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Research article

Carbon reduction behavior of waste power battery recycling enterprises considering learning effects

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ABSTRACT

The carbon reduction behavior of waste power battery recycling (WPBR) enterprises is essential for promoting resource conservation and environmental protection. Introducing the learning effects of carbon reduction research and development (R&D) investment, this study constructs an evolutionary game model between local governments and WPBR enterprises to study the behavior choice of carbon reduction. The paper explores the evolutionary process and factors affecting carbon reduction behavior choices of WPBR enterprises from internal R&D motivation and external regulation perspectives. The critical results reveal that the existence of learning effects significantly reduces the probability of environmental regulation by local governments while effectively increasing the probability of WPBR enterprises implementing carbon reduction. The learning rate index positively correlates with the likelihood of enterprises implementing carbon emissions reduction. In addition, carbon reduction subsidies considerably maintain considerably negative relation with the probability of enterprise carbon reduction behavior. The following conclusions are drawn: (1) The learning effect of carbon reduction R&D investment is the intrinsic driving force for WPBR enterprises' carbon reduction behavior, which can promote enterprises to proactively implement carbon reduction under fewer constraints of government environmental regulation; (2) Pollution fines and carbon trade prices in environmental regulation can promote enterprises carbon reduction, while carbon reduction subsidies inhibit their reduction behavior; (3) There exists an evolutionarily stable strategy between government-enterprise game only under the dynamic mechanism. The research provides insights for decision-making on enterprises' carbon reduction R&D investment and local government environmental regulation policy under carbon reduction targets.

1. Introduction

Rapid industrialization and urbanization, coupled with burning fossil fuels and using fertilizers (Turan et al., 2022), have led to a substantial increase in global greenhouse gas emissions (Duan, 2023), posing critical challenges to both Earth's ecosystems and human living environment due to climate change (Yuan et al., 2023). Effectively reducing greenhouse gas emissions and mitigating the threats of climate change has become a focal topic for governments and scholars worldwide. As the world's largest carbon emitter, China has been promoting new energy vehicles since 2012 to achieve decarbonization in the transportation sector. However, end-of-life batteries have become a pressing concern, as the average lifespan of power batteries is 5–8 years (Sun et al., 2022). Data shows that by 2020, the accumulated retired power batteries exceeded 200,000 tons, estimated to reach 780,000 tons by 2025 (Lin et al., 2023). Clean and low-carbon recycling of waste power batteries can help reduce greenhouse gas emissions and minimize resource waste and environmental pollution, as clean recycling of valuable metals from waste batteries can reduce carbon emissions from the recycling process and secondary manufacturing while alleviating the shortage of industrial raw materials (Lin et al., 2023). Otherwise, leakage of elements such as nickel in the cathode material of batteries can lead to soil contamination (Turan, 2021, 2022), posing a threat to the ecological environment and human health (Li et al., 2023).

However, the current process of recycling waste power batteries is not environmentally friendly either low-carbon. Most enterprises are

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unwilling to implement carbon reduction as a green innovation activity in waste power battery recycling. As economic entities, companies often prioritize direct economic benefits in recycling and remanufacturing, while carbon reduction technologies have long R&D timeframes, high investment costs, uncertain return on investment, and dual externalities of environment and knowledge (Xu et al., 2023b). The high R&D investment and reliance on mainstream technological paths have lowered the willingness of enterprises to implement carbon reduction (Chen et al., 2022a). In addition, the disorderly practices in China's current recycling market and the immaturity of the green consumption market have also become important factors that restrict enterprises' choices for carbon reduction, as the "bad money drives out good money" phenomenon is prevalent (Sun et al., 2022). Therefore, it is worth conducting in-depth research on promoting the active implementation of carbon emissions reduction by WPBR enterprises.

There exists abundant literature about carbon reduction behavior, with scholars primarily focusing on exploring the influences of various internal and external factors on it. In terms of internal factors, previous studies have analyzed the impacts of corporate governance (Elsayih et al., 2021), digital transformation (Shang et al., 2023), corporate social responsibility (Saeed et al., 2021), board of directors (Mardini and Elleuch Lahyani, 2022), political affiliations (Wang et al., 2023), and corporate structure (Akey and Appel, 2021) on enterprise carbon reduction. Concerning external factors, such as environmental regulations (Song and Han, 2022), industrial agglomeration (Meng and Xu, 2022), institutional pressures (Tang et al., 2022), climate risks (Ren et al., 2022), and low-carbon urban development (Chen et al., 2022b) are considered key factors influencing enterprise carbon reduction, according to scholars. This study focuses on the perspective of internal R&D motivation and external environmental regulation, investigating the influences of learning effects and environmental regulations on the carbon reduction behavior choices of WPBR enterprises.

The learning effect refers to the gradual improvement and enhancement of skills, technologies, or behaviors of employees, organizations, or entire industries through repetition of work and accumulation of experience in the production or operation process. Existing research on the learning effect mainly focuses on economic theory, operations management, and technological innovation. Scholars have already explored the impact of the learning effect on economic growth, production scheduling, and the cost of emerging energy technologies (Asif and Lahiri, 2021; Chen et al., 2021; Sahoo et al., 2022; Yao et al., 2021; Zhang et al., 2023; Zhou, 2021). These studies involve various fields, indicating that the learning effect exists in various industries and plays a role in reducing costs or improving performance. The research on the influence of various learning mechanisms on carbon reduction behavior is summarized in Table 1. What's more, a small amount of literature explicitly examines the impact of the learning effect on pollution control costs. Chen et al. (2020b) considered the accumulation and depreciation effects of learning-by-doing pollution reduction investments. It was found that pollution control experience from "learning from doing" can promote the transformation of governance processes and pollution control technologies, leading to a continuous decrease in pollution control costs with the accumulation of pollution control experience. Chen et al. (2020a) also demonstrated through their research on ecological compensation and transboundary pollution reduction in water pollution that the learning effect of pollution control can effectively reduce pollution control costs. These studies have attempted to explore the learning effect of environmental governance. As a practice of green innovation, WPBR enterprises achieve carbon reduction goals through substantial R&D investment, and the exact process of carbon reduction through the accumulation of R&D investment represents a "learning-by-researching" mechanism. However, the learning effect of R&D investment in carbon reduction is currently unclear, and there is a lack of attention to the emerging phenomenon of waste power battery recycling.

Local governments, as powerful external regulatory bodies, play an essential role in influencing the willingness of enterprises to implement carbon reduction practices. Faced with the dual challenges of environmental pollution and climate change, the Chinese government has attempted to reduce carbon emissions through various environmental regulations. However, there is no consensus in the academic community regarding the impact of environmental regulations on carbon reduction. The "green paradox" hypothesis suggests that environmental regulations may increase carbon emissions and harm carbon reduction efforts (Liang et al., 2022), while the "mandatory reduction " viewpoint argues that environmental regulations can effectively curb carbon emissions (Wang and Zhang, 2022). Some scholars also believe that environmental regulations have a nonlinear impact on carbon emissions (Lu et al., 2022). Table 1 briefly overviews various environmental regulatory tools that affect carbon reduction behavior. Various environmental regulations play different policy roles, but many studies indicate that government-led regulation falls short in many aspects (Bai et al., 2023). In reality, China has implemented market-based environmental policies as regulatory mechanisms to constrain carbon emissions, and implementing carbon taxes is still under theoretical discussion without practical application. Therefore, this study selects carbon reduction subsidies, pollution fines, and carbon trading as the research objects for environmental regulatory tools. The above literature provides a solid theoretical foundation for studying enterprises' carbon reduction behavior. However, most of these researches are based on the assumption of static environmental regulation policies or tools, focusing on a particular point in time or during a specific period while neglecting the influence of policy dynamics on enterprise behavioral choices.

Table 1
The factors influencing carbon reduction behavior.

Factor	Type	Channel	Reference
Learning effect	Leaning-by-doing	Cost improvement	Chen et al. (2020b)
	Learning-by-researching	Performance improvement	Castrejon-Campos et al. (2022); Liu et al. (2022)
	Learning-by-using	Proficiency improvement	Zhang et al. (2022a)
	Learning-by-interacting	Information improvement	Kucharska and Erickson (2023)
Environmental regulation	Command-and-Control-based	Environmental protection law	Gao et al. (2022)
		Cleaner production standards	Cui et al. (2022)
		Environmental permit	Wang et al. (2022)
	Market-based	Carbon reduction subsidy	Li et al. (2021); Wu et al. (2022)
		Pollution fine	Bu and Shi (2021)
		Carbon trade	Wei et al. (2022); Shi et al. (2022);
		Carbon tax	Xu et al. (2023a)
	Voluntary-based	Environmental transparency	Zhang et al. (2022b)
		Environmental management system certification	Jiang et al. (2020)

Based on the background and research gap mentioned above, this study will investigate the following issues:

(1) Can the learning effect of carbon reduction R&D investment promote the proactive implementation of carbon reduction by WPBR enterprises?
(2) How does dynamic environmental regulation influence the carbon reduction behavior choices of WPBR enterprises?

The marginal contributions of this study lie in the following aspects. First of all, applying the concept of learning effects to the field of carbon reduction, we explicitly investigate the influence of learning effects of carbon reduction R&D investment on the carbon reduction behavioral choices of WPBR enterprises. Secondly, we consider dynamic environmental regulations, comparing the evolutionary process and differences in behavioral strategies of local governments and waste electric vehicle battery recycling enterprises under static and dynamic mechanisms, and exploring the behavioral interactions and interest games between governments and enterprises in carbon emissions reduction issues. The research found that the learning effects of carbon emissions reduction R&D investment are the intrinsic driving force for waste electric vehicle battery recycling enterprises to implement carbon emissions reduction. Under dynamic mechanisms, the strategic interaction between government and enterprises only reaches an evolutionarily stable state. The study not only elucidates the positive impact of learning effects of R&D investment on carbon emissions reduction but also provides a reference for governments to formulate more targeted environmental policies and explore new perspectives for promoting corporate carbon emissions reduction levels.

The remaining sections of this article are structured as follows: Section 2 describes the research problem and parameters and presents an evolutionary game model that considers the learning effects of R&D investment in carbon reduction. Section 3 analyzes the stability of the evolutionary game model under static and dynamic mechanisms. Section 4 conducts numerical simulations to intuitively reflect the impact of learning effects and environmental regulations on the carbon reduction behavior of WPBR enterprises and the influence of relevant parameters. Section 5 shows the conclusions and policy implications of this study.

2. Evolutionary game model

2.1. Problem description

WPBR enterprises and local governments play crucial roles in improving carbon emission reduction. The former prioritizes profit maximization, whereas the latter focus on social benefits maximization. Due to their conflicting objectives, these two parties establish a game relationship. The equilibrium strategy must often be achieved through multiple dynamic repeated games under bounded rationality and information asymmetry constraints.

Local governments, as the regulator, can choose to conduct environmental regulation or not, with the probability of $x(0 \leq x \leq 1)$ and $1-x$ respectively. We assume that the government implements carbon reduction subsidies, pollution fines, and carbon trading as the three tools of environmental regulation. Local governments encourage and guide enterprises to reduce carbon emissions, providing carbon reduction subsidies αT to those implementing carbon reduction and imposing pollution penalties βF on those who do not. Meanwhile, when governments actively carry out carbon trading, apart from gaining profits according to the whole carbon trading income, it incurs regulatory costs G such as human and material resources. They receive transfer payments ηG from the central government. If local governments choose not to implement environmental regulation, it means there is no interference in the behavior of enterprises, incurring no regulation costs. However, they may face complaints and criticism from enterprises and the public for their inaction, damaging the local government's reputation and social image M and failing to receive transfer payments from the central government.

As the main body of green innovation, WPBR enterprises have two behavioral strategies to choose from implementing carbon reduction and not implementing it, with the probability of $y(0 \leq y \leq 1)$ and $1-y$, respectively. When the enterprise adopts carbon reduction, it can reduce carbon emissions through various means, such as upgrading equipment and modifying traditional high-carbon emission processes, which requires investment in research and development T. In this way, the income from recycled and remanufactured products under low-carbon green technology denotes R_1 corresponding production costs C_1 and carbon emissions e_1. Meanwhile, due to low-carbon emissions, the enterprise receives carbon reduction subsidies αT from local governments and the brand image N. The enterprise can achieve the established carbon reduction goals, sell surplus carbon emission quotas in the carbon trading market, and earn income P_1. Local governments benefit from the environmental benefits E of the company's implementation of carbon reduction. When WPBR enterprises do not implement carbon reduction, they retain traditional recycling equipment and processes for power battery recycling and remanufacturing. At this time, the income of recycled and remanufactured products denotes as $R_2(R_2 < R_1)$, with related production costs $C_2(C_2 < C_1)$ and carbon emissions $e_2(e_2 > e_1)$. In addition, the enterprise will be subject to pollution penalties βF from local governments due to high carbon and pollution emissions. To achieve the carbon reduction goals, the company has to purchase a certain amount of carbon emission quotas in the carbon trading market and pay carbon trading costs P_2. Local governments must bear the environmental management costs of pollution emissions L caused by the enterprise's failure to implement carbon reduction measures.

2.2. Parameters settings

Based on the above analysis, there are the following assumptions regarding the relevant parameters:

Hypothesis 1. When WPBR enterprises implement carbon reduction technology, there exist learning effects of R&D investment, shown by the

Table 2
Parameter symbols and meanings.

Game agent	Parameter	Meaning
Local governments	E	Environmental benefits from carbon reduction
	G	Regulatory costs of conducting environmental regulation
	L	Pollution control fee for environmental pollution caused by enterprises without implementing carbon emission
	M	Loss of government reputation and social image
	α	The ratio of carbon reduction subsidy
	β	The intensity of pollution penalty
	θ	The allocation coefficient of carbon trading revenue
	η	The strength of central government transfer payment
	e	Free carbon quotas for enterprises
	μ	The efficiency of carbon reduction
	p	Carbon trading price
Waste power battery recycling enterprises	$R_1(R_2)$	The revenue of the recycled and remanufactured product when implementing (not implementing) carbon emission reduction
	$C_1(C_2)$	The cost of the recycled and remanufactured product when implementing (not implementing) carbon emission reduction
	N	Enhancement of enterprise brand image
	T	R&D investment cost
	F	Penalties on pollutant emissions imposed by the government on enterprises that do not implement carbon emission reductions
	$P_1(P_2)$	Carbon trading revenue when implementing (not implementing)carbon emission reduction
	π	Carbon emission reduction R&D effort
	γ	R&D investment coefficient
	$e_1(e_2)$	Carbon emissions when implementing (not implementing)carbon reduction
	e_1'	Carbon emissions when implementing carbon reduction considering learning effects
	k	The learning rate index, i.e., the degree to which carbon reduction can be achieved through carbon reduction R&D investment

marginal reduction in carbon emissions based on accumulated time and experience. According to the learning curve model (Castrejon-Campos et al., 2022), when considering the learning effects of R&D investment, it is assumed that the carbon emissions of WPBR enterprises implementing carbon reduction technology denote $e_1' = e_1 T^{-k}$, which T indicates R&D investment cost and k means learning rate index. $LR = 1-2^{-k}$ is the corresponding learning rate, which k represents the efficiency of R&D investment under learning effects.

Hypothesis 2. The R&D investment cost for the company is $T = \frac{1}{2}\gamma\pi^2$ (Ling et al., 2022; Zhang et al., 2020), where γ denotes the R&D investment coefficient of carbon reduction and π denotes the R&D effort for carbon reduction.

Hypothesis 3. The local government allocates free carbon quotas $e(e_1 < e < e_2)$ to the enterprise. The enterprise implementing carbon reduction sells surplus carbon emissions rights on the carbon trading market to obtain carbon trading income $P_1 = p(e - e_1') = p(e - e_1 T^{-k})$. The enterprise that does not implement carbon reduction pays carbon trading costs for purchasing carbon emissions rights exceeding the quota, recording as $P_2 = p(e_2 - e)$, where p is the carbon trading price.

Hypothesis 4. When adopting environmental regulations, the carbon trading profit obtained by local governments as WPBR enterprises implement carbon reduction is θP_1, and the carbon trading profit obtained by local governments when the enterprise does not implement carbon reduction is θP_2 , where θ is the allocation coefficient of carbon trading revenue.

Hypothesis 5. Local governments obtain environmental benefits $E = \mu(e2 - e_1')$ from WPBR enterprises implementing carbon reduction, where $e2 - e_1'$ is the carbon emission reduction achieved during the carbon reduction process considering learning effects, and μ is the environmental benefit conversion rate (H et al., 2021).

Table 2 shows the parameters and definitions involved in the study. All parameters are greater than 0 to comply with actual conditions.

2.3. Model construction

Based on the problem description and hypotheses, a payoff matrix of the evolutionary game between local governments and WPBR enterprises considering learning effects is constructed, as shown in Table 3.

Table 3
Payoff matrix of local governments and waste power battery recycling enterprises.

Local governments	Waste power battery recycling enterprises	
	Carbon reduction (y)	No carbon reduction $(1-y)$
Environmental regulation (x)	$E-(1-\eta)G-\alpha T+\theta P_1$ $R_1-C_1+N-(1-\alpha)T+P_1$	$-L-(1-\eta)G+\beta F+\theta P_2$ $R_2-C_2-\beta F-P_2$
No environmental regulation $(1-x)$	$E-M$ R_1-C_1+N-T	$-L-M$ R_2-C_2

3. Evolutionary game analysis

3.1. Evolutionary game analysis under the static mechanism

Assuming that local governments' expected payoff with implementing environmental regulations in the game is U_{11}, the expected payoff without implementing environmental regulations is U_{12} , and the average expected payoff in the game is $\overline{U_1}$, then:

$$U_{11} = y[E-(1-\eta)G-\alpha T+\theta P_1] + (1-y)[-L-(1-\eta)G+\beta F+\theta P_2] \tag{1}$$

$$U_{12} = y(E-M) + (1-y)(-L-M) \tag{2}$$

$$\overline{U_1} = xU_{11} + (1-x)U_{12} \tag{3}$$

According to equations (1)–(3), the replicative dynamic equation of local government's adoption of the 'Environmental regulation' strategy is shown as follows:

$$F(x) = \frac{dx}{dt} = x(U_{11} - \overline{U_1}) = x(1-x)[\beta F - (1-\eta)G + M + \theta P_2 - y(\beta F + \theta P_1 - \theta P_2 + \alpha T)] \tag{4}$$

Similarly, concerning WPBR enterprises, the expected payoff of the 'Carbon reduction' strategy and 'No carbon reduction' strategy and the average expected payoff, which is denoted as U_{21}、 U_{22}、 $\overline{U_2}$, are shown as follows:

$$U_{21} = x[R_1 - C_1 + N - (1-\alpha)T + P_1] + (1-x)(R_1 - C_1 + N - T) \tag{5}$$

$$U_{22} = x(R_2 - C_2 - \beta F - P_2) + (1-x)(R_2 - C_2) \tag{6}$$

$$\overline{U_2} = yU_{21} + (1-y)U_{22} \tag{7}$$

Correspondingly, the replicator dynamic equation for the strategy of wasted power battery recycling enterprises is obtained from Equations (5)–(7), showing as follows:

$$F(y) = \frac{dy}{dt} = y(U_{21} - \overline{U_2}) = y(1-y)[C_2 - C_1 + N + R_1 - R_2 - T + x(\beta F + P_1 - P_2 + \alpha T)] \tag{8}$$

According to equations (4) and (8), a two-dimensional replicator dynamic system (I) can be obtained as follows:

$$\begin{cases} \dfrac{dx}{dt} = x(1-x)[\beta F - (1-\eta)G + M + \theta P_2 - y(\beta F + \theta P_1 - \theta P_2 + \alpha T)] \\ \dfrac{dy}{dt} = y(1-y)[C_2 - C_1 + N + R_1 - R_2 - T + x(\beta F + P_1 - P_2 + \alpha T)] \end{cases} \tag{9}$$

Set equations in the replicator dynamic system(I) equal to 0 and solving them yields the fixed equilibrium point $(0,0), (1,0), (0,1), (1,1)$.

Moreover, when satisfying $0 < C_1 - C_2 - N - R_1 + R_2 + T < P_1 + P_2 + \alpha T + \beta F$, $0 < \beta F - (1-\eta)G + M + \theta P_2 < \beta F - \theta P_1 + \theta P_2 + \alpha T$, the point $(x_1 y_1)$ is also an equilibrium point of system (I), where $x_1 = \frac{C_1 - C_2 - N - R_1 + R_2 + T}{P_1 + P_2 + \alpha T + \beta F}$, $y_1 = \frac{\beta F - (1-\eta)G + M + \theta P_2}{\beta F - \theta P_1 + \theta P_2 + \alpha T}$.

$C_1 - C_2 - N - R_1 + R_2 + T = (R_2 - C_2) - (R_1 - C_1 - T + N)$ represents the difference between the benefits of not implementing and implementing carbon reduction by WPBR enterprises without government intervention. Generally, due to the negative externalities of green innovation and other characteristics, the benefits of implementing carbon reduction are often lower than those of not implementing carbon reduction. Therefore, $C_1 - C_2 - N - R_1 + R_2 + T > 0$. When $C_1 - C_2 - N - R_1 + R_2 + T < P_1 + P_2 + \alpha T + N + P_1$, i.e. $R_2 - C_2 - \beta F - P_2 < Rl - C1 - T + \alpha T + N + P_1$, the government can provide carbon reduction subsidies, levy pollution penalties, and carry out carbon trading, through which to make the benefits of implementing carbon reduction higher than those of not implementing. It can encourage more WPBR enterprises to implement carbon reduction and improve the level of carbon reduction, which is consistent with the research objectives of this paper. Therefore, the following part only discusses the case $0 < C_1 - C_2 - N - R_1 + R_2 + T < P_1 + P_2 + \alpha T + \beta F, 0 < \beta F - (1-\eta)G + M + \theta P_2$.

According to the method proposed by Friedman, the stability of the equilibrium point of the evolution system can be analyzed by using the local stability of the Jacobian matrix (Friedman, 1991). The Jacobian matrix of the evolutionary system can be obtained from the replicator dynamic equation system:

$$J = \begin{pmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} = \begin{pmatrix} -(2x-1)(\beta F - G + M + \theta P_2 + \eta G - \beta F y + \theta P_1 y - \theta P_2 y - \alpha T y) & x(x-1)(\beta F - \theta P_1 + \theta P_2 + \alpha T) \\ -y(y-1)(\beta F + P_1 + P_2 + \alpha T) & -(2y-1)(C_2 - C_1 + N + R_1 - R_2 - T + \beta F x + P_1 x + P_2 x + \alpha T x) \end{pmatrix} \tag{10}$$

Using the method of analyzing local stability based on the Jacobian matrix, it can be determined that the equilibrium point is a locally asymptotically stable state during the dynamic evolution process of the system when it satisfies conditions (1) $tr(J) = a_{11} + a_{22} < 0$ and (2) $det(J) = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{12}a_{21} > 0$. This point is a locally evolutionary stable strategy (ESS), while the remaining points are unstable. The stability analysis of the equilibrium points in the replicator dynamic equation (9) is shown in Table 4.

Based on the above analysis, the evolutionary game model has four saddle points and one center point, which are $(0,0), (1,0), (0,1), (1,1)$ and (x_1, y_1).

Table 4
Analysis of the local stability of the equilibrium point.

Point	detJ	trJ	Results
$(0,0)$	–	Uncertain	Saddle point
$(1,0)$	–	Uncertain	Saddle point
$(0,1)$	–	Uncertain	Saddle point
$(1,1)$	–	Uncertain	Saddle point
(x_1, y_1)	+	0	Central point

According to the model solution, the corresponding eigenvalues of the point $(x_1 y_1)$ are a pure imaginary pair. According to the research by Taylor and Jonker (1978), (x_1, y_1) is a stable equilibrium point of the system but not an asymptotically stable point. The evolution trajectory of the system is a closed loop around the equilibrium point.

Therefore, when satisfied the condition $0 < C_1 - C_2 - N - R_1 + R_2 + T < P_1 + P_2 + \alpha T + \beta F$, $0 < \beta F - (1-\eta)G + M + \theta P_2$, the strategic choices of local governments and WPBR enterprises revolve around the equilibrium point, and the system will not automatically stabilize at the equilibrium point. In other words, the point (x_1, y_1) is not the evolutionary stable strategy (ESS) of system (I).

3.2. Evolutionary game analysis under the dynamic mechanism

Based on the analysis in section 3.1, if local governments' environmental regulations are not adjusted according to the market development and the implementation of carbon reduction by WPBR enterprises, it will be impossible to guide the companies to reach a stable equilibrium state of carbon reduction. Therefore, this section considers a dynamically adjusted environmental regulation mechanism. Assuming that local governments' carbon reduction subsidy is denoted as $f(y) = (1-y)sT$ (s representing the subsidy intensity) and the pollution penalty is denoted as $g(y) = (1-y)Q$ (Q representing the maximum penalty)。

We replace αT and βF in the static system(I) considering learning effects with $f(y) = (1-y)sT$ and $g(y) = (1-y)Q$, respectively, then obtain the replicator dynamic system (II) as follows:

$$\begin{cases} F(x) = \frac{dx}{dt} = x(1-x)[f(y) - (1-\eta)G + M + \theta P_2 - \theta P_1 + g(y)] \\ F(y) = \frac{dy}{dt} = y(1-y)[C_2 - C_1 + N + R_1 - R_2 - T + x(g(y) + P_1 - P_2 + f(y))] \end{cases} \tag{11}$$

The fixed equilibrium point of system (II) is $(0,0), (1,0), (0,1), (1,1)$. When $0 < C_1 - C_2 - N - R_1 + R_2 + T < P_1 + P_2 + f(y) + g(y)$ and $0 < g(y) - (1-\eta)G + M + \theta P_2 < g(y) - \theta P_1 + \theta P_2 + f(y)$, points (x_2, y_2) is also an equilibrium point of system (II), where $x_2 = \frac{C_1 - C_2 - N - R_1 + R_2 + T}{P_1 + P_2 + f(y) + g(y)}$, $y_2 = \frac{g(y) - (1-\eta)G + M + \theta P_2}{g(y) - \theta P_1 + \theta P_2 + f(y)}$.

When $0 < C_1 - C_2 - N - R_1 + R_2 + T < P_1 + P_2 + f(y) + g(y)$ and $0 < g(y) - (1-\eta)G + M + \theta P_2 < g(y) - \theta P_1 + \theta P_2 + f(y)$, the stability of the equilibrium point is analyzed using the local stability analysis method of the Jacobian matrix. The results are the same as those in Table 4.

Substituting (x_2, y_2) into the Jacobian matrix and solving for the eigenvalues, it is found that the eigenvalues are a pair of complex conjugate roots with negative real parts. According to the study by Taylor and Jonker (1978), system (II) is asymptotically stable and (x_2, y_2) is a stable focus. The evolutionary trajectory of the system tends towards the stable equilibrium point.

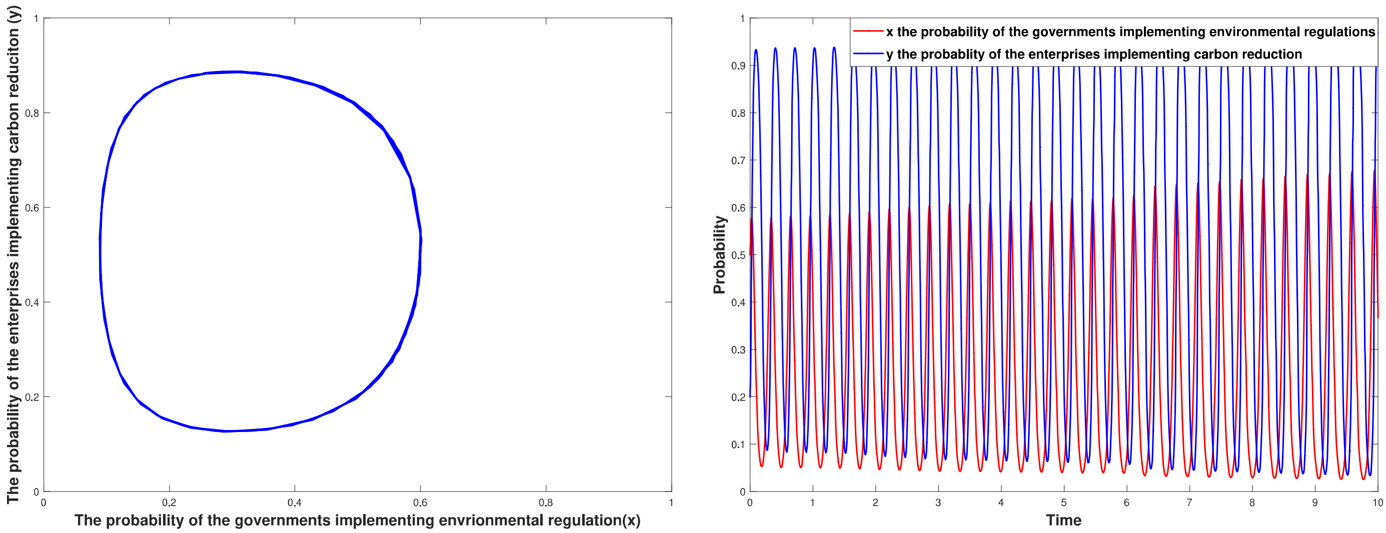


Fig. 1. Dynamic evolution of system (I) under the static mechanism.

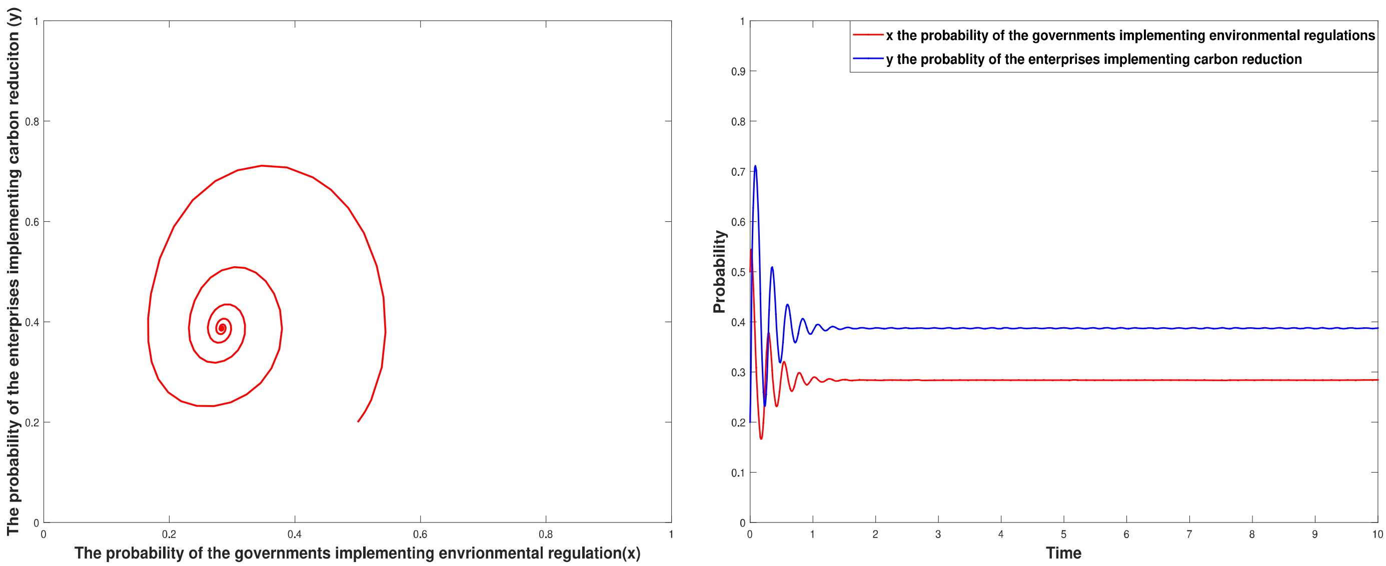


Fig. 2. Dynamic evolution of system (II) under the dynamic mechanism.

4. Numerical simulations

To investigate the evolution and changes in behavior strategies of local governments and WPBR enterprises and to explore the effects of learning and environmental regulations, this study uses MATLAB software to conduct numerical simulation and emulation. Based on an evolution game model considering learning effects under certain conditions, we assign values to various parameters and follow existing literature (H et al., 2021). Specifically, we set the values as follows:

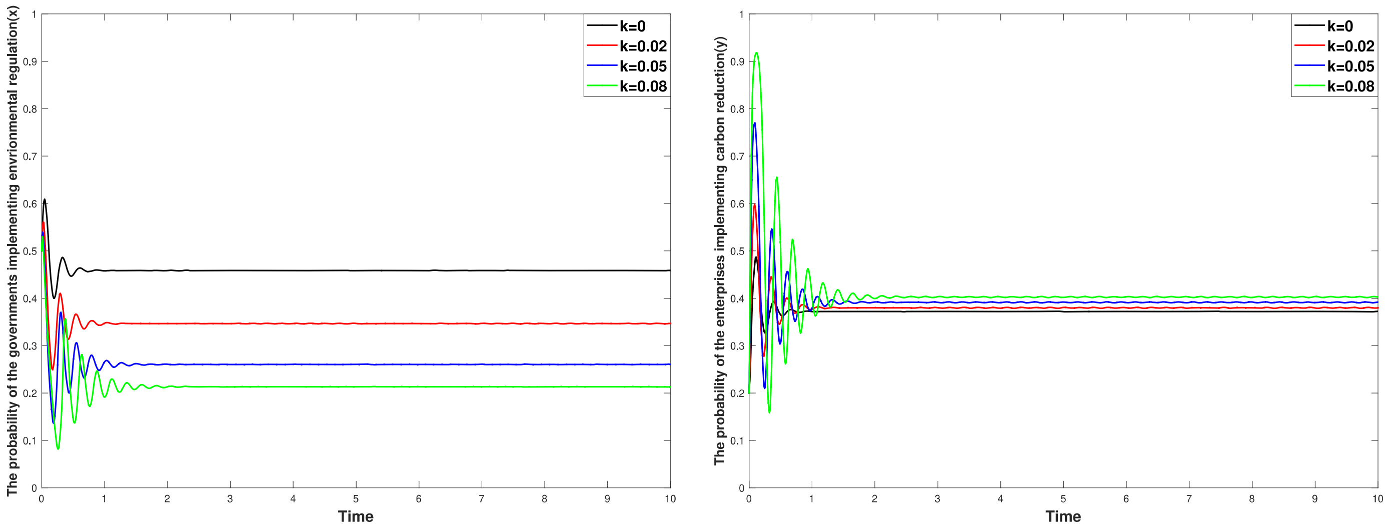
$$L = 20, M = 20, G = 55, N = 10, F = 60, Q = 60, R_1 = 120, R_2 = 100, C_1 = 90, C_2 = 60, p = 20, e = 25, e_1 = 24, e_2 = 26, \alpha = 0.5, \beta = 0.8, \theta = 0.1, \mu = 10, \gamma = 1, \pi = 10, k = 0.05x = 0.5, y = 0.2$$

4.1. The static and dynamic mechanism

Under the static mechanism, the evolutionary game system between local governments and WPBR enterprises fails to achieve stability. The behavior of both parties shows periodic fluctuations, displaying stochastic and unpredictable characteristics. As depicted in the left graph of Fig. 1, the evolutionary trajectory of the binary game system composed of local government and WPBR enterprise is a closed-loop ellipse around the equilibrium point, indicating no asymptotic evolutionary stable state between the game players. The right graph of Fig. 1 reflects the periodic fluctuations of the probability of local government implementing environmental regulation and WPBR enterprises conducting carbon reduction over time. The fluctuation trajectory oscillates around the stable point but never reaches a stable equilibrium.

Under the dynamic mechanism, the game system between local governments and WPBR enterprises can achieve asymptotic stability. The left graph of Fig. 2 illustrates that the evolutionary trajectory of the game system between local government and WPBR enterprise is a spiral that converges towards a stable focus. The right graph of Fig. 2 demonstrates that, under the dynamic subsidy and punishment mechanisms, the probability of local government implementing environmental regulation and WPBR enterprise conducting carbon reduction stabilizes gradually with the increase of time and game rounds, indicating the stability of the system under the dynamic mechanism.

Therefore, the local government cannot effectively regulate WPBR enterprises to implement carbon reduction strategies under the static



（a）the impact of learning rate index on local governments strategy selection （b）the impact of learning rate index on enterprises strategy selection

Fig. 3. The impact of learning effect on game agent strategy selection.

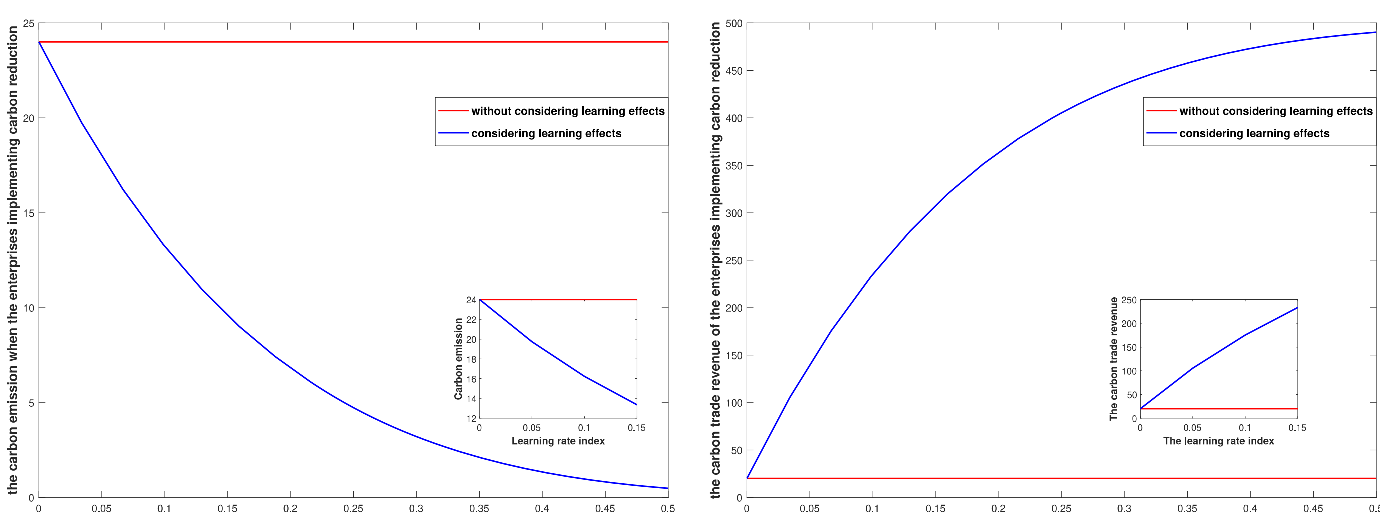
mechanism. The evolutionary path between the two exhibits periodic cyclical fluctuations, preventing the system from reaching a stable state. In contrast, under the dynamic mechanism, the evolutionary game trajectory between the local government and WPBR enterprises shows a trend of spiral convergence, indicating that the system has stability. This suggests that local governments should consider the current status of the industry and the actual situation of enterprises when formulating and promoting policies to make timely adjustments accordingly. WPBR enterprises should also adhere to the policy guidance of the local government, actively respond to the call for carbon reduction, and proactively implement carbon reduction measures.

4.2. The impact of learning effects

To investigate the impact of learning effects on the evolution path of the system, we set $k = 0, k = 0.02, k = 0.05, k = 0.08$ and analyze learning effects on the strategy selection of local governments and WPBR enterprises, holding all other conditions constant. The simulation results are shown in Fig. 3.

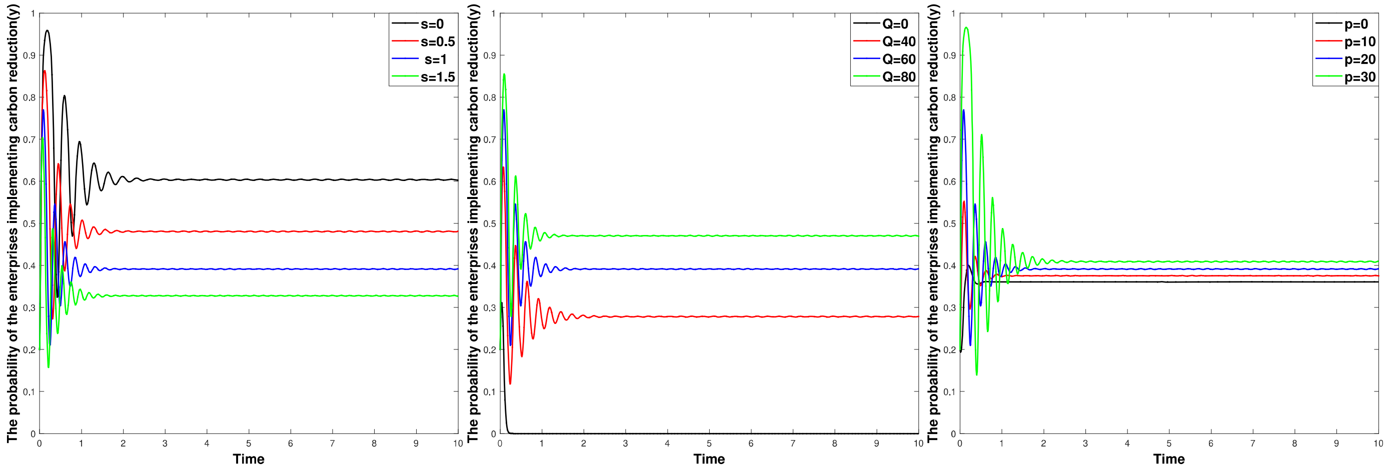
According to Fig. 3(a), the presence of learning effects effectively reduces the probability of the local government implementing environmental regulations. The learning rate index negatively correlates with the likelihood of local governments implementing environmental regulations. Compared with the case without considering learning effects, the probability of local government implementing environmental regulation is consistently lower when considering the learning effect. It implies that the presence of learning effects can reduce the probability of government environmental regulation, thus alleviating the burden on local government. Furthermore, as the learning rate index increases, the probability of local government implementing environmental regulation continually decreases, showing a negative correlation between the two.

In Fig. 3(b), learning effects increase the probability of WPBR enterprises implementing carbon reduction. The learning rate index positively affects the probability of enterprises implementing carbon reduction. Compared with the initial value, the probability of WPBR enterprises implementing carbon reduction significantly increases when considering learning effects and is consistently higher than without considering learning effects. This indicates that the presence of learning effects can enhance the willingness of enterprises to implement carbon reduction. Additionally, as the learning rate index increases, the



（a）the carbon emission when the enterprises implementing carbon reduction （b）the carbon trade revenue of the enterprises implementing carbon reduction

Fig. 4. The impact of learning effect on carbon emission and carbon trade revenue.



(a) the impact of carbon reduction subsidy ratio on enterprises behavior strategy (b) the impact of pollution penalty intensity on enterprises behavior strategy (c) the impact of carbon trade price on the enterprises behavior strategy

Fig. 5. The impact of different environmental regulation tools on enterprises' behavior strategy.

probability of WPBR enterprises implementing carbon reduction continues to rise, and learning effects positively affect the willingness of enterprises to implement carbon reduction.

Generally, when the local government reduces its guidance and regulations, the constraints on enterprises are relaxed, which leads to a decrease in the probability of implementing green innovation. However, the presence of learning effects in the carbon reduction process of enterprises can increase their probability of implementing carbon reduction while simultaneously reducing the probability of local government implementing environmental regulations. This effect encourages enterprises to take the initiative to shift toward green innovation. Therefore, the learning effects in the R&D investment process can be regarded as an internal driving force for WPBR enterprises to implement carbon reduction, which benefits the efficiency of the carbon reduction game system between local governments and WPBR enterprises.

Fig. 4 (a) and (b) illustrate the impact of learning effects on carbon emissions and carbon trading revenue under enterprises' carbon reduction behavior strategy. There is a negative correlation between carbon emissions and learning effects, while carbon trading revenue positively relates to learning effects. Without considering learning effects, carbon emissions and carbon trading revenue always follow a horizontal line. However, with the consideration of learning effects, as the learning rate increases, carbon emissions exhibit an exponentially decreasing trend, and carbon trading revenue shows an exponentially increasing trend. This is consistent with the exponential function expression of learning effects in Hypothesis 1. Learning effects result in a periodic reduction of carbon emissions in the WPBR process. Under the condition of a free carbon quota and constant carbon price provided by the local government, the fewer carbon emissions in the production process, the more surplus carbon emission rights can be sold on the carbon market. Therefore, enterprises can obtain more carbon trading revenue.

4.3. The impact of different tools of environmental regulation

In this part, we conduct a sensitivity analysis of the parameters of carbon reduction subsidy ratio (s), pollution penalty intensity (Q), and carbon trade price (p) to examine the impact of different environmental regulatory tools on the implementation of carbon emission reduction strategies by WPBR enterprises. The simulation results are presented in Fig. 5.

Implementing carbon reduction behaviors by WPBR enterprises negatively correlates with carbon reduction subsidies. As shown in Fig. 5 (a), as the ratio of subsidies (s) increases, the probability of WPBR enterprises implementing carbon reduction technology decreases. This indicates that subsidies for carbon reduction adversely inhibit enterprises' carbon reduction behavior, which differs from most current research. Previous studies have shown that enterprises tend to respond to government proposals and implement carbon reduction actions to obtain scarce financial resources such as subsidies. For example, Dai et al. (2022) empirically analyzed the impact of fiscal subsidies on carbon reduction in mining enterprises and found that fiscal subsidies can significantly reduce enterprise carbon emissions by incentivizing and strengthening green innovation. The difference in findings is due to considering the two-way interactive relationship between enterprises and governments, as opposed to previous studies that only focused on the one-way response of enterprises to government proposals. In the short term, enterprises may willing to implement carbon reduction actions to obtain corresponding fiscal subsidies. However, in the process of achieving carbon reduction, enterprises and governments are engaged in a long-term game of strategy. Changes in subsidy intensity directly affect the cost of carbon reduction subsidies that local governments must bear. Excessive implementation of subsidy mechanisms may result in excessive government spending, which can be challenging to maintain fiscal balance (Li and Shi, 2022). This may cause local governments to become less inclined to implement environmental regulations, while the benefits of WPBR enterprises implementing carbon reduction behaviors are uncertain and risky. There is still a certain degree of dependence on government subsidies, and as the subsidy intensity increases, the probability of local government implementing environmental regulations decreases. As a result, the willingness of WPBR enterprises to implement carbon reduction behaviors during the game process decreases. This demonstrates that the incentive effect of subsidies does not always follow the principle of "the more subsidies, the better." Appropriate subsidy intensity can ensure the effectiveness of grants (Sun et al., 2023).

Imposing pollution penalties can positively influence WPBR enterprises to implement carbon reduction behaviors, as penalties act as a negative incentive. As illustrated in Fig. 5(b), as the punishment intensity (Q) increases, the probability of WPBR enterprises implementing carbon reduction technology rises steadily, indicating a positive correlation between the two. Thus, the greater the severity of penalties, the higher the chances of WPBR enterprises adopting carbon reduction behaviors. The negative incentive effect of penalties is the reason behind this. Local governments enhance the severity of penalties for non-carbon reduction enterprises by raising the violation costs. Thus, WPBR enterprises have to bear for not implementing carbon reduction behaviors. Pollution penalty internalizes the adverse environmental effects of emissions into the operating costs of enterprises, reducing the probability of non-carbon reduction strategies and guiding them towards carbon reduction implementation, thereby promoting green technology innovation. This view is consistent with Fu et al.'s argument that enterprises tend to follow strategies guided by local governments under the deterrence of high penalties (Fu et al., 2022).

Carbon trade price positively impacts the green innovation behavior of WPBR enterprises. As illustrated in Fig. 5(c), the probability of waste power battery enterprises implementing carbon reduction increases continuously as the carbon trade price (p) rises, indicating a positive correlation between the two. The reason behind this is the existence of learning effects that can effectively reduce the carbon emissions in the recycling and manufacturing process of enterprises implementing carbon reduction. Under the condition of unchanged free carbon quotas issued by local governments, the surplus carbon emission rights that can be sold in the carbon trading market increase. The carbon trading income from implementing carbon reduction technology rises, and under the dual incentives of emission reduction goals and carbon trading income, the willingness of WPBR enterprises to implement carbon reduction increases. This finding aligns with the research of Fu et al. (2023), who found that the carbon price signal can force companies to adopt green technology innovation. Shi et al. (2022) also approved the positive impact of carbon trade prices on carbon reduction.

Comparing WPBR enterprises' carbon reduction behavior strategies under subsidies, penalties, and carbon trading, we found that they are more responsive to the intensity of penalties and subsidies than carbon trading. Penalties were more effective than carbon reduction subsidies in encouraging carbon reduction behavior. This could be because carbon reduction subsidies and pollution penalty policies are top-down environmental regulations implemented by local governments, directly impacting enterprise behavior once implemented. Carbon trading policy, in contrast, belongs to a market-driven policy, and although the government organizes carbon trading, its effectiveness still depends on the price. Market mechanisms have a certain degree of lag and indirectness. Therefore, WPBR enterprises are relatively insensitive to the influence of carbon pricing on their implementation of carbon reduction behavior. Furthermore, penalties' effectiveness is more remarkable than subsidies, consistent with the research of Yang et al. (2021), which found that enterprises are more sensitive to punishment than rewards. This suggests that enterprises are more susceptible to foreseeable losses than expected benefits, which aligns with the behavioral economics concept of "loss aversion" (Ilbahar et al., 2022).

5. Conclusions and implications

The low-carbon and clean recycling of waste power batteries are crucial, yet the willingness of WPBR enterprises to implement carbon reduction behaviors is not high. Considering the learning effects of carbon reduction R&D investment, this study investigates the impact of learning effects and dynamic environmental regulations on the behavioral choices of WPBR enterprises in terms of carbon reduction, intending to explore how to enhance their willingness to engage in carbon emissions reduction behaviors. The following conclusions are drawn:

(1) The learning effects of carbon reduction R&D investment are an intrinsic driving force for WPBR enterprises to pursue carbon reduction actively. Simulation results show that when considering the learning effects of R&D investment, as the probability of government environmental regulations decreases, the probability of WPBR enterprises implementing carbon reduction increases continuously. It indicates that in the absence of external regulatory constraints, the willingness of WPBR enterprises to engage in carbon reduction behaviors increases due to the intrinsic motivation of learning effects.

(2) The behavior game between WPBR enterprises and local governments regarding carbon reduction reaches an evolutionarily stable state only in the dynamic mechanism. Under static mechanisms, the evolutionary trajectory of the behavioral game system between local governments and WPBR enterprises shows periodic fluctuations, while under dynamic mechanisms, the system exhibits asymptotic stability. It indicates that the behavior game of both parties can evolve to a stable equilibrium state under dynamic mechanisms.

(3) Pollution fines and carbon trade prices positively promote the behavioral choices of WPBR enterprises implementing carbon reduction, while carbon emissions reduction subsidies inhibit such behaviors.

Based on the above conclusions, this article proposes the following recommendations:

(1) From the perspective of enterprises, it is essential to pay attention to the accumulation and summary of learning effects during the carbon reduction research and development process and to be proactive in developing green innovation. Enterprises can drive overall performance improvement using green technology innovation as a fulcrum. On the one hand, enterprises should increase R&D investment in the carbon reduction process, attach importance to the cumulative learning effects of R&D investment, and actively manage the knowledge and technology of carbon reduction. Besides, they should accurately evaluate their internal financial conditions and reasonably allocate R&D investment while actively seeking support from national finance and green financial credit institutions. By collaborating with other companies for innovation, they can continuously increase their cumulative R&D investment to maximize the learning effects of R&D investment in the carbon reduction process and obtain competitive advantages such as low-carbon emissions and low cost. On the other hand, enterprises should take multiple measures to speed up the conversion efficiency of R&D investment results. For example, they should strengthen the construction of internal innovation teams, cultivate and employ critical talents, and work with external research institutions, universities, and other organizations to tackle critical green innovative technologies in the carbon emission reduction process. Eliminating outdated capacity and optimizing the process flow can also effectively convert R&D investment in carbon emission reduction into low-carbon achievements.

(2) From the government's perspective, environmental regulation policies should be dynamically adjusted according to the carbon reduction behavior of enterprises. Currently, waste power battery recycling is still in its infant development stage, and the profit of implementing carbon reduction in WPBR enterprises is lower than that of not implementing it. The behavior of WPBR enterprises under static environmental regulation tools is uncertain. Fixed and rigid policies will increase the government's financial burden and be ineffective in regulating enterprises' carbon emission reduction behavior. Therefore, the government should pay close attention to the behavior of WPBR enterprises and adjust the policies timely when the carbon reduction behavior of enterprises has changed. It can be realized by big data and information technology from the waste power battery recycling industry to play the policies' effectiveness and guide enterprises' emission reduction behavior more precisely. However, dynamic policies are often prone to confusion and instability, and changing overnight will only impact the credibility of government policies. Therefore, it is wise for local governments to grasp the principle of moderation in implementing dynamic environmental regulations. Make adequate market research and policy transition preparations in advance, and make policy decisions that are closest to the current situation of carbon emission reduction of enterprises without losing foresight and development.

Credit author statement

Jianling Jiao: Conceptualization, Design, Methodology, Formal analysis, Resources, Writing- Reviewing and Editing, Funding acquisition. **Yuqin Chen**: Conceptualization, Design, Methodology, Writing – original draft and Revision. **Jingjing Li**: Revision, Language editing, Resources, Funding acquisition. **Shanlin Yang:** Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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