon finance but also significantly contributes to the global pursuit of sustainable development.

Keywords: Government participation; Carbon emission rights; Evolutionary game; Pledge financing; Electric power enterprises; Environmental regulation

1. Introduction

As China approaches the critical final phase of its 14th Five-Year Plan (2021–2025), it has significantly accelerated its endeavors to build an ecological civilization and advance a green transition. Leveraging "carbon reduction" to spearhead this green transition has emerged as a defining feature of China's pursuit of high-quality growth amid cyclical economic fluctuations (Zhou et al., 2022). In Chinese Guiding Opinions on Accelerating the Establishment of a Sound Green, Low-Carbon, and Circular Development Economic System, the State Council proposes vigorous development of green finance, green credit, and direct green financing, thus providing clear direction for hastening the realization of carbon peaking and carbon neutrality (Zhang et al., 2022). Indeed, green development has already become a pivotal new engine propelling China's high-quality economic expansion.

In the short run, renewable energy, economic growth, and carbon emissions exhibit significant relationships effects (Li et al., 2023). This indicates that accelerating the deployment of renewable energy not only fosters economic growth but also directly advances carbon emission reduction. However, in sub-Saharan Africa, economic growth, energy consumption, and rising industrialization levels are typically accompanied by higher carbon emissions, thereby posing threats to environmental sustainability(Appiah et al., 2023). These findings underscore that the pathways to green transition may differ across regions and that only by aligning with local resource endowments and economic structures can both development and emission reduction goals be achieved in tandem.

Since the global community is increasingly emphasizing environmental protection and sustainable development against this backdrop, green finance, which is centered on green credit, has become one of the primary driving forces for China's green development (Ye et al., 2023). Employing green credit to support sustainable growth is the inevitable choice for China in the latter half of the 14th Five-Year Plan and beyond, as it seeks to maintain stable growth and optimize industrial structure. Such efforts are also crucial to upgrading green finance domestically and improving the broader green finance system. In November 2024, China SPIC Jingmen Green Motion Energy Co., Ltd. pledged its carbon emission allowances as collateral to apply for a cross-compliance period loan from the Hubei branch of the China

Construction Bank, totaling 50 million RMB for a one-year term (Yang et al., 2019). This innovative carbon finance model in China provides an instructive and replicable example of how electric power enterprises can utilize carbon assets for financing. How best to unlock the potential of green credit while balancing economic gains with ecological benefits has thus become a pressing question in China's ongoing green transition.

To investigate both the theoretical underpinnings and practical applications of green finance in China, this paper, which adopts an evolutionary game theory approach, constructs an evolutionary game model that encompasses enterprises, carbon emission trading exchanges, and financial institutions, and then, after examining the dynamic evolutionary process under two different mechanisms–one with government participation and the other without–it proposes corresponding policy recommendations based on the findings from a carbon emission allowance pledge financing model in the context of China's electricity market.

2. Literature Review

2.1 Green Credit

For a long time, China's environmental regulation and governance processes have primarily relied on administrative measures (Y. Sun et al., 2023; Zhou, 2020). Despite some progress in environmental governance under strong administrative pressure, issues such as high management costs, low efficiency, and the potential for rebound effects have also emerged (An et al., 2023; OECD, 2006). Therefore, governmental administrative measures should possess short-termality and moderation (Zhong & Peng, 2022). Economic instruments, noted for their efficiency, flexibility, and long-term effectiveness, have garnered widespread attention, thereby promoting the development of green credit policies(Bao & He, 2022; Zhang et al., 2022). Overall, green credit policies have facilitated corporate innovation and transformation, enhancing the financing accessibility for enterprises listed on green indices (Xie & Zhang, 2021). Additionally, research indicates that as the degree of greenness increases, the interest rates on green credit issued by banks gradually decrease, thereby alleviating the financing difficulties faced by enterprises (Maqsood et al., 2022). Consequently, corporate green initiatives provide consumers with higher quality green products, contributing to the improvement of consumer welfare (Xu et al., 2018). To further promote green development and revitalize corporate assets, a comprehensive suite of green credit products is indispensable (Yang et al., 2019). Currently, green credit products primarily include energy efficiency financing, clean energy financing, environmental financing, green transportation, and carbon emission rights, among others(Bharany et al., 2022; Bhattacharyya, 2021; Khan et al., 2022; Sun et al., 2023; Wang et al., 2021). These products, as social goods, should be subject to consumer and governmental regulatory constraints (Liu et al., 2023).

2.2 Carbon Emission Rights

As part of the ecological civilization construction strategy, the formal launch and successful operation of the domestic carbon trading market have created a promising start(Agyeman et al., 2022; Chen et al., 2022; Kim et al., 2022). Similar to stocks and real estate, carbon emission rights are also regarded as investment assets (Bolton & Kacperczyk, 2021). Studies have shown that increasing government subsidies and developing and perfecting the carbon trading market can effectively stimulate investment(Ferreira & Vieira, 2010; Murgas et al., 2021). Research indicates that introducing a tiered carbon trading reward and penalty mechanism allows enterprises, primarily in the power sector, to profit from their energy supply facilities (Liang et al., 2021). This mechanism not only reduces the total carbon emissions but also offers numerous economic benefits, achieving a win-win situation for the environment and the economy, and serves as a valuable complement to carbon cap policies (Ao et al., 2023). Utilizing carbon emission rights for credit and pledge loans helps enterprises activate their carbon emission rights, allowing them to continue trading in the market after the pledge period ends (Ye et al., 2023). For instance, in October 2022, Harbin Bank pioneered "Future Carbon Emission Rights" pledge financing loan services (Yuan et al., 2022). Correspondingly, researchers have noted that providing government support through environmental responsibility policies such as green agreements helps private financial institutions in Brazil, Colombia, and Argentina develop socially and environmentally responsible financial products (Hidalgo-Onate et al., 2023). The existing studies discussed above indicate that carbon emission rights are becoming increasingly important and their applications are expanding(Agyeman et al., 2022; Fu et al., 2023; Li et al., 2021).

However, although there have been numerous studies in the related field, the aforementioned ones fail to examine and address several key issues, such as the pledge of carbon emission rights, carbon pricing and trading, the valuation of carbon asset allocations, and the basis for pricing, which are of great significance in the context of carbon - related economic and environmental research. In order to fill this research gap and contribute to the limited body of knowledge on this important topic, this study aims to incorporate these critical issues into the analysis, with the hope of providing new insights and promoting a more in - depth understanding of the subject matter. Therefore, if there are changes in carbon prices, inconsistent business rules, or insufficient information, the legitimate rights and interests of pledgees may be infringed upon (Mejia-Escobar et al., 2020). Another reason is that the pledge rules for carbon emission rights vary across regions. To exploit loopholes, some enterprises collude with exchanges to engage in repeated pledges using information asymmetry to obtain bank financing loans. Additionally, indicators such as technological innovation and carbon emissions affect the fairness of the initial allocation of carbon emission rights (Song et al., 2022). On the one hand, deterministic equal allocation (DES) can encourage enterprises to increase investment in clean technologies to reduce carbon emission rates (An & Lee, 2018). On the other hand, technological innovation has a U-shaped threshold effect on environmental pollution; thus, technological innovation must be combined with increased capital injection and energy transition(Appiah et al., 2022).

2.3 Carbon Trading in the Power Generation Industry

The pursuit of environmental quality has driven China to establish the national carbon emission trading market in 2017 to promote the development of the power generation industry (Wang et al., 2018). Incorporating national carbon emission rights into the trading system in China is motivated by several key reasons: First, the power generation industry should possess a more comprehensive database. Power generation enterprises, with their abundant production data, can provide differentiated services to users at lower prices, thereby promoting economic growth (Gao & Pan, 2022). Therefore, enterprises should be incentivized to accumulate sufficient operational experience in a competitive environment (Wang et al., 2023). Second, relevant regulations require an annual carbon dioxide emission threshold of 26,000 tons of CO_2

equivalent for inclusion in the carbon emission market. Given the inherently high carbon emissions in the power generation industry, over 2,000 power generation enterprises were included in the market by 2021 (Wang et al., 2022; Xu et al., 2021).

Carbon finance holds a pivotal position in advancing China’s sustainable development, a fact underscored by its evident importance. Nevertheless, this realm remains in its infancy, supported by a comparatively fragile foundation. At its core, carbon emission rights pledge financing serves as a crucial mechanism for accelerating green finance and strengthening the comprehensive green financial architecture. To further carbon finance and facilitate the transition toward a greener economy, it is essential to heighten risk awareness, implement robust risk management strategies, and exercise rigorous oversight of major pledge financing initiatives.In light of these considerations, the current research concentrates on the power generation sector—a frontrunner in the carbon emission trading market—and employs an evolutionary game approach. A multifaceted evolutionary game system is developed, encompassing enterprises, carbon emission exchanges, and financial institutions, in order to thoroughly investigate the evolutionary dynamics that emerge when government participation mechanisms are introduced. Overall, this study substantially enriches the existing literature by highlighting the critical role of carbon pledge financing in fortifying the green finance framework. By zeroing in on the power generation industry and utilizing an evolutionary game model, the findings offer fresh perspectives on the trajectory of carbon finance under governmental involvement, thereby emphasizing the study’s innovative dimension. These insights serve as valuable references for scholars and policymakers, aiding in the simultaneous pursuit of environmental sustainability and economic prosperity.

3. The Evolutionary Game Model of Carbon Emission Allowance Pledge Financing

3.1Methodology

The selection of game theory, specifically evolutionary game theory, as the research method in this study is pivotal for several reasons. First, game theory provides a robust framework for analyzing strategic interactions among rational decision-makers. In the context of carbon emission rights financing, the stakeholders include the government, power enterprises, and financial institutions, each with their own objectives and strategies. Evolutionary game theory extends traditional game theory by considering the dynamics of strategy evolution over time, which is particularly relevant for understanding the long-term behaviors and adaptations of these stakeholders under varying regulatory and economic conditions (Avila & Mullon, 2023).

Additionally, evolutionary game theory allows for the analysis of stable strategy distributions, known as evolutionary stable strategies (ESS), which provide insights into which strategies are likely to persist in the population over time (Van Cleve, 2023). This feature is particularly valuable for policymakers who need to understand the long-term implications of different regulatory frameworks and incentives on the behavior of power enterprises and financial institutions. For instance, by analyzing the ESS, we can determine under what conditions stricter regulations or increased subsidies will lead to sustainable and honest practices in carbon emission rights financing.

Furthermore, the use of evolutionary game theory facilitates the examination of multi-agent interactions and co-evolutionary processes. This is critical in the context of carbon finance, where the actions of one stakeholder can significantly impact the strategies and outcomes of others. The government's regulatory decisions, for example, influence the compliance and investment behaviors of enterprises, which in turn affect the risk assessments and lending practices of banks (Li et al., 2024).

3.2 Hypotheses

In the context of the electric power sector' s transition toward low-carbon operations, carbon emission rights pledge financing has emerged as a pivotal instrument to reconcile economic returns and environmental imperatives. Motivated by policy directives to achieve carbon neutrality, and by the growing interest of financial institutions in green credit mechanisms, the following hypotheses provide a structured framework for analyzing the strategies of key stakeholders—namely power enterprises, carbon emission exchanges, and banks—under various regulatory conditions. Each hypothesis elucidates both the incentives and the constraints that shape stakeholder behavior, incorporating the cost–benefit trade-offs associated with green finance, supervisory intensity, reputational factors, and government intervention. By presenting these hypotheses in an integrated logical sequence (Figure 1) , the goal is to offer a clear theoretical foundation for subsequent empirical verification and evolutionary game modeling.

3.2.1 Hypothesis 1: Electric Power Enterprises Pledge Carbon Emission Allowances to Obtain Preferential Loans

Under increasingly stringent carbon reduction requirements, electric power enterprises often need financing to advance energy-saving retrofits, adopt renewable energy technologies, or upgrade emission-reduction equipment. To encourage low-carbon transitions, banks can offer green loans featuring preferential interest rates or other incentives when carbon emission allowances are pledged as collateral. Let the rate of return on low-carbon projects be denoted by α , which represents the intrinsic economic gains of the project itself. In addition, an enterprise may obtain "green benefits," denoted by E_1, such as enhanced brand value and stakeholder recognition. These green benefits E_1 depend on both the enterprise's level of investment in low-carbon practices and how the market perceives and rewards such efforts. Meanwhile, enterprises may also receive additional external benefits I_0 (e.g., government subsidies, tax breaks, and positive reputational effects). These external benefits I_0 depend on the degree of policy support in the external environment, including subsidy levels, tax incentives, and any extra returns arising from governmental oversight or carbon quota trading mechanisms.

However, in order to acquire carbon emission allowances, Chinese electric power enterprises have to purchase or otherwise obtain a requisite number of allowances from authorized trading platforms, incurring a purchase cost denoted by ΔC . If a bank is unwilling or unable to provide green financing options, the enterprise can still seek a standard loan B_2 —albeit typically at higher interest rates or on less favorable terms. For electric power enterprises, the critical factor in deciding whether to pledge carbon emission allowances for a preferential loan lies in whether the overall expected net benefit exceeds the returns they would anticipate from conventional credit. Hence, in weighing the choice between collateral-based green financing and traditional loans, electric power enterprises must compare the preferential terms of green lending against the associated costs. Based on Hypothesis 1, when the aggregate net benefits α —taking into account project returns, green benefits E_1, and external benefits I_0 surpass those of a conventional loan B_2, the enterprise will choose to pledge its carbon emission allowances. Formally, we can express this as follows:

$$\alpha + E_1 + I_0 - \Delta C > B_2$$

That is to say, when this condition is met, power enterprises are more inclined to adopt carbon emission right pledge financing rather than merely relying on traditional loan channels.

In this paper, the net earnings of a power enterprise's pledge financing refers to the net value obtained by the power enterprise after choosing to use carbon emission rights for pledge financing. It is the total revenue minus various costs. The total revenue includes the economic earnings of the project itself (e.g., the profits from renewable energy investments), the green reputation gains (e.g., the enhancement of brand value), as well as subsidies or tax incentives at the policy level, etc. The costs include the expenses for purchasing carbon emission allowances, the costs for compliant operations, etc. If the net earnings of the power enterprise are less than or equal to zero, the enterprise has no incentive to conduct carbon emission right pledge financing. Under the state of evolutionary game equilibrium, a rational enterprise will not choose a strategy that leads to losses or zero earnings. In the real economy, the potential earnings of an enterprise may fluctuate significantly due to the strength of policies and market conditions. Generally speaking, however, the maximized earnings pursued by an enterprise should not expand indefinitely. Therefore, the net earnings parameter reflects whether the internal incentive for a power enterprise to participate in green credit is sufficient. Only when the comprehensive rate of return from pledge financing is higher than that of the traditional credit model will the enterprise be motivated to choose carbon emission right pledge.

3.2.2 Hypothesis 2: Electric Power Enterprises Fabricating Carbon Emission Allowance Data and Its Potential Consequences

Although pledging carbon emission allowances can yield both economic and reputational benefits for Chinese electric power enterprises, some may consider falsifying carbon emission data to illicitly obtain preferential green loans. Let the cost of fabricating carbon emission allowances be denoted by C_1. This cost encompasses the following major components: (1)Data and Technical Expenditures.These include the expenses associated with tampering with monitoring systems, manipulating emission reports, installing deceptive equipment or software, as well as the internal efforts required to conceal such falsifications–such as data reorganization, staff training, and interdepartmental coordination. (2)Legal Risks and Compliance Costs. Once fabrication is detected by regulatory agencies or other external entities (e.g., the media or environmental organizations), the enterprise faces potential administrative penalties, legal actions, fines, and even personal liability for executives. These legal risks figure prominently in the overall cost of data falsification and can substantially affect the firm's future compliance operations and financing activities. (3)Internal Governance and Organizational Costs. Implementing fraudulent practices often involves multiple departments or individuals within the enterprise, which may lead to collusion or "willful neglect" behaviors. Such misconduct undermines the internal control system. To prevent detection by external or internal audits and supervisory bodies, additional resources must be allocated to strengthen internal monitoring, further inflating governance costs.

When carbon emission trading exchanges enforce strict oversight, any fraudulent behavior, once exposed, not only disqualifies an enterprise from obtaining preferential loans but also inflicts additional reputational harm I_1 by eroding public and investor trust. This erosion may manifest in diminished investor confidence, consumer boycotts, or the loss of eligibility for future government subsidies. In financial and legal arenas, the enterprise may be compelled to repay existing loans ahead of schedule, pay substantial default penalties, or lose subsequent financing opportunities. Within carbon trading markets and the broader industry, the firm's credibility would also suffer a significant blow. Moreover, both the enterprise and its management may be subject to penalties under environmental and financial regulations–ranging from fines and restricted market access to more severe legal liabilities. These various sanctions not only result in immediate economic losses but can also place the firm on a long-term compliance "blacklist," sharply raising future governance and operating costs.

Conversely, if the carbon emission trading exchange adopts lax regulations, falsified data may be less likely to be detected promptly, allowing certain enterprises to secure preferential loans in the short term. Nevertheless, this fraud erodes social welfare $-\pi_1$ by undermining environmental objectives, distorting market credibility, and compromising the integrity of the green finance system. For the enterprise, the decision to engage in data falsification hinges on carefully calculating and weighing the short - term gains procured from deceitfully obtained loans, which seem alluring in the moment, against the menacing and latent threat of severe punishment and substantial reputational damage that would inevitably ensue if fraud is exposed. In regulatory environments where the rules are less stringent and the supervision is relatively lax, firms, driven by the allure of quick financial gains, might be more inclined to take this perilous risk. However, in contrast, within more stringent regulatory settings, where the watchful eyes of authorities and public scrutiny are more intense, the costs of fraud, not only in terms of direct financial penalties but also including the intangible yet far - reaching reputational losses, far exceed and overshadow any meager and temporary economic benefits that could be obtained through such unethical means.

Owing to these substantial and multifaceted costs and consequences, enterprises must carefully weigh whether to resort to data fabrication. The short-term, illegitimate profits may pale in comparison to the cumulative losses incurred once fraud is detected. Consequently, from an evolutionary game perspective, fabricating carbon emission data is generally unsustainable, particularly as regulatory scrutiny intensifies and society grows increasingly attentive to green integrity, both of which substantially elevate the long-term risks and negative impacts of fraud.

3.2.3 Hypothesis 3: Regulatory Intensity of Carbon Emission Trading Exchanges and Their Intermediary Role

As the central intermediary connecting electric power enterprises with potential buyers and financing institutions, carbon emission trading exchanges must implement rigorous regulatory mechanisms to preserve market credibility. Such mechanisms entail regulatory costs C_2, including market surveillance, audits, and administrative oversight; concurrently, exchanges recoup some of these expenses by charging service fees E_2 to participating firms.

Under stringent regulatory conditions, if an electric power enterprise attempts fraud, such misconduct is more likely to be detected and punished, thereby safeguarding the legitimacy of green finance transactions and ensuring environmental objectives are upheld. However, some exchanges may choose to relax regulatory scrutiny in the short run to boost trading volume and increase revenue. Should government agencies ultimately uncover fraudulent activities, both the enterprise βF and the platform $(1-\beta)F$ may be penalized—for instance, through fines—on the grounds that the trading exchange has failed to discharge its regulatory obligations. Thus, the exchange must balance its pursuit of short-term profits against the maintenance of long-term trust and credibility. Accordingly, Hypothesis 3 highlights the dilemma faced by carbon emission trading exchanges: on one hand, robust regulatory mechanisms are indispensable for sustaining market transparency and healthy development; on the other hand, lax oversight may yield higher short-term income but, once government sanctions are imposed, can severely undermine the platform' s long-term reputation and standing in the market.

3.2.4 Hypothesis 4: Banks' Engagement in Green Finance and Government Support Mechanisms

From the perspective of banks, offering preferential loans for carbon emission allowance pledge projects entails certain operational costs. Let the cost of engaging in green finance be denoted by C_3, encompassing expenditures such as professional talent acquisition, the development of green financial products, and the environmental risk assessment of pledged assets. At the same time, the returns on green loans $eB_1(1+R)$ may be higher, partially due to enhanced social reputation, more favorable interest rate spreads, or the potential to attract green investment funds. Nevertheless, banks also incur additional expenses $B_1(1+r)$, such as those related to reviewing and continuously monitoring pledged carbon assets.

In many countries or regions, governments actively encourage financial institutions to broaden their green finance portfolios, primarily by providing subsidies S to offset some of the bank's operating costs or by sharing a portion of the risks. For instance, if a green loan project defaults, the government may cover a certain percentage (denoted by λ) of the bank's loss, thereby mitigating concerns over lending risks. If a bank opts not to engage in green finance, it can continue to earn revenue $eB_2(1+R)$ from conventional credit activities and bear only the usual costs $B_2(1+r)$ of standard lending operations, which typically involve lower procedural and compliance burdens.

Therefore, Hypothesis 4 posits that a bank's inclination to favor carbon emission allowance pledge financing depends on whether, in light of government subsidies and risk-sharing mechanisms, the expected net benefits and risks of green finance surpass those of traditional lending. If government incentives—such as subsidies and risk-sharing—effectively reduce the uncertainties associated with green loans, banks become more willing to support carbon emission allowance pledge projects. However, if such incentives are insufficient or if conventional lending is comparatively more straightforward and stable, banks may continue to focus on their traditional loan offerings.

In summary, 4 hypotheses together construct an interrelated theoretical framework that comprehensively illustrates the dynamic interplay among electric power enterprises, carbon emission trading exchanges, and banks in the realm of carbon emission allowance pledge financing (see Figure 1). While electric power enterprises weigh project returns, reputational factors, and potential regulatory risks (Hypotheses 1 and 2), carbon emission trading exchanges grapple with the tension between rigorous oversight and short-term earnings (Hypothesis 3). Meanwhile, banks evaluate whether to engage in green finance based on available government subsidies and their own profit considerations (Hypothesis 4). Within this ecosystem, government actions—including strengthened supervision and financial subsidies—not only increase the likelihood of detecting fraudulent activities but also motivate banks to expand the scale and depth of green credit. Overall, only when regulatory measures are sufficiently robust and subsidy and risk-sharing mechanisms are appropriately designed can carbon emission allowance pledge financing achieve both economic viability and environmental sustainability, thereby contributing more substantially to society's broader green transition objectives.

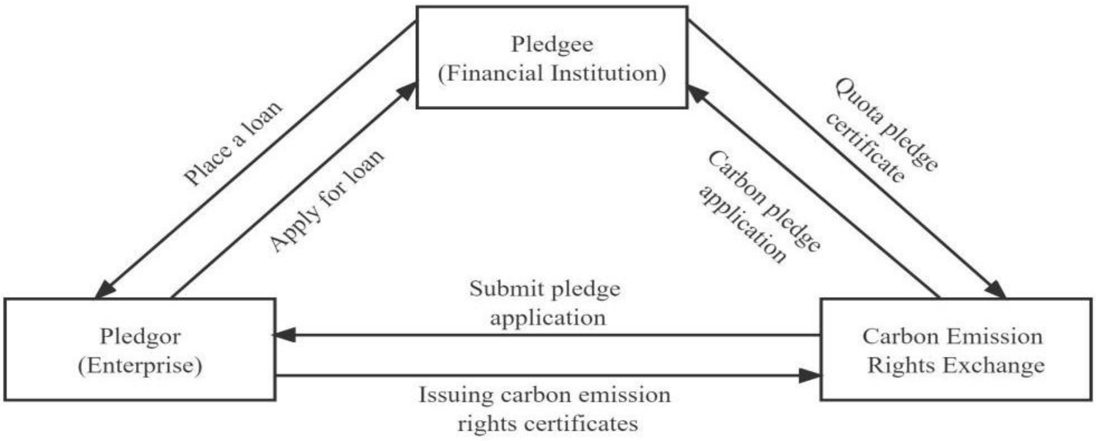

Figure 1 Process of carbon pledge financing

Based on the above assumptions, the definitions of the specific variable and symbols of interest are set out in Table 1 Representation and meaning of variables.

Table 1 Representation and meaning of variables

Variable Meaning	Variable representation	Variable Meaning	Variable representation
Enterprises get green financial preferential loans	B_1	Service fees paid by enterprises to carbon emission rights exchange	E_2
Project Yield	α	Government Penalty coefficient	F
Corporate green income	E_1	Government fines for fraudulent loan enterprises	βF
Additional cost of purchasing carbon emission rights	ΔC	Cost of green financial business for banks	C_3
External benefits for companies using carbon emission rights pledge financing	I_0	Bank loan principal and interest recovery rate	e
Ordinary loan amount	B_2	Bank loan rates	R
Cost of corporate counterfeiting	C_1	Bank deposit rates	r
Reputational damage when corporate counterfeiting is discovered	I_1	Banks receive government subsidies for green financial business	S
The negative social effects of deregulation of carbon emission rights exchange that allow companies to defraud successfully	$-\pi_1$	The proportion of bank losses borne by the government	λ
The cost of strict regulatory controls on the carbon emissions rights exchange	C_2	Reputational benefits of banks offering carbon emission rights pledged loan business	π_2

4. Equilibrium Solutions

4.1 Jacobian Matrix

It is therefore assumed that the integrity awareness of electric power enterprises is represented as x. That is, the proportion of choosing an honest strategy is described as $x\left(0 \le x \le 1\right)$, and the proportion of pretending to defraud the bank's preferential loan amount is denoted as $1-x$. The probability of strict supervision of carbon emission rights exchange is $y\left(0 \le y \le 1\right)$, and the probability of deregulation is represented as $1-y$. The probability of banks providing green preferential loans is $z\left(0 \le z \le 1\right)$. Furthermore, the game payoff matrix is shown in Table 2 Benefit matrix for power companies, carbon emission rights exchanges, and banks.

Table 2 Benefit matrix for power companies, carbon emission rights exchanges, and banks

Game subjects			Bank	
			Green concessional loan amount available	No concessional loan amount available
Enterprise	Honesty	Exchange: Strict regulation	$\alpha B_1 + E_1 + I_0 - \Delta C - E_2$	$\alpha B_2 + E_1 + I_0 - \Delta C - E_2$
			$\pi_2 + S + eB(1+R) - B_1(1+r) - C_3$	$eB_2(1+R) - B_2(1+r)$
			$E_2 - C_2 + \pi_1$	$E_2 - C_2 + \pi_1$
		Exchange: Deregulation	$\alpha B_1 + E_1 + I_0 - \Delta C - E_2$	$\alpha B_2 + E_1 + I_0 - \Delta C - E_2$
			$\pi_2 + S + eB_1(1+R) - B_1(1+r) - C_3$	$eB_2(1+R) - B_2(1+r)$
			$E_2 - \pi_1$	$E_2 - \pi_1$
	Counterfeiting	Exchange: Strict regulation	$\alpha B_2 - C_1 - I_1 - E_2$	$\alpha B_2 - C_1 - I_1 - E_2$
			$S + eB_2(1+R) - B_2(1+r) - C_3$	$eB_2(1+R) - B_2(1+r)$
			$E_2 - C_2 + \pi_1$	$E_2 - C_2 + \pi_1$
		Exchange: Deregulation	$\alpha B_1 - C_1 - I_1 - \beta F - E_2$	$\alpha B_2 - C_1 - E_2$
			$S + eB_1(1+R) - B_1(1+r) - C_3 - \pi_2 + \lambda(1-e)B_1$	$eB_2(1+R) - B_2(1+r)$
			$E_2 - \pi_1 - (1-\beta)F$	$E_2 - \pi_1$

4.2 Equilibrium Point Solutions

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Premised on the benefits matrix for power companies, carbon emission rights exchanges, and banks, as indicated in Table 2, the expected return of electric power enterprises using their own owned or purchased carbon emission rights to pledge financing to banks is represented as E_{11}, and the expected return of pretending to defraud bank loans is E_{12}:

$$E_{11} = z\alpha B_1 - z\alpha B_2 + \alpha B_2 + E_1 - E_2 + I_0 - \Delta C \tag{1}$$

$$E_{12} = yz\alpha B_2 - yz\alpha B_1 + z\alpha B_1 - z\alpha B_2 + yE_2 - yE_1 + yzI_1 + yz\beta F - yI_1 - zI_1 - z\beta F + \alpha B_2 - C_1 - E_2 \tag{2}$$

$$A_1 = E_{11} - E_{12} \tag{3}$$

Hence, the dynamic replication equation of the enterprise is:

$$F(x) = \frac{dx}{dt} = x(1-x)\left(E_1 + I_0 - \Delta C + C_1 + yz\alpha B_1 - yz\alpha B_2 + yE_1 - yE_2 + yI_1 - yzI_1 - yz\beta F + zI_1 + z\beta F\right)$$

.

The expected benefit of strict regulation of the carbon emission rights exchange is E_{21}, and the expected benefit of deregulation is E_{22}:

$$E_{21} = E_2 - C_2 + \pi_1 \tag{4}$$

$$E_{22} = xz(1-\beta)F - z(1-\beta)F + E_2 - \pi_1 \tag{5}$$

$$A_2 = E_{21} - E_{22} \tag{6}$$

The replication dynamics equation for a carbon emission rights exchange is: $F(y) = \frac{dy}{dx} = y(1-y)\left[z(1-\beta)F - xz(1-\beta)F + 2\pi_1 - C_2\right]$. Also, the bank's expected return for providing carbon emission rights pledge financing is E_{31}, and the expected return for not providing pledge financing is E_{32}:

$$E_{31}=\left[e\left(1+R\right)-\left(1+r\right)\right]\left(yB_2-xyB_2+B_1-yB_1+xyB_1\right)+\lambda\left(1-e\right)\left(B_1-yB_1+xyB_1-xB_1\right)$$
$$+2x\pi_2+y\pi_2-xy\pi_2+S-C_3-\pi_2 \tag{7}$$

$$E_{32}=eB_2\left(1+R\right)-B_2\left(1-r\right) \tag{8}$$

$$A_3=E_{31}-E_{32} \tag{9}$$

The replication dynamics equation for the bank is:

$$F\left(z\right)=\frac{dz}{dt}=z\left(1-z\right)\begin{Bmatrix}\left[\left(e+eR-1-r\right)\left(1+xy-y\right)\left(B_1-B_2\right)+\lambda\left(1-e\right)B_1-\pi_2\right] \\ -x\lambda\left(1-e\right)B_1+2x\pi_2+S-C_3\end{Bmatrix} \tag{10}$$

To find the equilibrium point of the evolutionary stabilization strategy, let $F\left(x\right)=0$, $F\left(y\right)=0$ and $F\left(z\right)=0$, the evolutionary stabilization equilibrium points of the firm, the carbon emission rights exchange, and the bank can be obtained as $E_1\left(0,0,0\right)$, $E_2\left(0,0,1\right)$, $E_3\left(0,0,1\right)$, $E_4\left(0,0,1\right)$, $E_5\left(1,0,0\right)$, $E_6\left(1,0,1\right)$, $E_7\left(1,1,0\right)$, $E_8\left(1,1,1\right)$ and $E_9\left(x^*,y^*,z^*\right)$. Where $E_9\left(x^*,y^*,z^*\right)$ is the equilibrium point requires the following conditions to be met:

$$\begin{cases} E_1+I_0-\Delta C+C_1+yz\alpha B_1-yz\alpha B_2+yE_1-yE_2+yI_1-yzI_1-yz\beta F+zI_1+z\beta F=0 \\ z\left(1-\beta\right)F-xz\left(1-\beta\right)F+2\pi_1-C_2=0 \\ \left[\left(e+eR-1-r\right)\left(1+xy-y\right)\left(B_1-B_2\right)+\lambda\left(1-e\right)B_1-\pi_2\right]-x\lambda\left(1-e\right)B_1+2x\pi_2+S-C_3=0 \end{cases} \tag{11}$$

4.3 Stability Analysis

4.3.1 Asymptotic stability analysis of power companies

Based on the above dynamic equations, the stability of the evolutionary strategy of power companies is analyzed (Cowden, 2012; Gao & Zhao, 2018; Gao et al., 2022). Let $F\left(x\right)=0$, then we have $x=0$, $x=1$ and $z=\frac{yE_2-yE_1+\Delta C-E_1-I_0-C_1-yI_1}{y\left(\alpha B_1+\alpha B_2-I_1-\beta F\right)+I_1+\beta F}$. According to the stability theorem of the dynamic replication equation, when $F(x)=0$, $F^{'}(x)<0$, x is an evolutionarily stable strategy. Where $F^{'}(x)=(1-2x)A_1$.

When $z=\frac{yE_2-yE_1+\Delta C-E_1-I_0-C_1-yI_1}{y(\alpha B_1+\alpha B_2-I_1-\beta F)+I_1+\beta F}$, then $F(x)\equiv 0$, then any value of x is a stable state, and the strategic choice of power enterprises does not change with time.

When $0<z<\frac{yE_2-yE_1+\Delta C-E_1-I_0-C_1-yI_1}{y(\alpha B_1+\alpha B_2-I_1-\beta F)+I_1+\beta F}$, substitute $x=0$ and $x=1$ into $F^{'}(x)$ respectively to obtain $F^{'}(0)<0$, $F^{'}(1)>0$, then $x=0$ is known to be a stable point. In other words, when banks are less willing to provide green concessional loans than $\frac{yE_2-yE_1+\Delta C-E_1-I_0-C_1-yI_1}{y(\alpha B_1+\alpha B_2-I_1-\beta F)+I_1+\beta F}$, power companies will not choose to use the carbon emission rights they own or purchase additionally to pledge financing.

When $\frac{yE_2-yE_1+\Delta C-E_1-I_0-C_1-yI_1}{y(\alpha B_1+\alpha B_2-I_1-\beta F)+I_1+\beta F}<z<1$, substitute $x=0$ and $x=1$ into $F^{'}(x)$ respectively to obtain $F^{'}(0)>0$, $F^{'}(1)<0$, then $x=1$ is known to be a stable point. When banks are more willing to conduct green lending, power companies use carbon emission rights to pledge finance.

4.3.2 Equilibrium point stability analysis

The Jacobian matrix can be obtained by calculating the partial derivative from the dynamic equation as follows:

$$J_1 = \begin{bmatrix} (1-2X)A_1 & x(1-x)\begin{pmatrix} z\alpha B_1 - z\alpha B_2 \\ +E_1 - E_2 + I_1 \\ -zI_1 - z\beta F \end{pmatrix} & x(1-x)\begin{pmatrix} y\alpha B_1 - y\alpha B_2 \\ -yI_1 - y\beta F \\ +I_1 + \beta F \end{pmatrix} \\ -y(1-y)z(1-\beta)F & (1-2y)A_2 & y(1-y)(1-\beta)F(1-x) \\ y(B_1 - B_2)\begin{bmatrix} e(1+R)-(1+r) \\ +\lambda(1-e)B_1 - \pi_2 \end{bmatrix} \\ -\lambda(1-e)B_1 + 2\pi_2 & (x-1)(B_1-B_2)\begin{bmatrix} e(1+R)-(1+r) \\ +\lambda(1-e)B_1 - \pi_2 \end{bmatrix} & (1-2z)A_3 \end{bmatrix} \tag{12}$$

The stability of each equilibrium point is examined according to the eigenvalues of the Jacobian matrix, as shown in Table 3 Estimation of the Eigenvalues.

Table 3 Estimation of the Eigenvalues

Equilibrium Point	Eigenvalue 1	Eigenvalue 2	Eigenvalue 3
$(0,0,0)$	$E_1 + I_0 - \Delta C + I_1$	$2\pi_1 - C_2$	$(B_1 - B_2)[e(1+R)-(1+r)]$ $+\lambda(1-e)B_1 - \pi_2 + S - C_3$
$(1,0,0)$	$-(E_1 + I_0 - \Delta C + I_1)$	$2\pi_1 - C_2$	$(B_1 - B_2)[e(1+R)-(1+r)]$ $+\pi_2 + S - C_3$
$(0,1,0)$	$2E_1 + I_0 - \Delta C + C_1 - E_2 + I_1$	$-(2\pi_1 - C_2)$	$S - C_3$
$(0,0,1)$	$E_1 + I_0 - \Delta C + C_1 + I_1 + \beta F$	$2\pi_1 - C_2 + (1-\beta)F$	$-(B_1 - B_2)[e(1+R)-(1+r)]$ $-\lambda(1-e)B_1 + \pi_2 - S + C_3$
$(0,1,1)$	$2E_1 + I_0 - \Delta C + C_1$ $+\alpha B_1 - \alpha B_2 - E_2 + I_1$	$-[2\pi_1 - C_2 + (1-\beta)F]$	$-(S - C_3)$
$(1,0,1)$	$-(E_1 + I_0 - \Delta C + C_1 + I_1 + \beta F)$	$2\pi_1 - C_2$	$-(B_1 - B_2)[e(1+R)-(1+r)]$ $-\pi_2 - S + C_3$
$(1,1,0)$	$-(2E_1 + I_0 - \Delta C + C_1 - E_2 + I_1)$	$-(2\pi_1 - C_2)$	$-\lambda(1-e)B_1 + 2\pi_2 + S - C_3$
$(1,1,1)$	$-(2E_1 + I_0 - \Delta C + C_1 + \alpha B_1 - \alpha B_2 - E_2 + I_1)$	$-(2\pi_1 - C_2)$	$\lambda(1-e)B_1 - 2\pi_2 - S + C_3$

According to the assumptions, the participants are all rational people, so the net return of power enterprises using the carbon emission rights they own or purchase to pledge financing to banks should be positive, which is represented as: $\alpha B_1 + E_1 + I_0 - \Delta C - E_2 > 0$. Similarly, under the maximum loan principal and interest recovery rate e, the net return of banks carrying out pledge financing business should be greater than 0, i.e., $\pi_2 + eB_1(1+R) - B_1(1+r) - C_3 > 0$. Under the government risk compensation mechanism, the loss of banks will be minimized, but banks will not be turned into profit as a result, and the bank will turn its losses into profits, represented as: $eB_1(1+R) - B_1(1+r) - C_3 + \lambda(1-e)\mathrm{B}_1 < 0$. In the case of not being discovered by the government, the carbon emission rights exchange is more inclined to choose to relax the audit compared to strict regulatory review, at which time the net return is positive, i.e., $E_2 - \pi_1 > 0$. Moreover, in the case that the interests of all parties are satisfied, it makes the equilibrium point analysis more concise and intuitive, and it helps to determine and ensure that the initial parameters are consistent with $2E_1 + I_0 - \Delta C + C_1 + \alpha B_1 - \alpha B_2 - E_2 + I_1 > 0$, $2\pi_1 - C_2 > 0$, $\lambda(1-e)B_1 - 2\pi_2 - S + C_3 < 0$.

Based on the above assumptions, the asymptotic stability of each equilibrium point under different situations is evaluated separately, as shown in Table 4 Stability analysis of the equilibrium point in the sub-case.

Table 4 Stability analysis of the equilibrium point in the sub-case

Equilibrium Point	$S=0,\lambda=0$				$\lambda=0$				$S=0$			
	Eigenvalue symbol			Result	Eigenvalue symbol			Result	Eigenvalue symbol			Result
(0,0,0)	N	+	−	Unstable	N	+	−	Unstable	N	+	−	Unstable
(1,0,0)	N	+	N	Unstable	N	+	N	Unstable	N	+	N	Unstable
(0,1,0)	N	−	−	Unstable	N	−	N	Unstable	N	−	−	Unstable
(0,0,1)	N	+	+	Unstable	N	+	+	Unstable	N	+	+	Unstable
(0,1,1)	+	−	+	Unstable	+	−	N	Unstable	+	−	+	Unstable
(1,0,1)	N	+	N	Unstable	N	+	N	Unstable	N	+	N	Unstable
(1,1,0)	N	−	+	Unstable	N	−	+	Unstable	N	−	+	Unstable
(1,1,1)	−	−	−	ESS	−	−	−	ESS	−	−	−	ESS

When $2E_1 + I_0 - \Delta C + C_1 - E_2 + I_1 < 0$, the sum of the benefits of owning or purchasing carbon emission rights by the power company to obtain a pledged bank financing loan, the indirect benefits of green production, and the costs of disguised deception are less than the costs of green production, at which point the eigenvalues are negative and the equilibrium point $(0,1,0)$ depicts evolutionary stabilization strategy, with the corresponding strategy combination {fake, regulate, no green concessional loans}.

When $2E_1 + I_0 - \Delta C + C_1 + \alpha B_1 - \alpha B_2 - E_2 + I_1 > 0$, the sum of the credit benefits and the government's share of the loan financing risk from the bank's green concessional loan business is greater than the indirect benefits and social welfare from the new business, and the eigenvalues of the matrix are negative at this point, the equilibrium point $(1,1,1)$ is the evolutionary stability strategy, and the corresponding strategy combination is {honesty, regulation, and providing green concessional loans}.

5. Simulation Analysis

5.1 Simulation Settings

According to the dynamic replication equation and its constraints, MATLAB software is employed for simulation to analyze various aspects of the evolutionary game model. This analysis focuses on the initial willingness of each participant, the proportion of government subsidies, risk-taking, and the impact of punishment on the evolution process. The specific parameters used in the simulation are carefully chosen to reflect realistic conditions and are set as follows:

$$\alpha = 1.2, \beta = 0.3, I_0 = 3, I_1 = 4, \Delta C = 20, C_1 = 15, C_2 = 2, C_3 = 2, B_1 = 6, B_2 = 4, \pi_1 = 3,$$

$$\pi_2 = 2, R = 0.6, r = 0.1, e = 0.95, E_1 = 5, E_2 = 3, F = 30, S = 8, \lambda = 0.5$$

The initial participation willingness of power enterprises, carbon emission rights exchanges, and banks is set at $x = y = z = 0.5$, indicating a neutral starting point where each participant has a 50% probability of engaging in their respective strategies. This setup allows for the examination of how initial conditions influence the evolutionary outcomes over time.

The choice of these parameters is grounded in both theoretical considerations and empirical data, ensuring that the simulation results are relevant and applicable to real-world scenarios. For instance, the values α of and β reflect the intensity of ecological protection efforts and government subsidies, respectively, while C_1 and C_2 represent the costs associated with enterprise fraud and strict regulatory controls. By using MATLAB for these simulations, we can visualize the evolution of strategies among stakeholders and assess the stability of various equilibria. The analysis reveals how different levels of government intervention, such as varying the amount of subsidies S or the proportion of risk borne by the government λ, impact the behavior of power enterprises and financial institutions. Additionally, the role of punishment F in deterring fraudulent activities and promoting honest behavior is critically evaluated.

5.2 Evolution Trends and Equilibrium States

Hence, Figure 2. Trends in the tripartite evolution of pledge financeshows the evolution trend of the three-carbon emission rights pledge financing parties. It is, therefore, not cumbersome to conclude that each subject eventually tends to the equilibrium point $(1,1,1)$ and reaches the ideal state, that is, power enterprises choose the honest strategy, carbon emission rights exchanges strictly supervise, and banks actively carry out green pledge financing business. Figure 3. The impact of initial willingness and penalties on power companies also depicts the impact of initial willingness and penalties on power companies.

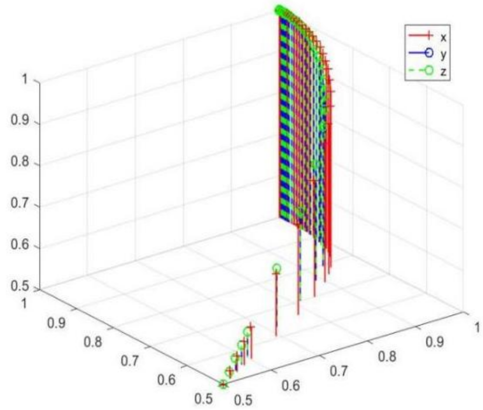

Figure 2. Trends in the tripartite evolution of pledge finance

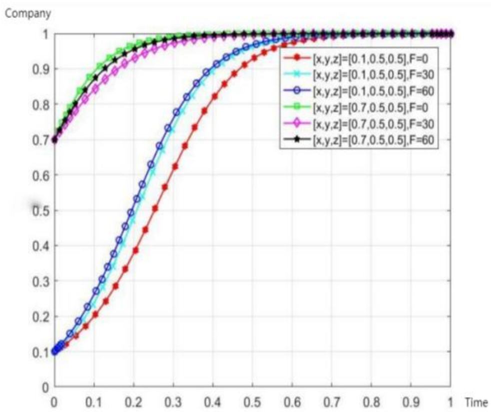

Figure 3. The impact of initial willingness and penalties on power companies

5.3 Effect of Penalty Ratios on Stakeholder Behavior

As seen from Figure 3. The impact of initial willingness and penalties on power companies, when the penalty is zero, and the willingness of power companies to provide honest pledges of carbon emission rights is low, the stabilization rate is slow. The cost of pledging carbon emission rights owned or purchased by power companies is relatively high. Hence, the motivation of power companies to reduce emissions and to provide green credit becomes low. However, as power companies become more aware of the need to control emissions, their initial willingness to do so accelerates the rate at which they evolve a stabilization strategy. In addition, the increase in government penalties plays a more prominent role when the initial willingness is low; when the initial willingness is 0.7, and the penalties continue to increase, the motivation of power enterprises does not increase significantly, and the rate of evolution decreases rather than increases.

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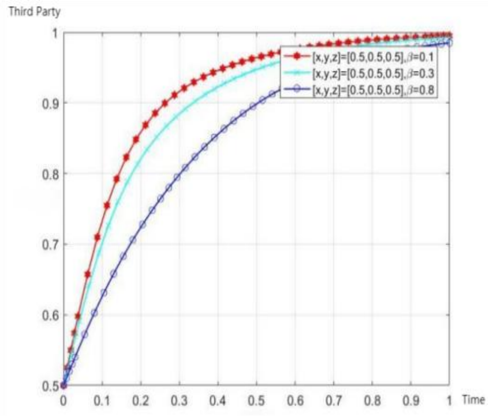

Figure 4. Impact of penalty ratios on the carbon emission rights exchange

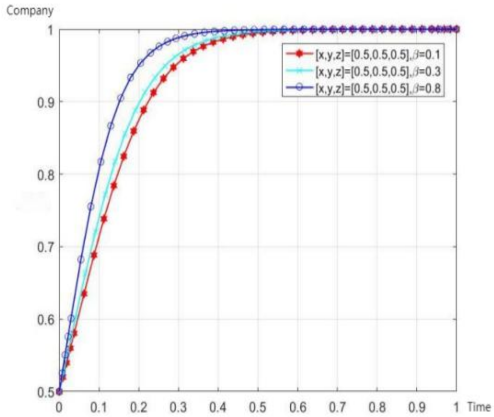

Figure 5. The impact of penalty ratios on power companies

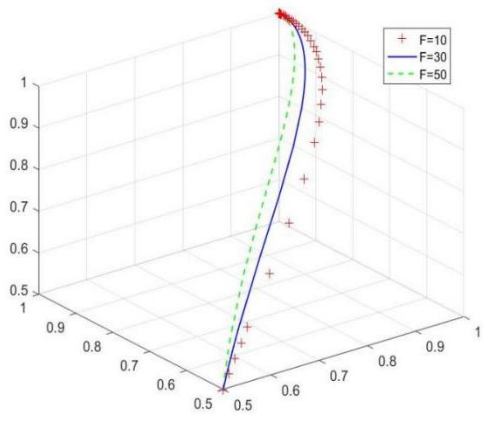

Figure 6. Impact of penalty amount on three parties

The analysis in Figure 4. Impact of penalty ratios on the carbon emission rights exchange shows that when the initial willingness is the same, the proportion of government penalties borne by the carbon emission rights exchange is represented as $1-\beta$. As β gradually increases and $1-\beta$ gradually decreases, the willingness of the carbon emission rights exchange to strictly regulate companies decreases, and the rate of evolution slows down significantly. When government penalties on exchanges increase, the pressure on the amount of penalties leads carbon exchanges to opt for strict regulation voluntarily, and the rate of evolution accelerates over time. Also, Figure 5. The impact of penalty ratios on power companies demonstrates that when the initial willingness remains constant, the rate of evolution gradually accelerates as the government's penalties for falsifying falsifications increase. Therefore, it deters power companies from paying the penalty amount and uses carbon emission rights for pledge financing to avoid the penalties as much as possible.

In contrast to grid enterprises, power generation enterprises, small and medium-sized micro power users urgently need loans from financial enterprise banks to finance their operations. Carbon emission rights pledges can provide greater financing channels for power companies, micro-enterprises, and small and medium-sized electricity users. Conversely, they can also help grid enterprises unlock the value of data elements. It can be further observed from Figure 6. Impact of penalty amount on three parties that when the initial willingness value of all three parties is controlled at 0.5, the penalty amount significantly affects the evolution rate, and the larger the penalty, the faster the evolution rate tends to stabilize. Therefore, the government should strictly supervise the pledge financing process of the power industry and appropriately increase the penalty amount to guide and regulate power enterprises' financing behaviour.

5.4 Effect of Government Subsidies on Banks

As shown in Figure 7. Impact of government subsidies on Banks, the effects of the two types of support, direct government subsidies and the assumption of bank losses, differ. In both cases $(S=0, \lambda=0.5)$ and $(S=8, \lambda=0)$, the direct government subsidy has a more pronounced effect on the rate of bank evolution. That is, banks are more sensitive to ex-ante subsidies than ex-post subsidies as a form of support. Ex-ante direct government subsidies can reduce the cost of starting new businesses for banks and are more conducive to motivating banks to develop green pledges and credit services. When government subsidies are low, banks' willingness to start green businesses tends to decrease. The comparison between scenarios $(S=8, \lambda=0)$ and $(S=8, \lambda=0.9)$ shows that banks are most motivated when the government combines ex-ante and ex-post subsidies; the evolutionary process's stabilization rate accelerates over time.

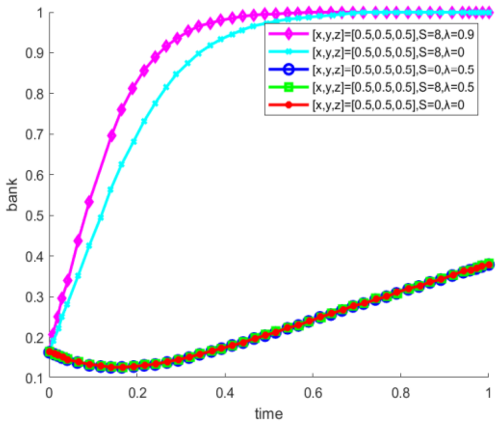

Figure 7. Impact of government subsidies on Banks

6. Conclusion

This paper analyzed the amount of carbon emission rights pledges as the subject matter and constructed an evolutionary game model of pledge financing composed of power enterprises, carbon emission rights exchanges, and banks under the participation of the government. Based on the numerical simulation results, this paper explores effective measures to maximize carbon emission rights and achieve a Pareto optimal state from the four perspectives of government, enterprises, carbon emission rights exchanges, and banks. The main conclusions are as follows: Firstly, the Pareto optimum of pledged financing can be honestly achieved by power companies using carbon emission rights they own or purchase to apply for loans from banks for financing. This strategy is accomplished through strict regulations by carbon emission rights exchanges and active provision of green preferential loans by banks, which can maximize utility and social welfare. Secondly, it is worth noting that when power companies' willingness to raise funds honestly is low, increasing the penalties can help curb undesirable behaviors; however, when companies' willingness to raise funds honestly is high, increasing the penalties can undermine their motivation. Third, the broader the proportion of penalties borne by the government, the greater the willingness to strengthen audit and regulation. In other words, when the government gradually increases carbon emission rights exchange penalties, it will voluntarily enhance its regulation to avoid penalties. Last but the least, the effect of the government's ex-ante subsidy and ex-post compensation is not the same, with banks being more sensitive to ex-ante subsidies and ex-post compensation being less effective at motivating banks. When the ratio of the two types of support is coordinated and used appropriately, the willingness of banks to undertake green pledge financing will increase significantly.

7. Suggestions

This paper put forward the following policy recommendations for the government, industries, and other third parties to ensure the sustainability of the carbon emission financing pledge policies. At the government level, policymakers must work on "mechanism", "model", and "policy" innovation and ensure strict supervision. First, the governments should improve the new carbon emission rights pledge financing mechanism and unify the trading mechanism. They should improve communication between power companies, market intermediaries, and financial institutions. Whether it is a financing supply body (banks and other financial institutions as fund suppliers), a financing guarantee body (guarantee institutions as fund guarantors), or a financing counseling body (service institutions as professional service providers), all of these institutions should serve power enterprises (especially power generation enterprises) in carbon asset pledge financing activities such as carbon emission rights.

Therefore, constructing this multi-sectoral coordination and linkage mechanism will help all relevant departments and units interconnect and share financing information, easing the "bottleneck" of financing information in the pledge process. In addition, as there is no national carbon trading market in China, each province and municipality have the right to operate its carbon trading market, with different rules and regulations, including allocation methods, coverage, and penalties for non-compliance. Simultaneously, in terms of the carbon quota mechanism, the government has to control the relationship between the initial amount of carbon emissions and the cost of emission reduction for enterprises through which the carbon quota mechanism will take effect (Wang et al., 2022). The differences in regional market rules and the existence of local protection and support will make the price of carbon emission rights trading unique and support interoperability of carbon quota trading between regions to avoid the difficulty in achieving the objective.

Furthermore, if the liquidity is weak, it hinders the maturity and growth of the carbon trading market. Therefore, governments should try to reach regional agreements and establish a unified regional carbon market to facilitate carbon trading (Ju et al., 2023). Second, promoting and implementing new carbon emission rights pledge financing models. Firstly, unblocking pledge financing channels. Under the collaborative effort of the local government, banks, other financial institutions, and power generation enterprises should sign cooperation agreements on carbon emission rights pledge financing to open further the pledge financing channels between the government, banks, and enterprises and innovate a new model of cooperation among "government, banks, and enterprises". Drawing on the updated model of "carbon emission allowance pledge overlay insurance financing" agreed between the Bank of Communications, Shenneng Carbon Technology Company. This will fully play the critical role of financial support for carbon peaking and neutrality (Gallo & Marinelli, 2020; Larsson, 2009). Secondly, on the premise of risk control and commercial sustainability, drawing on critical lessons from the successful experience of carbon emission rights pledge financing in China (Sun et al., 2022;Chen & Chen, 2021). It will help promote the effective integration of green finance with inclusive finance, science, and innovation, to support the green development of technology-based enterprises and industrial transformation and upgrading on a more extensive and deeper level (Kang et al., 2020). Improve the public disclosure mechanism for carbon emission pledge financing to prevent duplicate pledges (Zhou et al., 2022). The nationwide carbon emission rights registration and inquiry agency is still in its infancy in China. Implementing these systems can help record carbon emission allowance holdings and changes. It will help prevent companies from using allowance pledges repeatedly, and more professional and authoritative tools should be adopted for testing.

Moreover, registration and public disclosure have greater credibility and broader oversight. For industries that have yet to be regulated, registration and public disclosure can reduce multiple registrations, scattered registrations, and duplicate pledges by enterprises (Chen & Wu, 2023). Banks and other financial institutions should practice green financial credit services solidly. To begin with, banks and other financial institutions should actively respond to the call of the Party Central Committee on the development of green finance, land carbon emission rights pledge loan funds and increase green credit investment; make full use of the carbon emission rights pledge credit policy to support clean production, environmental protection and transformation, energy-saving and environmental protection mechanisms, and new energy manufacturing projects (Han et al., 2023). Additionally, banks and other financial institutions should deeply implement the concept of green development and use green credit and other tools to promote the low-carbon transformation of investment and financing structures (Su et al., 2022; Zhang et al., 2022). They should encourage the development of carbon finance and give full support to power generation and consumption enterprises that use carbon emission rights and carbon assets as the main pledges to conduct financing and "green light" projects. For instance, in the contract energy management model, a moderate increase in the risk premium can make the model achieve a desirable effect. However, too high a risk premium can make companies less willing to invest in green (Guo et al., 2022; Zhang et al., 2022). Therefore, banks need to control risk levels with the degree of green market saturation.

At the carbon emission rights exchange level, it is vital to ensure that data information is authentic and valuation results are reliable. Unlike other properties pledged for financing, carbon emission rights are notable for their inherent natural policy nature and are highly susceptible to external circumstances and policies. As the current standards for valuation in the domestic carbon emission rights trading market are not entirely unified, the valuation methods are confusing and inefficient. Thus, the valuation system is too arbitrary and subjective, leading to significant differences in valuation results between the two parties. In the long run, it will also not be conducive to implementing supervision and control, and the risks in the carbon trading market will increase steeply. Therefore, to promote the smooth development of carbon emission rights pledge financing, it is necessary to review, regulate and standardize the valuation practices of carbon emission rights exchanges with blockchain technology and improve their authenticity and credibility. In addition to the self-restraint of carbon emission rights exchanges, the government, as the highest-level regulator, should pay more attention to carbon emission rights pledge financing projects and proper penalties that can guide carbon emission rights exchanges to establish a correct view of financing, further regulate financing behavior and resolve financing risks.

References

Agyeman, F. O., Ma, Z., Li, M., Sampene, A. K., Dapaah, M. F., Kedjanyi, E. A. G., & Heydari, M. (2022). Probing the Effect of Governance of Tourism Development, Economic Growth, and Foreign Direct Investment on Carbon Dioxide Emissions in Africa: The African Experience . *Energies*, *15*(13). https://doi.org/10.3390/en15134530

Agyeman, F. O., Ma, Z., Li, M., Sampene, A. K., Adikah, I., & Dapaah, M. F. (2022). Relevance of COVID-19 vaccine on the tourism industry: Evidence from China. *Plos One*, *17*(8). https://doi.org/10.1371/journal.pone.0269200

An, J., & Lee, J. (2018). A Newsvendor Non-Cooperative Game for Efficient Allocation of Carbon Emissions. *Sustainability*, *10*(1). https://doi.org/10.3390/su10010154

An, Q., Lin, C., Li, Q., & Zheng, L. (2023). Research on the impact of green finance development on energy intensity in China. *Frontiers in Earth Science*, *11*. https://doi.org/10.3389/feart.2023.1118939

Ao, X., Ong, T. S., & Teh, B. H. (2023). Corporate Sustainability Development Strategy and Corporate Environmental Governance-The Moderating Role of Corporate Environmental Investments. *Int J Environ Res Public Health*, *20*(5), 4528. https://doi.org/10.3390/ijerph20054528

Appiah, M., Li, M., Onifade, S. T., & Gyamfi, B. A. (2022). Investigating institutional quality and carbon mitigation drive in Sub-Saharan Africa: Are growth levels, energy use, population, and industrialization consequential factors? *Energy & Environment*. https://doi.org/10.1177/0958305x221147602

Appiah, M., Li, M., Sehrish, S., & Abaji, E. E. (2023). Investigating the connections between innovation, natural resource extraction, and environmental pollution in OECD nations; examining the role of capital formation . *Resources Policy*, *81*. https://doi.org/10.1016/j.resourpol.2023.103312

Avila, P., & Mullon, C. (2023). Evolutionary game theory and the adaptive dynamics approach: adaptation where individuals interact. *Philos Trans R Soc Lond B Biol Sci*, *378*(1876). https://doi.org/10.1098/rstb.2021.0502

Bao, J., & He, M. (2022). Does green credit promote green sustainable development in regional economies?-Empirical evidence from 280 cities in China. *Plos One*, *17*(11). https://doi.org/10.1371/journal.pone.0277569

Bharany, S., Sharma, S., Khalaf, O. I., Abdulsahib, G. M., Al Humaimeedy, A. S., Aldhyani, T. H. H., . . . Alkahtani, H. (2022). A Systematic Survey on Energy-Efficient Techniques in Sustainable Cloud Computing. *Sustainability*, *14*(10). https://doi.org/10.3390/su14106256

Bhattacharyya, R. J. G. F. (2021). Green finance for energy transition, climate action and sustainable development: overview of concepts, applications, implementation and challenges. *Green Finance, 4*(1), 1-35. https://doi.org/10.3934/gf.2022001

Bolton, P., & Kacperczyk, M. (2021). Do investors care about carbon risk? [Article]. *Journal of Financial Economics*, *142*(2), 517-549. https://doi.org/10.1016/j.jfineco.2021.05.008

Chen, B., & Wu, R. (2023). Legal and Policy Pathways of Carbon Finance: Comparative Analysis of the Carbon Market in the EU and China [Article]. *European Business Organization Law Review*, *24*(1), 41-68. https://doi.org/10.1007/s40804-022-00259-x

Chen, J., Xu, C., Gao, M., & Li, D. (2022). Carbon peak and its mitigation implications for China in the post-pandemic era. *Scientific Reports*, *12*(1). https://doi.org/10.1038/s41598-022-07283-4

Chen, X., & Chen, Z. (2021). Can China's Environmental Regulations Effectively Reduce Pollution Emissions? [Article]. *International Journal of Environmental Research and Public Health*, *18*(9). https://doi.org/10.3390/ijerph18094658

Cowden, C. C. (2012). *Game Theory, Evolutionary Stable Strategies and the Evolution of Biological Interactions*. Nature Education Knowledge. https://www.nature.com/scitable/knowledge/library/game-theory-evolutionary-stable-strategies-and-the-25953132/

Ferreira, P. F. V., & Vieira, F. D. (2010). Evaluation of an Offshore Wind Power Project: Economic, Strategic and Environmental Value. *World Academy of Science, Engineering and Technology, Open Science Index 47, International Journal of Economics and Management Engineering*, *4*(11), 2132-2137. https://doi.org/10.5281/zenodo.1332598

Fu, S., Chen, W., & Ding, J. (2023). Can carbon asset pledge financing be beneficial for carbon emission-dependent engineering machinery remanufacturing? *International Journal of Production Research*, *61*(19), 6533-6551. https://doi.org/10.1080/00207543.2022.2131929

Gallo, M., & Marinelli, M. (2020). Sustainable Mobility: A Review of Possible Actions and Policies . *Sustainability*, *12*(18). https://doi.org/10.3390/su12187499

Gao, J., & Pan, L. (2022). A System Dynamic Analysis of Urban Development Paths under Carbon Peaking and Carbon Neutrality Targets: A Case Study of Shanghai. *Sustainability*, *14*(22). https://doi.org/10.3390/su142215045

Gao, L., & Zhao, Z.-Y. (2018). System Dynamics Analysis of Evolutionary Game Strategies between the Government and Investors Based on New Energy Power Construction Public-Private-Partnership (PPP) Project. *Sustainability*, *10*(7). https://doi.org/10.3390/su10072533

Gao, Y., Jia, R., Yao, Y., & Xu, J. (2022). Evolutionary Game Theory and the Simulation of Green Building Development Based on Dynamic Government Subsidies. *Sustainability, 14*(12). https://doi.org/10.3390/su14127294

Guo, C.-Q., Wang, X., Cao, D.-D., & Hou, Y.-G. (2022). The Impact of Green Finance on Carbon Emission-Analysis Based on Mediation Effect and Spatial Effect. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.844988

Han, L., Shi, Y., & Zheng, J. (2023). Can green credit policies improve corporate ESG performance? *Sustainable Development*. https://doi.org/10.1002/sd.2803

Hidalgo-Onate, D., Fuertes-Fuertes, I., & Cabedo, J. D. (2023). Climate-related prudential regulation tools in the context of sustainable and responsible investment: a systematic review. *Climate Policy*, *23*(6), 704-721. https://doi.org/10.1080/14693062.2023.2179587

Ju, X., Wan, J., Zhang, Z., Ma, C., Zhang, L., & Zhao, X. (2023). Impact of Chinese Carbon Emissions Trading Policy on Chongqing's Carbon Emissions and Economic Development [Article]. *Sustainability*, *15*(5). https://doi.org/10.3390/su15054253

Kang, M., Zhao, W., Jia, L., & Liu, Y. (2020). Balancing Carbon Emission Reductions and Social Economic Development for Sustainable Development: Experience from 24 Countries. *Chinese Geographical Science*, *30*(3), 379-396. https://doi.org/10.1007/s11769-020-1117-0

Khan, S., Akbar, A., Nasim, I., Hedvicakova, M., & Bashir, F. (2022). Green finance development and environmental sustainability: A panel data analysis . *Frontiers in Environmental Science, 10*. https://doi.org/10.3389/fenvs.2022.1039705

Kim, H., Kim, Y., Ko, Y., & Han, S. (2022). Performance Comparison of Predictive Methodologies for Carbon Emission Credit Price in the Korea Emission Trading System. *Sustainability*, *14*(13). https://doi.org/10.3390/su14138177

Larsson, M. (2009). Global Energy Transformation: Four Necessary Steps to Make Clean Energy the Next Success Story. *Palgrave Macmillan*. https://doi.org/10.1057/9780230244092

Li, F., Guo, Y., Dong, T., Liu, B., & Geng, X. (2024). Tripartite evolutionary game analysis on corporate carbon reduction decisions considering dual supervision under carbon trading. *Computers & Industrial Engineering*, *187*. https://doi.org/10.1016/j.cie.2023.109786

Li, M., Ashraf, M. S., Ma, Z., Ashraf, R. U., Usman, M., & Khan, I. (2023). Adaptation to globalization in renewable energy sources: Environmental implications of financial development and human capital in China [Article]. *Frontiers in Environmental Science, 10*. https://doi.org/10.3389/fenvs.2022.1060559

Li, M., Sun, H., Agyeman, F. O., Heydari, M., Jameel, A., & Khan, H. S. u. d. (2021). Analysis of Potential Factors Influencing China's Regional Sustainable Economic Growth [Article]. *Applied Sciences-Basel*, *11*(22). https://doi.org/10.3390/app112210832

Li, M., Wang, X., Agyeman, F. O., Gao, Y., & Sarfraz, M. (2023). Efficiency Evaluation and the Impact Factors of Sustainable Forestry Development in China: Adoption of Super-Efficiency Data Envelopment Analysis and Malmquist Index Methods [Article]. *Forests*, *14*(5). https://doi.org/10.3390/f14050909

Liang, Y., Wang, Y., Liu, H., Wang, P., Jing, Y., & Li, J. (2021). Optimal Operation Of Integrated Energy System Considering Demand Response. *Journal of Physics: Conference Series*, *2087*(1). https://doi.org/10.1088/1742-6596/2087/1/012017

Liu, F., Huang, X., & Li, L. (2023). The impact of green consumers on electric vehicle charging station diffusion based on complex network evolutionary game. *Energy & Environment*. https://doi.org/10.1177/0958305x231164678

Maqsood, S., Zhou, Y., Lin, X., Huang, S., Jamil, I., & Shahzad, K. (2022). Critical success factors for adopting green supply chain management and clean innovation technology in the small and medium-sized enterprises: A structural equation modeling approach [Article]. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.1008982

Mejia-Escobar, J. C., González-Ruiz, J. D., & Duque-Grisales, E. (2020). Sustainable Financial Products in the Latin America Banking Industry: Current Status and Insights. *Sustainability*, *12*(14), 5648. https://doi.org/10.3390/su12145648

Murgas, B., Henao, A., & Guzman, L. (2021). Evaluation of Investments in Wind Energy Projects, under Uncertainty. State of the Art Review [Review]. *Applied Sciences-Basel*, *11*(21), Article 10213. https://doi.org/10.3390/app112110213

OECD. (2006). Environmental Compliance and Enforcement in China: An Assessment of Current Practices and Ways Forward. *Environmental Compliance and Enforcement Network Meeting*, *12*, 4-5. https://www.oecd.org/environment/outreach/37867511.pdf

Song, Q., Rong, N., Han, S., Ao, W., Huang, H., & Wei, Y. (2022). Decarbonization pathways of China's provincial energy systems under carbon constraints: A case study of Guizhou Province. *Energy Reports*, *8*, 9363-9378. https://doi.org/10.1016/j.egyr.2022.07.045

Su, J., Ma, Z., Li, M., Agyeman, F. O., & Yue, Z. (2022). Efficiency Evaluation and Influencing Factors of Government Financial Expenditure on Environmental Protection: An SBM Super-efficiency Model Based on Undesired Outputs. *Problemy Ekorozwoju*, *17*(1). https://doi.org/10.35784/pe.2022.1.13

Sun, J., Zhai, N., Miao, J., & Sun, H. (2022). Can Green Finance Effectively Promote the Carbon Emission Reduction in "Local-Neighborhood" Areas?-Empirical Evidence from China [Article]. *Agriculture-Basel*, *12*(10). https://doi.org/10.3390/agriculture12101550

Sun, X., Zhou, C., & Gan, Z. (2023). Green Finance Policy and ESG Performance: Evidence from Chinese Manufacturing Firms [Article]. *Sustainability*, *15*(8). https://doi.org/10.3390/su15086781

Sun, Y., Ding, G., Li, M., Zhang, M., Agyeman, F. O., & Liu, F. (2023). The spillover effect of green finance development on rural revitalization: an empirical analysis based on China's provincial panel data. *Environmental Science and Pollution Research*, *30*(20), 58907-58919. https://doi.org/10.1007/s11356-023-26655-5

Van Cleve, J. (2023). Evolutionarily stable strategy analysis and its links to demography and genetics through invasion fitness. *Philos Trans R Soc Lond B Biol Sci*, *378*(1876). https://doi.org/10.1098/rstb.2021.0496

Wang, E., Nie, J., & Zhan, H. (2022). The Impact of Carbon Emissions Trading on the Profitability and Debt Burden of Listed Companies. *Sustainability*, *14*(20). https://doi.org/10.3390/su142013429

Wang, F., Harindintwali, J. D., Yuan, Z., Wang, M., Wang, F., Li, S., . . . Chen, J. M. (2021). Technologies and perspectives for achieving carbon neutrality. *Innovation (Camb)*, *2*(4). https://doi.org/10.1016/j.xinn.2021.100180

Wang, Y., Zhao, H., Duan, F., & Wang, Y. (2018). Initial Provincial Allocation and Equity Evaluation of China's Carbon Emission Rights-Based on the Improved TOPSIS Method. *Sustainability*, *10*(4). https://doi.org/10.3390/su10040982

Xie, Q., & Zhang, Y. (2021). Green credit policies, supporting hand and innovation transformation of enterprises. *Science Research Management*, *42*(1), 124-134. https://doi.org/10.19571/j.cnki.1000-2995.2021.01.012

Xu, B., Xu, Q., Bo, Q., & Hu, Q. (2018). Green Product Development with Consumer Heterogeneity under Horizontal Competition [Article]. *Sustainability*, *10*(6). https://doi.org/10.3390/su10061902

Xu, Y., Liu, S., Song, B., & Liu, R. (2021). Innovative Development of Power Grid Enterprises Under the Background of Energy Digital Economy Transformation. *Proceedings of the 2021 International Conference on Enterprise Management and Economic Development*. https://doi.org/10.2991/aebmr.k.210601.033

Yang, H., Miao, L., & Zhao, C. (2019). The credit strategy of a green supply chain based on capital constraints. *Journal of Cleaner Production*, *224*, 930-939. https://doi.org/10.1016/j.jclepro.2019.03.214

Ye, X., Ji, Z., Xu, J., & Liu, X. (2023). Optimal dispatch of integrated energy systems considering integrated demand response and stepped carbon trading. *Frontiers in Electronics*, *4*. https://doi.org/10.3389/felec.2023.1110039

Yuan, Y., Zhang, B., Wang, L., & Wang, L. (2022). Low-Carbon Strategies Considering Corporate Environmental Responsibility: Based on Carbon Trading and Carbon Reduction Technology Investment. *Sustainability*, *14*(11). https://doi.org/10.3390/su14116683

ISSN: 0067-3064

Zhang, G., Gao, Y., Li, J., Su, B., Chen, Z., & Lin, W. (2022). China's environmental policy intensity for 1978-2019. *Scientific Data*, *9*(1), Article 75. https://doi.org/10.1038/s41597-022-01183-y

Zhang, K. Q., Chen, H. H., Tang, L. Z., & Qiao, S. (2022). Green Finance, Innovation and the Energy-Environment-Climate Nexus. *Frontiers in Environmental Science, 10*. https://doi.org/10.3389/fenvs.2022.879681

Zhang, M., Li, M., Sun, H., Oteng Agyeman, F., Ud Din Khan, H. S., & Zhang, Z. (2022). Investigation of Nexus between Knowledge Learning and Enterprise Green Innovation Based on Meta-Analysis with a Focus on China. *Energies*, *15*(4). https://doi.org/10.3390/en15041590

Zhang, Z., Duan, H., Shan, S., Liu, Q., & Geng, W. (2022). The Impact of Green Credit on the Green Innovation Level of Heavy-Polluting Enterprises-Evidence from China. *International Journal of Environmental Research and Public Health*, *19*(2). https://doi.org/10.3390/ijerph19020650

Zhong, Z., & Peng, B. (2022). Multi-agent behavior strategy game and evolutionary simulation analysis under environmental regulation. *Energy & Environment*. https://doi.org/10.1177/0958305x221125126

Zhou, D. (2020). China’s Environmental Vertical Management Reform: An Effective and Sustainable Way Forward or Trouble in Itself? *Laws*, *9*(4), 25. https://doi.org/10.3390/laws9040025

Zhou, Z., Ma, Z., & Lin, X. (2022). Carbon emissions trading policy and green transformation of China's manufacturing industry: Mechanism assessment and policy implications [Article]. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.984612