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A Tripartite Evolutionary Game Model for Power Battery Recycling Considering the Product Life Cycle Theory

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Abstract:

The recycling of electric vehicle batteries (EVBR) not only helps mitigate environmental pollution and resource depletion but also promotes the sustainable development of industries such as electric vehicles and energy storage. In China, the EVBR industry remains in its early stages, and clarifying the interactions among key stakeholders is crucial to promoting its maturity. This paper proposes a tripartite evolutionary game model for battery recycling based on the product life cycle theory, incorporating the government, NEVMs and consumers as participants. Based on a systematic literature review, the factors and corresponding value ranges affecting stakeholders' strategic choices were identified, and numerical simulations were conducted using MATLAB R2024b to explore stakeholders' strategic evolution and underlying mechanisms across various stages of the industry life cycle. The results show that in the early stage of EVBR industry, the government plays a leading role in guiding NEVMs to invest in blockchain traceability technology through incentive policies. As the EVBR industry develops and value creation becomes more prominent, market mechanisms gradually take effect, encouraging NEVMs and consumers to adopt a "collaborative participation" model. In the mature stage, the government's role shifts from intervention to oversight. From the results of sensitivity analysis, a moderate reward-punishment mechanism can effectively stimulate NEVM technological innovation, while excessive subsidies may impose a heavy financial burden. Enhancing recycling revenue and environmental benefits is the core driving force to stimulate the active participation of NEVMs and consumers. This study provides theoretical support for rational decision-making among stakeholders in the EVBR process and contributes to the sustainable development of the EVBR industry.

Keywords: Evolutionary game; Product life cycle; Power battery recycling; Blockchain technology; Stakeholder

INTRODUCTION

In recent years, as the global climate change problem has become increasingly serious, governments worldwide have introduced stringent carbon reduction policies. Under the guidance of the "dual carbon" strategy, China has put forward measures to accelerate emission reduction in multiple industries. As a major source of carbon emissions, the transportation sector has attracted significant attention, and the development of new energy vehicles has been incorporated into national strategic planning, playing a pivotal role in promoting green transportation and achieving carbon reduction goals. In China, with Tesla's announcement in 2018 of the establishment of its Gigafactory in Shanghai, domestic enterprises represented by Xiaomi, Huawei, BYD, and Zeekr have increasingly flocked to the new energy vehicle track, driving the industry's rapid development. Data from the China Association of Automobile Manufacturers (CAAM) shows that in 2024, China's new energy vehicle production and sales reached 12.888 million and 12.866 million respectively, with a year-on-year growth of 34.4% and 35.5%. New NEV sales accounted for 40.9% of total new vehicle sales in the automotive industry, marking a 9.3% increase compared to 2023, and driving the rapid development of the power battery industry as a core component of new energy vehicles. Available data shows that by 2023, China's retired power batteries exceeded 580,000 tons, with a new wave of retirements expected to push the total beyond 700,000 tons by 2030 [1]. To regulate power battery recycling, the Ministry of Industry and Information Technology (MIIT), along with other departments, jointly issued the *Interim Measures for the Management of New Energy Vehicle Power Battery Recycling and Utilization* in 2021. This document clarifies the management requirements for power battery recycling, including the responsibilities of enterprises, the recycling information traceability, and the disposal of waste power batteries. Nevertheless, there are still many opportunistic individuals who continue to establish numerous informal power battery recycling points, leaving about half of the retired batteries "homeless". Therefore, the standardized management of the power battery recycling industry is urgently needed. In addition, how to effectively track the energy consumption of power batteries and predict the recyclability of power batteries is also a technical challenge in the current power battery recycling industry.

Blockchain technology, known for enhancing information transparency and traceability, effectively addresses information asymmetry. Its application in the power battery recycling sector has garnered widespread attention from both the government and society [2]. Blockchain technology can record detailed information at every stage of the power battery's lifecycle, from production to recycling, and offers significant advantages in preventing illegal recycling and violations of regulations. At present, enterprises in Europe and the United States have already implemented blockchain technology for power battery recycling and traceability. Tesla (USA), Siemens (Germany), and Veolia (Netherlands) have each established blockchain platforms to trace their entire power battery supply chain. The National Energy Administration and the Ministry of Industry and Information Technology (MIIT) in China have introduced policies encouraging NEVMs to adopt blockchain for power battery recycling traceability. However, deploying blockchain technology inevitably incurs high costs for companies, including technology, operations, maintenance, and transaction costs, making it difficult to achieve economies of scale. At present, only leading enterprises such as BYD and CATL have taken action in China, while other companies remain in a "wait-and-see" stance.

To address the above problems and promote the EVBR industry into a mature stage, it is essential to conduct an in-depth analysis of the factors and value ranges that influence stakeholder strategy choices during the recycling process at different stages of development. This paper proposes a tripartite evolutionary game model for battery recycling based on product life cycle theory, incorporating the government, NEVMs, and consumers as participants, and analyzing the strategy changes and influence mechanisms of these three parties across different development stages. Furthermore, this paper aims to address the following questions:

(1) What are the key factors influencing the behavioral strategy changes of each stakeholder in the sustainable development of the new energy vehicle power battery recycling industry?

(2) What are the interactions among the stakeholders, the stability state of the system under different strategy choices, and the overall system stability?

(3) What mechanisms contribute to the sustainable development of the new energy vehicle power battery recycling industry at different stages of its development?

LITERATURE REVIEW

Power Battery Recycling Model for New Energy Vehicles

Concerning the recycling of retired power batteries for new energy vehicles, many scholars have conducted in-depth studies on recycling models and channels. Zhang et al. (2022) constructed a Stackelberg game model involving retailers, third-party recyclers, and echelon utilization enterprises, revealing the optimal recycling mechanism in a closed-loop supply chain under carbon quota and trading policies. Their findings indicate that when the competition intensity and price sensitivity are in the moderate range, a tripartite collaborative model is the optimal choice, otherwise the echelon utilization model is preferable [3]. Li & Zhang (2024) developed a low-carbon innovation game framework among the government, enterprises and recyclers. Their research indicates that, in contrast to recyclers, manufacturers' willingness to innovate is positively correlated with their benefit ratio but is negatively affected by cost pressure [4]. Li et al. (2025) modeled recycling strategies from the perspectives of manufacturers, retailers and third-party platforms to explore the evolution of volume-based subsidies under carbon trading mechanisms. Their results demonstrate that in a manufacturer- and retailer-led model, optimal pricing declines as subsidies increase, with sensitivity to subsidies determined by the battery recycling rate [5]. Based on Stackelberg game theory, Zhou et al. (2025) developed models for both manufacturer-led and alliance-based cooperative recycling, analyzing how carbon trading prices and echelon utilization rates affect corporate profits [6]. Xing & Wang (2025) constructed a multi-channel recycling model involving a battery supplier, third-party recycler, and new energy vehicle manufacturer, to investigate how blockchain adoption and government incentives influence channel selection, recycling rates, and broader socio-economic-environmental outcomes [7].

In summary, existing research by both domestic and international scholars has classified mainstream power battery recycling models into four categories: (1) models led by power battery manufacturers; (2) models led by new energy vehicle manufacturers or distributors; (3) models led by professional third-party recyclers; and (4) models led by industry alliances.

Stakeholder's Strategy Choice

Existing studies by domestic and international scholars on governmental strategy selection primarily focus on incentive and penalty policies. Ding et al. (2020) investigated the behavioral strategies of battery recyclers under government-imposed collection and dismantling subsidies [8]. He and Sun (2022) demonstrated that a dynamic reward-punishment mechanism implemented by the government can enhance the carbon reduction effectiveness of new energy vehicle manufacturers participating in battery recycling [9]. Jiao et al. (2023) revealed that environmental pollution penalties and carbon trading costs imposed by the government can incentivize carbon emission reductions among battery recycling enterprises, while carbon emission reduction subsidies act as a disincentive [10]. Wang et al. (2023) found that governmental punitive measures are effective in promoting standardized recycling behaviors among recyclers, although these measures tend to exhibit a delayed effect compared to subsidy policies [11].

Regarding the strategy selection of enterprises involved in recycling, Li et al. (2023) demonstrated that the digital transformation strategies adopted by new energy vehicle manufacturers, power battery producers, and recycling firms serve as key drivers in the formation of a green closed-loop reverse supply chain for power batteries [12]. Lyu et al. (2021) investigated the evolutionary conditions and pathways of cooperative modes between battery recyclers and echelon utilization enterprises when both parties adopt cooperative strategies [13]. Gu et al (2018) examined the optimal pricing strategies between manufacturers and remanufacturers within the closed-loop power battery supply chain, providing theoretical support for improving recycling efficiency [14]. Qiu et al. (2020) constructed a two-level game model involving manufacturers and distributors in a closed-loop supply chain, revealing a profit incentive mechanism in which the strength of recycling subsidies is driven by incremental revenue under the constraint of recycling rate thresholds [15]. Feng et al. (2023) developed a Stackelberg game model to examine how blockchain technology affects recycling decisions, finding that traceability enhances supplier and recycler profits, while manufacturer gains depend on their influence over demand and consumer trust [16].

Product Life Cycle Theory

Currently, studies applying product life cycle (PLC) theory to power battery recycling remain limited. Jin (2016) conducted an in-depth analysis of the four stages of the electric vehicle life cycle and designed corresponding recycling models for power batteries during the introduction, growth, maturity, and decline stages [17]. Some scholars have applied PLC theory in related areas such as electric vehicles and closed-loop supply chains. Fan et al. (2008) introduced PLC theory to evaluate the usage costs and energy conversion efficiency of typical new energy vehicles and summarized their development prospects through a comparative analysis of the evaluation results [18]. Hu (2010) explored the characteristics of the automotive industry supply chain centered on vehicle manufacturers in different life cycle stages and proposed the automotive product supply chain strategies for their corresponding stages [19]. Huang et al. (2013) studied the pricing and production strategies of a closed-loop supply chain in a manufacturer's competitive environment based on the PLC theory and designed numerical simulations to verify the conclusions [20].

Evolutionary Game Theory

Evolutionary game theory originated in the 1970s and was initially proposed to study the selection and adaptability of individual strategies during biological evolution, focusing on the competitive and cooperative relationships among species within ecosystems. The theory has since been widely applied in the social sciences to analyze interdependent decision-making problems faced by boundedly rational individuals [21].Wan et al. (2022) constructed an evolutionary game model under blockchain technology, involving both ride-hailing platforms and governments. They analyzed the impact of factors such as negative management additional costs, technology development costs, and the intensity of government rewards and punishments on regulating the behavior of ride-hailing platforms, providing valuable insights for effective governance of the industry [22]. Li et al. (2024) developed an evolutionary game model involving the government, power grid companies, and the public to analyze factors influencing stakeholders' decisions at different stages of development, contributing to the sustainability of power projects [23]. Liu et al. (2023) proposed a multi-strategy evolutionary game model for electric vehicle charging and discharging scheduling based on the logit protocol. The optimal strategies for each participant were derived and validated through simulation examples, demonstrating the model's advantages in peak shaving and valley filling in the power grid [24].

At present, some scholars have also applied evolutionary game theory to the field of power battery recycling. Zhang et al.(2022) studied the problem of recycling and reuse of used power batteries based on the evolutionary game, which reached equilibrium among the government's support, manufacturers' choice of laddering and consumers' active participation in the strategy [25]. Wei et al. (2022) constructed a tripartite evolutionary game model considering the conflict of interests of the government, NEVMs and consumers, in which the governance strategies at different stages were examined through numerical simulations [26]. Wang et al. (2023) used an evolutionary game model to examine the recycling decisions between power battery manufacturers and NEVMs under "no intervention" and "subsidy-punishment" policies. The study found that the subsidy policy can reduce the threshold of recycling and encourage enterprises to recycle, while the combined policy accelerates the recycling process through economic leverage [27].

Research Gaps

The current research on the recycling of power batteries in new energy vehicles has developed a relatively systematic framework, focusing mainly on recycling models, stakeholder strategy choices, policy incentives, and the optimization of recycling systems. However, an analysis of the relevant literature reveals the following research gaps:

(1) The sustainable development of the retired power battery recycling industry is a dynamic process involving multiple stages. Existing studies often overlook the role evolution of stakeholders at different development stages, and the interaction mechanisms of their strategy adjustments have not been systematically explored.

(2) Although some studies have analyzed the feasibility of blockchain in the process of power battery recycling, most of them focus only on the technological advantages of blockchain, without delving into the strategy choices and profit changes of NEVMs in the recycling system.

(3) Current research primarily focuses on stakeholders such as battery manufacturers, recycling companies, and governments, while consumers are often treated as passive recipients, with insufficient consideration of their proactive role in battery recycling.

EVOLUTIONARY GAME MODEL

Problem Description

In the practical context of China's power battery recycling industry, the main participants in the industrial chain include the government, NEVMs, consumers and informal recyclers (IPBRs), as shown in Figure 1. According to policy guidance, the government expects NEVMs to take primary responsibility for battery recycling, collecting used batteries through formal channels and handing them over to downstream compliant enterprises for second-life use. However, the lucrative profits in the EVBR industry have attracted a large number of informal recyclers. Due to their limited processing technology, they struggle to meet environmental standards when handling used batteries, which results in severe environmental pollution, increases regulatory difficulties for the government, and adversely affects its social credibility.

To cope with this problem, some socially responsible NEVMs are increasing their investment in technological innovation to more accurately identify the status of power batteries and optimize the recycling process. The improved recycling efficiency not only enhances the economic feasibility of the industry chain but also brings significant social benefits to the government. In this process, the government has also actively supported these responsible enterprises, encouraging them to continuously optimize the recycling system through technological subsidies, tax incentives, and other measures. Additionally, to regulate the recycling flow of power batteries from the source, the government has intensified its environmental awareness campaigns targeting consumers, aiming to increase public awareness and participation in green recycling, thus promoting the sustainable and standardized development of the power battery recycling industry.

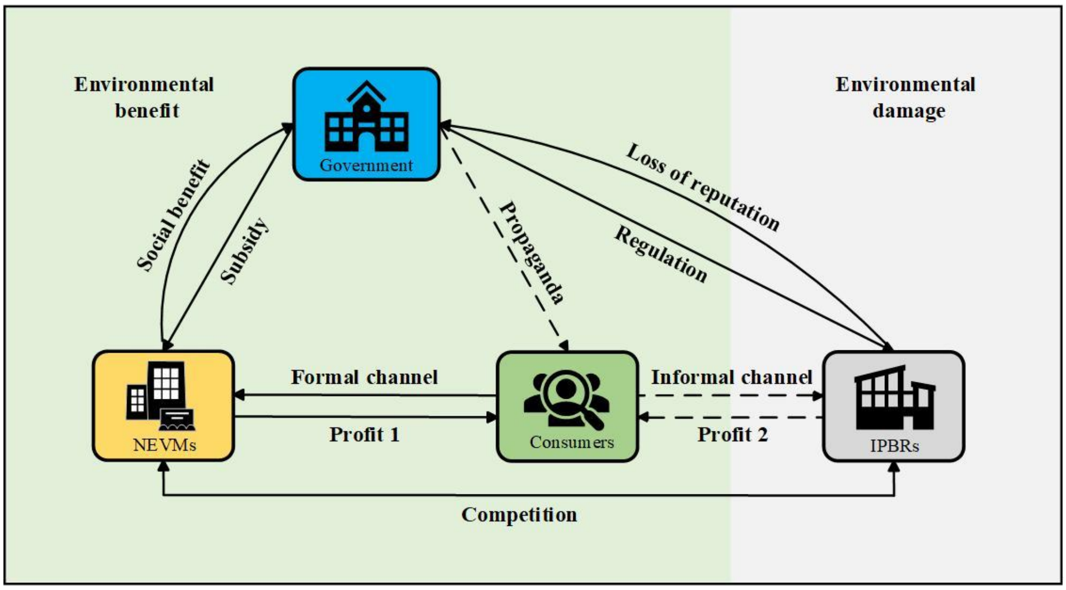

Figure 1 Logic of key stakeholders at different stages of EVBR industry

Model Assumptions and Parameter Introduction

This paper proposes the following research hypotheses:

Hypothesis 1: The stakeholders of the evolutionary game model constructed in this paper include the government, NEVMs and consumers. All three are limited rational participants who can make decisions independently, and their behavioral strategies are based on their interests to weigh up the choices and achieve stable optimal strategies.

Hypothesis 2: The government's behavioral strategy choices include strict regulation (RS) and lenient regulation (LS). The strict regulatory strategy implies that the government strictly scrutinizes the battery recycling plans of NEVMs, strengthens the constraints on informal recycling channels, and actively guides consumers to cooperate with formal recyclers. At the same time, the government will provide incentives such as policy subsidies to new energy vehicle manufacturers willing to participate and impose different levels of penalties on entities involved in informal power battery recycling. Strict regulation not only enhances the government's credibility but also provides consumers with a fairer and more transparent trading environment. On the contrary, lenient regulation manifests as reduced subsidies for the application of blockchain technology and a relaxation of the oversight on informal recycling channels, which could disrupt market order and hinder the sustainable development of the recycling system.

Hypothesis 3: Behavioral strategy choices for NEVMs include recycling solutions using blockchain technology (BA) and traditional recycling solutions (NB). Manufacturers choosing the blockchain technology recycling scheme are able to build a complete battery footprint tracking system by leveraging the transparency and traceability of the blockchain, thus enhancing recycling efficiency and reducing environmental risks. At the same time, the application of this technology enhances public trust and provides the government with more accurate regulatory data, bringing greater social benefits. However, some NEV manufacturers may still prefer traditional recycling options, which, while reducing short-term costs, increase the difficulty of power battery recycling and may lead to environmental pollution and resource waste.

Hypothesis 4: Consumers' behavioral strategy choices include active participation (PP) and negative participation (NP). The group of environmentally conscious consumers will choose to cooperate with NEVMs that have formal recycling qualifications. However, there is no shortage of groups that will sell retired batteries to higher bidders for personal gain. When the recycling price offered by informal recyclers exceeds the combined value of the formal recycling price and government subsidies, consumers are highly likely to opt out of recycling with formal companies.

Hypothesis 5: In terms of strategy adoption probabilities, the government, NEVMs, and consumers select strict regulation, blockchain-based recycling schemes, and active participation with probabilities of x $(0 \leq x \leq 1)$, y $(0 \leq y \leq 1)$, and z $(0 \leq z \leq 1)$, respectively. The probabilities of choosing lenient regulation, traditional recycling schemes and negative participation are (1-x), (1-y) and (1-z), respectively.

The government, NEVMs and consumers all have their behavioral strategies. The behavioral strategy choice of any one stakeholder will affect and be affected by the other two stakeholders, and different behavior strategy choices have varying impacts on the EVBR, making it a dynamic process. According to the above assumptions, this paper establishes a recycling model for power battery recovery, and the parameter variables and specific explanatory settings of the model are shown in Table 1.

Table 1 Model parameters and descriptions

Parameters	Descriptions
W_1	Social welfare when the government adopts the RS strategy
W_2	Social welfare when the government adopts the LS strategy
S_1	High subsidies provided by the government to NEVMs that adopted blockchain technology under the RS strategy
S_2	Low subsidies provided by the government to NEVMs that adopted blockchain technology under the LS strategy
C_0	Government publicity costs for blockchain technology and green recycling
E_0	Reputation loss resulting from the government's passive regulation when consumers choose a

	PP strategy
H_1	Environmental benefits to the government when the strategy choices of NEVMs and consumers are BA and PP
R_1	Recycling benefits of NEVMs after the deployment of blockchain technology
R_2	Recycling benefits of NEVMs without deploying blockchain technology
C_1	Cost of deploying blockchain technology for NEVMs
C_2	Additional recycling costs incurred by consumers' negative participation to NEVMs that adopt an NB strategy
H_2	Reputational benefits to NEVMs from improved recycling service quality after deploying blockchain technology
R_3	Revenue from battery sales when consumers adopt a PP strategy
E_1	Environmental benefits to consumers from adopting PP strategies
L_1	Subsidies provided to consumers by NEVMs' promotion activity such as "Trade-in activity"
P	Recycling prices offered to consumers by informal recycling channels
H_3	The health loss caused by environmental pollution resulting from consumers' adoption of NP strategies
F	The fines imposed by the government on consumers who cause serious environmental pollution
α_1	Government's regulatory intensity on informal recycling channels under the RS Strategy
α_2	Government's regulatory intensity on informal recycling channels under the LS Strategy

Based on the above assumptions, this paper establishes a multi-subject game tree containing payoff matrixes, as shown in Figure 2.

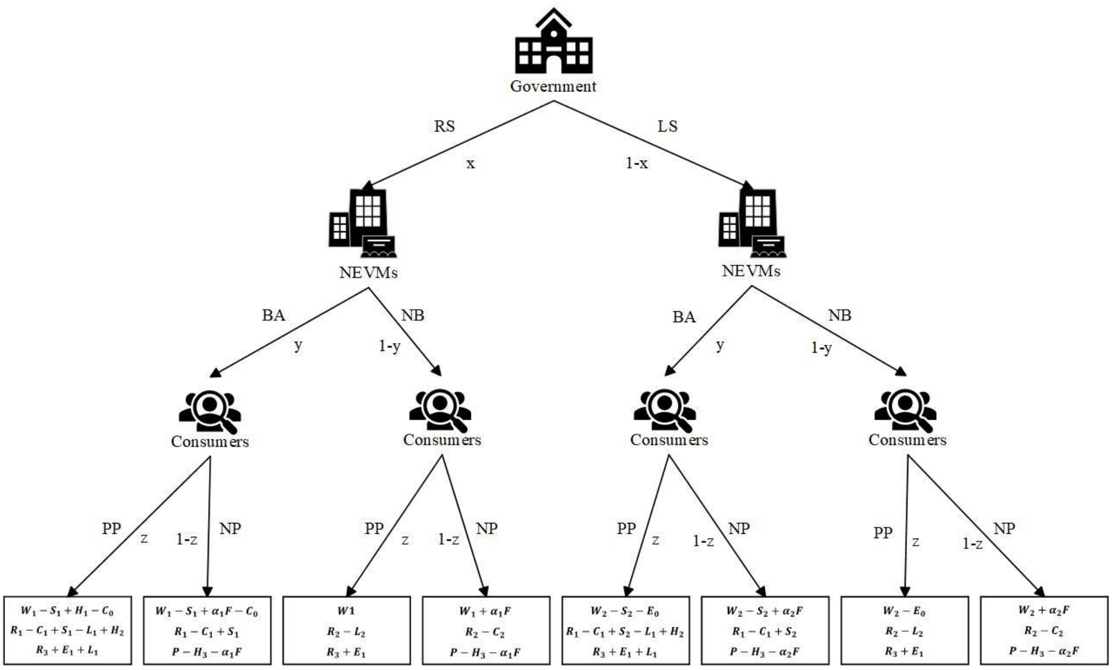

Figure 2 Strategy game diagram of key stakeholders with payoff matrixes

Modeling

Based on the above assumptions and parameter settings, this section will establish the replicated dynamic equations for the government, NEVMs and consumers based on the payoff matrix, and calculate the equilibrium point.

First, the expected profits of the government when choosing the RS and LS strategies are U_{1R} and U_{1L}, respectively, and the average profit is U_1.

$$U_{1R} = yz(W_1 - S_1 + H_1 - C_0) + y(1-z)(W_1 - S_1 + \alpha_1 F - C_0) + (1-y)zW1 + (1-y)(1-z)(W_1 + \alpha_1 F) \tag{1}$$

$$U_{1L} = yz(W_2 - S_2 - E_0) + y(1-z)(W_2 - S_2 + \alpha_2 F) + (1-y)z(W_2 - E_0) + (1-y)(1-z)(W_2 + \alpha_2 F) \tag{2}$$

$$U_1 = xU_{1R} + (1-x)U_{1L} \tag{3}$$

Secondly, we can calculate the expected profits of NEVMs when choosing to apply blockchain technology and not apply blockchain technology, which are U_{2B} and U_{2N}, respectively, with an average profit of U_2.

$$\begin{aligned} U_{2B} = {} & xz(R_1 - C_1 + S_1 - L_1 + H_2) + x(1-z)(R_1 - C_1 + S_1) + (1-x)z(R_1 - C_1 + S_2 - L_1 + H_2) \\ & + (1-x)(1-z)(R_1 - C_1 + S_2) \end{aligned} \tag{4}$$

$$U_{2N} = xz(R_2 - L_2) + x(1-z)(R_2 - C_2) + (1-x)z(R_2 - L_2) + (1-x)(1-z)(R_2 - C_2) \tag{5}$$

$$U_2 = yU_{2B} + (1-y)U_{2N} \tag{6}$$

Finally, this paper sets the expected profits of consumers when choosing the PP and NP strategies as U_{3P} and U_{3N}, respectively, with an average profit of U_3.

$$U_{3P} = xy(R_3 + E_1 + L_1) + x(1-y)(R_3 + E_1) + (1-x)y(R_3 + E_1 + L_1) + (1-x)(1-y)(R_3 + E_1) \tag{7}$$

$$U_{3N} = xy(P - H_3 - \alpha_1 F) + x(1-y)(P - H_3 - \alpha_1 F) + (1-x)y(P - H_3 - \alpha_2 F) + (1-x)(1-y)(P - H_3 - \alpha_2 F) \tag{8}$$

$$U_3 = zU_{3P} + (1-z)U_{3N} \tag{9}$$

According to the above equations, this paper can obtain the replication dynamic equations of government, NEVMs and consumers, as shown in equation (10):

$$\begin{cases} F(x) = \dfrac{dx}{dt} = x(1-x)\left(W_1 - W_2 + \left(\alpha_1 - (1+z)\alpha_2\right)F - yC_0 + zE_0 - y(S_1 - S_2) + yzH_1\right) \\ F(y) = \dfrac{dy}{dt} = y(1-y)\left(C_2 - C_1 + xS_1 + (1-x)S_2 + R_1 - R_2 - z(L_1 - L_2 + C_2 - H_2)\right) \\ F(z) = \dfrac{dz}{dt} = z(1-z)\left(E_1 + H_3 - P + R_3 + yL_1 + x\alpha_1 F + (1-x)\alpha_2 F\right) \end{cases} \tag{10}$$

Let $F(x) = 0$; $F(y) = 0$; $F(z) = 0$. We can get 14 equilibrium points of this dynamic system, which are $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, $E_8(1,1,1)$, $E_9(\frac{-(E_1+H_3-P+R_3+\alpha_2 F)}{(\alpha_1-\alpha_2)F}, 0, \frac{-(W_1-W_2+\alpha_1 F-\alpha_2 F)}{E_0-\alpha_1 F+\alpha_2 F})$, $E_{10}(\frac{-(H_2-C_1-L_1+L_2+R_1-R_2+S_2}{S_1-S_2}, \frac{E_0+W_1-W_2}{C_0-H_1+S_1-S_2}, 1)$, $E_{11}(0, \frac{E_1+H_3-P+R_3+\alpha_2 F}{-L_1}, \frac{C_2-C_1+R_1-R_2+S_2}{C_2-H_2+L_1-L_2})$, $E_{12}(1, \frac{E_1+H_3-P+R_3+\alpha_1 F}{-L_1}, \frac{C_2-C_1+R_1-R_2+S_1}{C_2-H_2+L_1-L_2})$, $E_{13}(\frac{C_2-C_1+R_1-R_2+S_2}{S_2-S_1}, \frac{W_1-W_2+\alpha_1 F-\alpha_2 F}{C_0+S_1-S_2}, 0)$, and $E_{14}(\frac{-(E_1+H_3+L_1-P+R_3+\alpha_2 F)}{(\alpha_1-\alpha_2)F}, 1, \frac{C_0+S_1-S_2-W_1+W_2-\alpha_1 F+\alpha_2 F}{E_0+H_1-\alpha_1 F+\alpha_2 F})$. According to the asymptotically stabilizing conditions in evolutionary game theory, it can be concluded that the mixed strategy points E_9 to E_{14} are unstable equilibrium points.

STABILITY ANALYSIS

In this section, the paper explores the stability of the strategies of the government, EV manufacturers, and consumers respectively and analyzes the ESS of the system.

Strategy Stability Analysis

ESS Stability Analysis for Government

From equation (10), the first-order derivative of the government's Replication dynamic equation is:

$$\frac{dF(x)}{dx} = (1-2x)\left(W_1 - W_2 + \left(\alpha_1 - (1+z)\alpha_2\right)F - yC_0 + zE_0 - y\left(S_1 - S_2\right) + yzH_1\right) \tag{11}$$

Let $I(y,z) = W_1 - W_2 + (\alpha_1 - (1+z)\alpha_2)F - yC_0 + zE_0 - y(S_1 - S_2) + yzH_1$, then the derivative of $F(x)$ with respect to x is given by: $\frac{dF(x)}{dx} = (1-2x)I(y,z)$. By setting $I(y,z) = 0$, the equilibrium value of y can be obtained as: $y^* = \frac{W_1 - W_2 + (\alpha_1 - \alpha_2)F + z(E_0 - \alpha_1 F + \alpha_2 F)}{C_0 + S_1 - S_2 - zH_1}$.

Proposition 1: When $y = y^*$, we have $F(x) \equiv 0$, indicating that regardless of the initial probability with which the government chooses the SR or NR strategy, the government's strategy choice will remain unchanged over time.

When $0 < y < y^*$, we have $I(y,z) > 0$, $\frac{dF(x)}{dx}|_{x=0} > 0$ and $\frac{dF(x)}{dx}|_{x=1} < 0$, implying that $x = 1$ is the equilibrium stabilization strategy.

When $y^* < y < 1$, we have $I(y,z) < 0$, $\frac{dF(x)}{dx}|_{x=0} < 0$ and $\frac{dF(x)}{dx}|_{x=1} > 0$, implying that $x = 0$ is the equilibrium stabilization strategy.

The phase diagram illustrating the dynamic evolution of the government's strategy is shown in Figure 3. The surface EFF_1E_1 divides the cubic space into two distinct regions. The region below this surface, denoted as $ADFE\text{-}A_1D_1F_1E_1$ represents the area where, when x=1, the government tends to adopt the RS strategy until reaching an evolutionarily stable state. In contrast, the upper-right region $EFBC\text{-}E_1F_1B_1C_1$ has the opposite meaning.

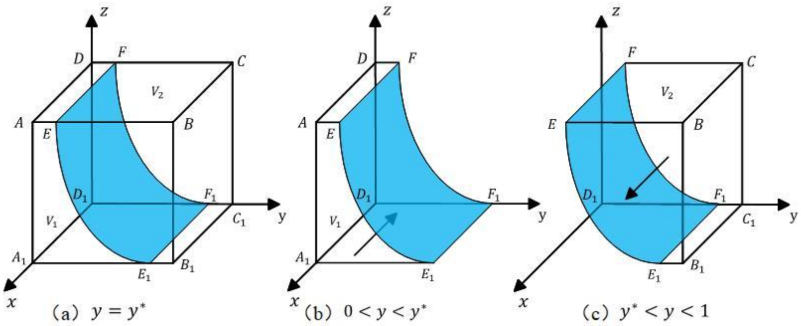

Figure 3 Trends in the dynamic evolution of government

ESS stability analysis of NEVMs

From equation (10), the first-order derivative of the NEVMs' Replication dynamic equation is:

$$\frac{dF(y)}{dy} = (1-2y)\left(C_2 - C_1 + xS_1 + (1-x)S_2 + R_1 - R_2 - z\left(L_1 - L_2 + C_2 - H_2\right)\right) \tag{12}$$

Let $I(x,z) = C_2 - C_1 + R_1 - R_2 + xS_1 + (1-x)S_2 - z(L_1 - L_2 + C_2 - H_2)$, then the derivative of $F(y)$ with respect to y is given by: $\frac{dF(y)}{dy} = (1-2y)I(x,z)$. By setting $I(x,z) = 0$, the equilibrium value of z can be obtained as: $z^* = \frac{C_2 - C_1 + R_1 - R_2 + (1-x)S_2 + xS_1}{C_2 - H_2 + L_1 - L_2}$.

Proposition 2: When $z = z^*$, we have $F(y) \equiv 0$, indicating that regardless of the initial probability with which NEVMs choose the BA or NB strategy, the NEVMs' strategy choice will remain unchanged over time.

When $0 < z < z^*$, we have $I(x,z) > 0$, $\frac{dF(y)}{dy}|_{y=0} > 0$ and $\frac{dF(y)}{dy}|_{y=1} < 0$, implying that $y = 1$ is the equilibrium stabilization strategy.

When $z^* < z < 1$,we have $I(x,z) < 0$, $\frac{dF(y)}{dy}|_{y=0} < 0$ and $\frac{dF(y)}{dy}|_{y=1} > 0$, implying that $y = 0$ is the equilibrium stabilization strategy.

Figure 4 illustrates the evolutionary process of strategy selection by NEVMs. The cubic space is divided into two regions by the plane EFF_1E_1. The region farther from the y-z axis EFF_1E_1- $A_1B_1C_1D_1$ indicates that NEVMs tend to apply blockchain technology. In contrast, the region near the y-z axis EFF_1E_1- $ABCD$ represents scenarios in which NEVMs do not adopt blockchain technology.

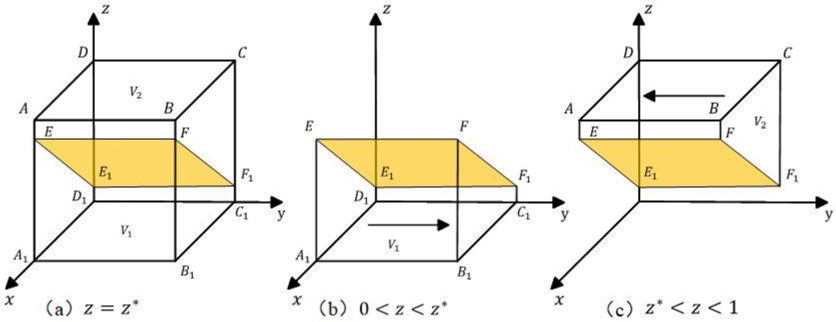

Figure 4 Trends in the dynamic evolution of NEVMs

ESS Stability Analysis of Consumers

From equation (10), the first order derivative of the consumer replication dynamic equation is:

$$\frac{dF(z)}{dz} = (1-2z)\left(E_1 + H_3 - P + R_3 + yL_1 + x\alpha_1 F + (1-x)\alpha_2 F\right) \tag{13}$$

Let $I(x,y) = (E_1 + H_3 - P + R_3 + yL_1 + x\alpha_1 F + (1-x)\alpha_2 F)$, then the derivative of $F(z)$ with respect to z is given by: $\frac{dF(z)}{dz} = (1-2z)I(x,y)$. By setting $I(x,y) = 0$, the equilibrium value of x can be obtained as: $x^* = \frac{-(E_1+H_3-P+R_3+\alpha_2 F+yL_1)}{(\alpha_1-\alpha_2)F}$.

Proposition 3: When $x = x^*$, we have $F(y) \equiv 0$, indicating that regardless of the initial probability with which consumers choose the PP or NP strategy, the consumers' strategy choice will remain unchanged over time.

When $0 < x < x^*$,we have $I(x,y) < 0$, $\frac{dF(z)}{dz}|_{z=0} < 0$ and $\frac{dF(y)}{dy}|_{z=1} > 0$, implying that $z = 0$ is the equilibrium stabilization strategy.

When $x^* < x < 1$,we have $I(x,y) > 0$, $\frac{dF(z)}{dz}|_{z=0} > 0$ and $\frac{dF(y)}{dy}|_{z=1} < 0$, implying that $z = 1$ is the equilibrium stabilization strategy.

As shown in Figure 5. The plane EFF_1E_1 divides the cubic space into two distinct regions. The region farther from the x-z axis, denoted as CEF-$C_1E_1F_1$, indicates that consumers prefer to participate in recycling by cooperating with NEVMs that possess formal recycling qualifications. In the region closer to the x-z axis, consumers are more likely to resell used batteries to third-party recycling institutions.

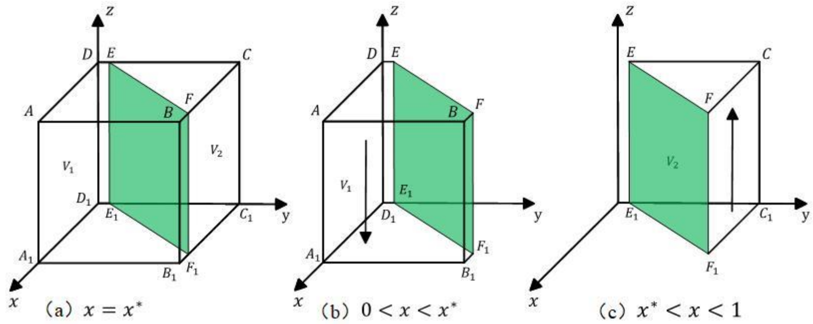

Figure 5 Trends in the dynamic evolution of consumers

Evolutionary Equilibrium Stability Analysis

The evolutionary stability strategy (ESS) for the system of differential equations can be derived from the local stability analysis of the system's Jacobi matrix, which can be obtained according to equation (10):

$$J=\begin{pmatrix}\frac{dF(x)}{dx} & \frac{dF(x)}{dy} & \frac{dF(x)}{dz}\\ \frac{dF(y)}{dx} & \frac{dF(y)}{dy} & \frac{dF(y)}{dz}\\ \frac{dF(z)}{dx} & \frac{dF(z)}{dy} & \frac{dF(z)}{dz}\end{pmatrix}=\begin{pmatrix}J_{11} & J_{12} & J_{13}\\ J_{21} & J_{22} & J_{23}\\ J_{31} & J_{32} & J_{33}\end{pmatrix}$$

$$=\begin{pmatrix}(1-2x)\begin{pmatrix}W_1-W_2-yC_0+zE_0\\ +(\alpha_1-(1+z)\alpha_2)F\\ -y(S_1-S_2)+yzH_1\end{pmatrix} & x(x-1)(C_0+S_1-S_2-zH_1) & x(1-x)(E_0-(\alpha_1-\alpha_2)F+yH_1)\\ y(1-y)(S_1-S_2) & (1-2y)\begin{pmatrix}C_2-C_1+R_1-R_2\\ +xS_1+(1-x)S_2\\ -z(L_1-L_2+C_2-H_2)\end{pmatrix} & y(y-1)(C_2-H_2+L_1-L_2)\\ z(1-z)(\alpha_1-\alpha_2)F & z(1-z)L_1 & J_{33}=(1-2z)\begin{pmatrix}E_1+H_3-P+R_3\\ +yL_1+x\alpha_1F\\ +(1-x)\alpha_2F\end{pmatrix}\end{pmatrix} \quad (14)$$

Table 2 presents the eigenvalues of all equilibrium points calculated in this study, along with the corresponding conditions under which each point satisfies the criteria for an ESS within the system.

Table 2 Model equilibrium points and eigenvalues

Balance point	Eigenvalue		
	λ_1	λ_2	λ_3
$E_1(0,0,0)$	$W_1-W_2+(\alpha_1-\alpha_2)F$	$R_1-R_2-C_1+C_2+S_2$	$R_3+E_1+H_3+\alpha_2F-P$
$E_2(1,0,0)$	$W_2-W_1-(\alpha_1-\alpha_2)F$	$R_1-R_2-C_1+C_2+S_1$	$R_3+E_1+H_3+\alpha_1F-P$
$E_3(0,1,0)$	$W_1-W_2+S_2-S_1-C_0+(\alpha_1-\alpha_2)F$	$R_2-R_1+C_1-C_2-S_2$	$R_3+E_1+H_3+\alpha_2F+L_1-P$
$E_4(0,0,1)$	$W_1-W_2+E_0$	$R_1-R_2-C_1+S_2-L_1+L_2+H_2$	$P-R_3-E_1-H_3-\alpha_2F$
$E_5(1,1,0)$	$W_2-W_1+S_1-S_2+C_0-(\alpha_1-\alpha_2)F$	$R_2-R_1+C_1-C_2-S_1$	$R_3+E_1+H_3+\alpha_1F+L_1-P$
$E_6(1,0,1)$	$W_2-W_1-E_0$	$R_1-R_2-C_1+S_1-L_1+L_2+H_2$	$P-R_3-E_1-H_3-\alpha_1F$

$E_7(0,1,1)$	$W_1 - W_2 - S_1 + S_2 - C_0 + E_0 + H_1$	$R_2 - R_1 + C_1 - S_2 + L_1 - L_2 - H_2$	$P - R_3 - E_1 - H_3 - L_1 - \alpha_2 F$
$E_8(1,1,1)$	$W_2 - W_1 + S_1 - S_2 + C_0 - E_0 - H_1$	$R_2 - R_1 + C_1 - S_1 + L_1 - L_2 - H_2$	$P - R_3 - E_1 - H_3 - L_1 - \alpha_1 F$

Due to space constraints, the analysis of system ESS is not fully provided in this study. As shown in Figure 6, the life cycle of EVBR is divided into initial, developmental, and maturity stages, with the ESS corresponding to each stage selected. In the initial stage of EVBR, the system ESS corresponds to $E_2(1,0,0)$, and the tripartite behavioral strategy chosen is (RS, NB, NP). The inequality $W_1 + \alpha_1 F > W_2 + \alpha_2 F$ indicates that the overall social welfare is higher when the government adopts a strict regulatory policy rather than a lax one. In this stage, the benefits of implementing the BA strategy are not significant, and the inequality $R_1 - C_1 + S_1 < R_2 - C_2$ further proves that NEVMs are more willing to forgo high government subsidies and opt for the NB strategy to secure their benefits. From the inequality $R_3 + E_1 + H_3 < P - \alpha_1 F$, when the total gains from active participation are lower than the difference between the informal recovery price and the government penalty, consumers will choose the NP strategy.

With the continuous improvement of government policies and related standards, the behavioral strategy choices of the government, NEVMs, and consumers tend to align with (RS, LCP, PP). The inequality $W_1 - S_1 - C_0 + H_1 > W_2 - S_2 - E_0$ indicates that the government attaches great importance to the reputation loss caused by the choice of LS strategy. From the inequality $R_1 - L_1 + S_1 - C_1 + H_2 > R_2 - L_2$, it can be observed that although NEVMs are bound to bear higher technological costs when choosing the BA strategy, this approach simultaneously gains recognition from both the government and consumers, which is crucial for their technological transformation. The inequality $P - H_3 - \alpha_1 F < R_3 - L_1 + E_1$ suggests that consumers' risk aversion preference drives their decision-making toward the PP strategy.

As the EVBR evolves into a fully sustainable system, the system's ESS corresponds to $E_7(0,1,1)$ and the selected tripartite behavioral strategy is (LS, BA, PP). The inequality $W_1 - S_1 - C_0 + H_1 < W_2 - S_2 - E_0$ suggests that the marginal impact of government regulation on social welfare changes is gradually diminishing, indicating that the EVBR industry is transitioning into its maturity stage. The inequality $R_1 - L_1 + S_2 - C_1 + H_2 > R_2 - L_2$ implies that the implementation of BA strategies by NEVMs under a market-driven mechanism generates a scale effect. Furthermore, the inequality $P - H_3 - \alpha_2 F < R_3 - L_1 + E_1$ suggests that the environmental benefits of the PP strategy stimulate public environmental awareness when it is implemented.

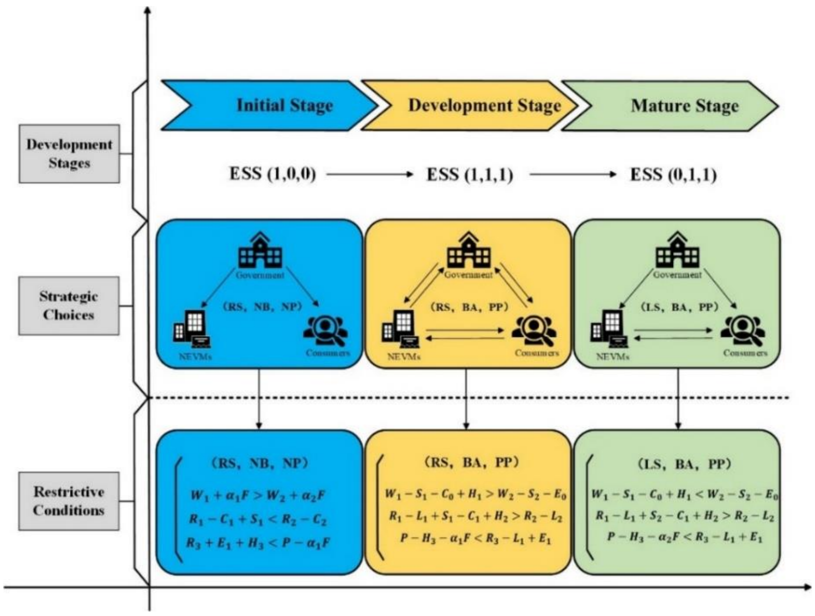

Figure 6 Different stages of EVBM industry development

EXAMPLE ANALYSIS

In this section, the focus is placed on the three stages of the EVBR industry: the initial stage, development stage, and maturity stage. Numerical analysis is carried out on MATLAB R2024b software to investigate the impact of model parameters on the behavioral strategies of the stakeholders, and to verify the validity of the evolutionary game model. Considering the symmetry of the initial state, the neutrality of strategy selection and the stability of calculation, this paper takes x = 0.5, y = 0.5 and z = 0.5 as the initial settings. Taking ternary batteries as an example, the assignment of certain variables is partly based on previous studies [28,29], and the parameter values of each development stage are set as shown in Table 3 (unit: 10,000 yuan/ton).

Table 3 Parameter assignments for each stage of development

Parameter	Initial Stage	Development Stage	Mature Stage
W_1	3.961	3.961	3.961
W_2	2.67	2.67	4.2
S_1	0.43	0.83	0.1
S_2	0.3	0.3	0.1
C_0	0.3	0.3	0.3
E_0	0.6	0.6	1.2
H_1	0.3	0.3	0.3
R_1	6	7.5	8.5
R_2	3.5	3.5	3.5
C_1	4	4	4
C_2	0.35	0.35	0.35
H_2	0.2	0.2	0.2
R_3	5	6	6
E_1	0.13	0.13	0.13
L_1	0.4	0.4	0.8
P	6.29	6.29	6.29
H_3	0.15	0.15	0.15
F	1.2	1.2	1.2
α_1	0.8	0.8	0.8
α_2	0.4	0.4	0.4

Dynamic Evolutionary Trajectories in the Initial Phase and Parameter Sensitivity Analysis

Dynamic Evolutionary Trajectories in the Initial Phase

The tripartite evolutionary game trajectories of 729 randomly generated non-fixed initial strategies, as shown in Figure 7(a), further validate the conclusion that "the equilibrium point (1,0,0) is the system's ESS" as depicted in Figure 3.

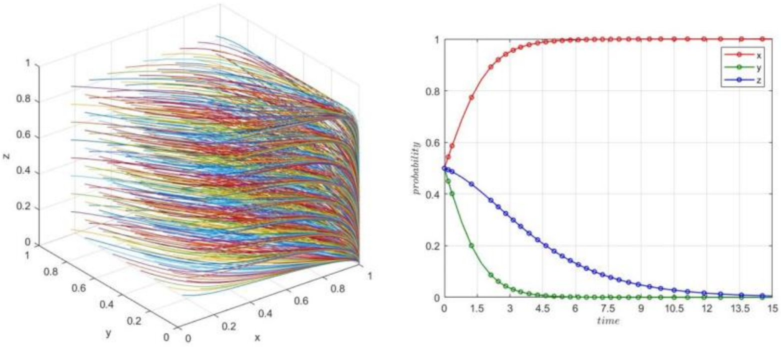

Figure 7 System evolution process in the initial stage of EVBR industry

As shown in Figure 7(b), over time, the government's strategy choice converges to the RS strategy, while the strategy choices of NEVMs and consumers converge to the NB and NP strategies, respectively, with consumers converging faster. In the early stages of the power battery recycling industry’s development, the government primarily drives industry growth through policy guidance, while NEVMs and consumers are more motivated by self-interest, resulting in a low willingness to adopt blockchain technology and participate in recycling.

Parameter Sensitivity Analysis in the Initial Stage

Given the government's pivotal role in the early stages of power battery recycling, its policy decisions significantly impact the industry's development. Therefore, it is essential to explore how changes in government-related parameters influence the strategy choices of other stakeholders and to conduct a sensitivity analysis through numerical simulations to assess their regulatory effects and practical implications.

Firstly, this study discusses the impact of S_1 on the decision-making behaviors of both the government and NEVMs, with the sensitivity analysis results shown in Figure 8. Figure 8(b) illustrates the effect of S_1 on NEVMs' implementation of the BA strategy when it takes values of 0.43, 0.83, 1.23, and 1.63, respectively. It can be observed that government subsidies for NEVMs play a significant role in promoting the formation of evolutionary stable points. When S_1 is set to 0.43, NEVMs show a low willingness to adopt blockchain technology. However, when S_1 is greater than or equal to 0.83, the speed at which NEVMs' strategy choices evolve towards a probability of 1 becomes more pronounced. Understandably, the high deployment cost of blockchain technology makes it difficult to achieve economies of scale in the short term, and that excessively low technological subsidies are insufficient to effectively incentivize NEVMs to drive technological innovation.

As shown in Figure 8(c), when S_1 is 0.43 and 0.83, the government's willingness to adopt the RS strategy is higher. However, as S_1 increases to 1.23, the government's strategy choice starts to waver. Combining this with Figure 8(a), it can be found that around the threshold value S_1=1.63, the government's strategy choice follows a spiraling evolutionary path, failing to converge to the ideal state. This suggests that, for the government, a moderate subsidy policy can promote the sustainable development of the electric vehicle industry, but excessive policy incentives may lead to greater financial pressure.

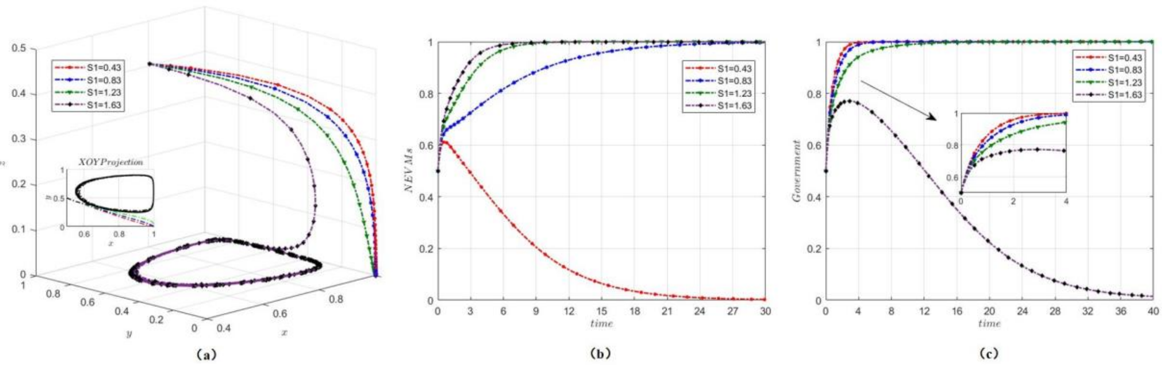

Figure 8 The impact of S_1 on the evolutionary process of NEVMs and consumers' behavioral strategies

In addition, this paper conducted a sensitivity analysis of multiple parameters, with the findings indicating that changes in R_1 have the most significant impact on NEVMs' strategy choices, as shown in Figure 9. The results show that when R_1 is 6 or 6.5, NEVMs' willingness to deploy blockchain technology is relatively low. When R_1 increases to 7, the trend of the curve's evolution to 1 is enhanced, albeit at a slower pace. However, once R_1 exceeds 7, the evolution speed is significantly accelerated, which suggests that when the profit per unit of recycling is raised to a certain level, the NEVMs will proactively consider technological innovation to optimize the entire process of power battery recycling.

Further combining the influence of S_1 on the strategy selection of NEVMs, it can be concluded that in the initial stage of EVBR, the incremental revenue generated by deploying blockchain technology (as compared to government subsidies) provides a stronger incentive for NEVMs. Therefore, the government should strengthen the development of the regulatory framework and guide market mechanisms, while establishing a mechanism to guarantee the stability of the revenue from technology adoption, so as to activate the endogenous motivation of NEVMs to continue to carry out blockchain technology innovation.

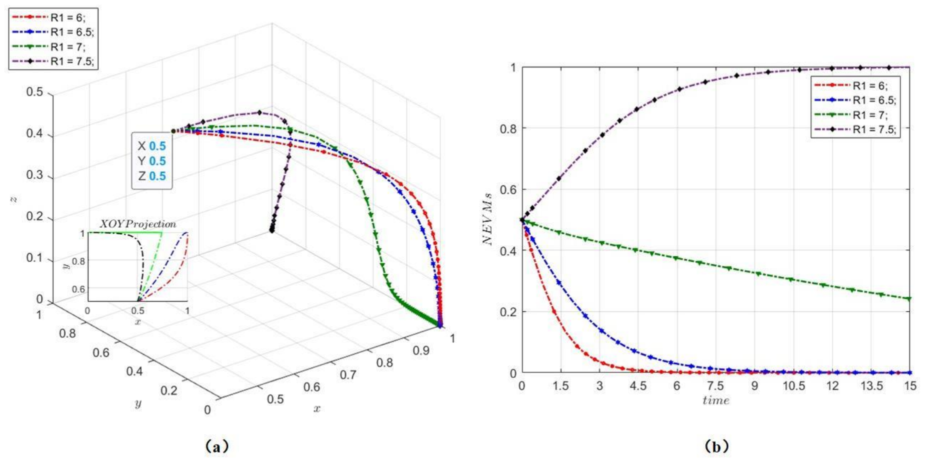

Figure 9 The impact of R_1 on the evolutionary process of NEVMs' behavioral strategies

Finally, this paper also examines the impact of the revenue from participating in formal recycling, denoted as R_3, on consumers' strategy choices. As shown in Figure 10(b), with the increase of R_3 pairs, the strategy choice of the consumer group gradually shifts from NP strategy to PP strategy. Due to market shortcomings, such as an underdeveloped recycling system and low information transparency in the early stages of the EVBR industry, some consumers, driven by economic rationality, resell power batteries to informal recyclers or "small workshops" to obtain higher financial returns. This paradox of choice will exacerbate the market disorder, which not only triggers environmental risks, but also creates the market dilemma of “bad money driving out good money”. Therefore, it is crucial to build a competitive formal recycling pricing mechanism, which is the key to solve the adverse selection problem in the early stage of power battery recycling market.

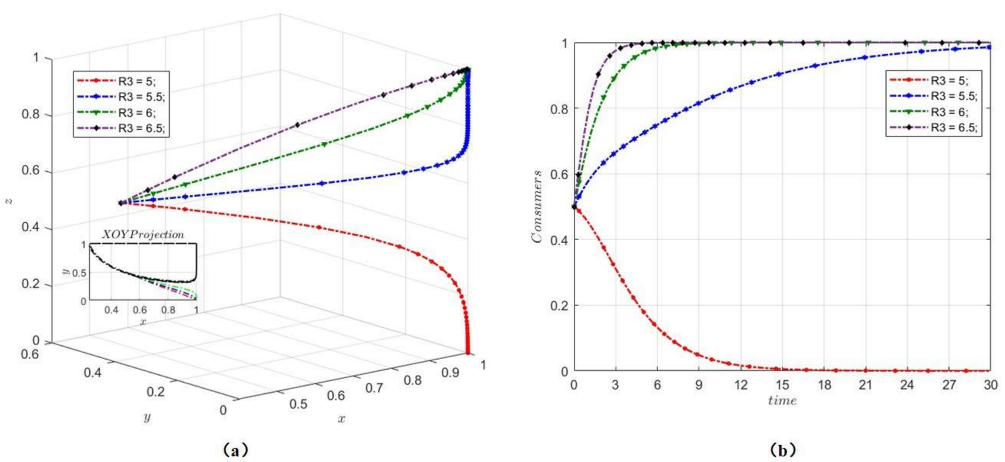

Figure 10 The impact of R_3 on the evolutionary process of consumers' behavioral strategies

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Dynamic evolution trajectory and parameter sensitivity analysis in the development stage

Dynamic evolution trajectory in the development stage

This section numerically simulates the constraints in the development stage of the EVBR and demonstrates that the government, NEVMs, and consumers converge to the system's steady state, as shown in Figure 11(a) and Figure 11(b). Over time, all behavioral strategy choices eventually stabilize at $E_8(1,1,1)$.

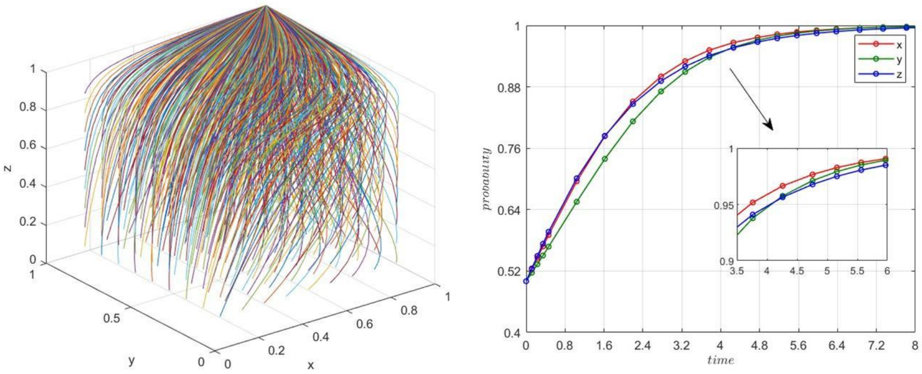

Figure 11 System evolution process in the development stage of EVBR industry

Parameter sensitivity analysis in the development stage

In the development stage, studying the parameters related to NEVMs and consumers is crucial for system stability. This section analyzes parameters including: the credibility loss E_0 incurred by the government's LS strategy when consumers participate, the subsidy L_1 (and L_2 similarly) provided by NEVMs to consumers to gain market share, and the government's publicity cost C_0 for green recycling.

Firstly, the changes in the government's behavioral strategy choice are shown in Figure 12. Obviously, the probability of the government adopting the RS strategy is inversely proportional to the value of E_0. When E_0 increases to 1.5, the government's strategy choice exhibits a spiral evolutionary trend, leading to the inability to converge. This indicates that during the EVBR development stage, the government, as the protector of the public's interests, places great importance on public opinion, and its strategy choices are significantly influenced by the public.

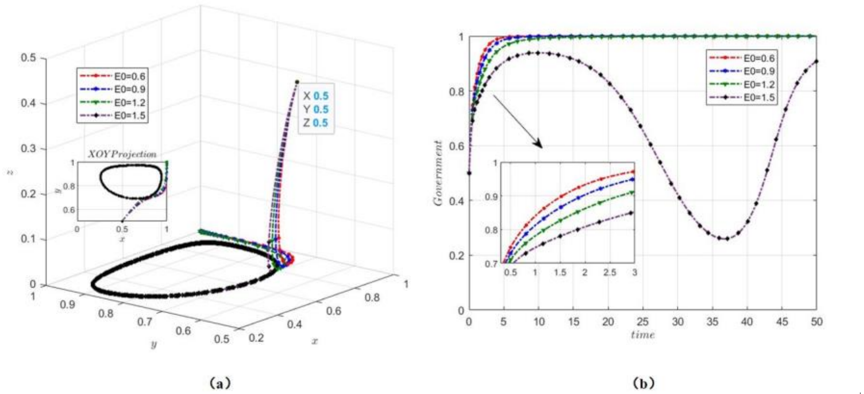

Figure 12 The impact of E_0 on the evolutionary process of the governments' behavioral strategies

Secondly, Figure 13 demonstrates the impact of L_1 on the evolutionary behavior strategies of consumers. It shows that when L_1 is small, NEVMs' influence on consumer participation in recycling is minimal. However, as L_1 increases, the rate at which consumers shift towards the PP strategy becomes positively correlated with the value of L_1. This indicates that the likelihood of consumers actively participating in recycling increases as manufacturers' preferential efforts rise, highlighting that NEVMs' use of incentives to guide consumers into formal recycling channels is an inevitable transition phase for advancing the maturity of the EVBR industry.

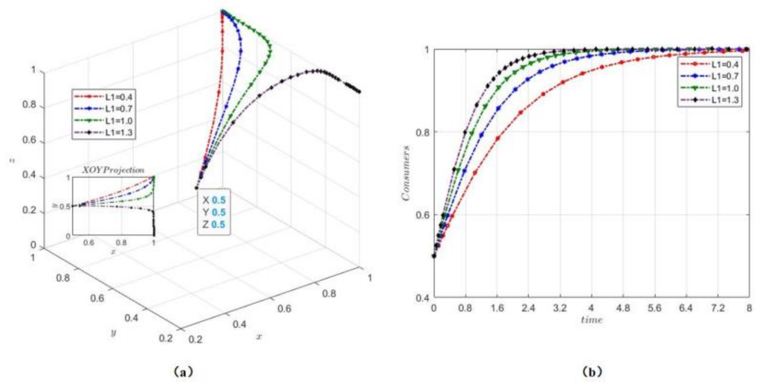

Figure 13 The impact of L_1 on the evolutionary process of consumers' behavioral strategies

Finally, this study explores the impact of the government's green recycling publicity cost C_0 on consumer strategy choice. As shown in Figure 14, with the continuous increase in the investment of C_0, there is a noticeable rise in consumers' willingness to choose formal recycling. This indicates that the government's investment in green recycling awareness campaigns plays a crucial role in enhancing consumers' environmental consciousness.

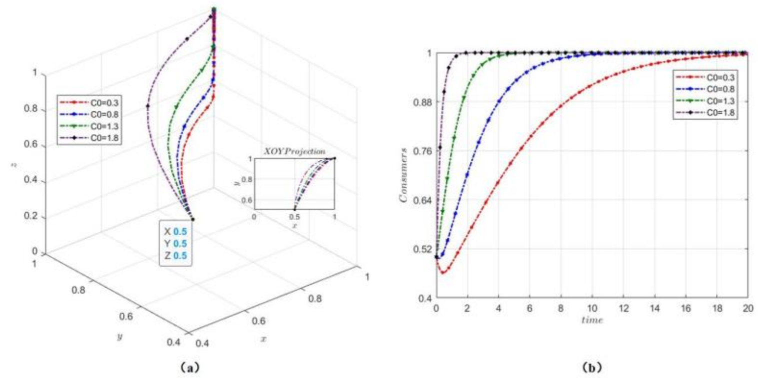

Figure 14 The impact of C_0 on the evolutionary process of consumers' behavioral strategies

Dynamic Evolution Trajectory and Parameter Sensitivity Analysis in Maturity Stage

Dynamic Evolution Trajectory in Maturity Stage

According to the product life cycle theory, the EVBR industry is mainly driven by the market mechanism in the maturity stage. As shown in Figure 15, the behavior strategies of all stakeholders stabilize at $E_7(0,1,1)$. The role of the government gradually shifts from “facilitator” to “regulator”, with the marginal benefits of weak and strong government regulation converging. Therefore, this section adjusts the technology subsidy parameters S_1/S_2 to 0.1, and the regulatory incentive coefficient W_1 is calibrated to 4.2.

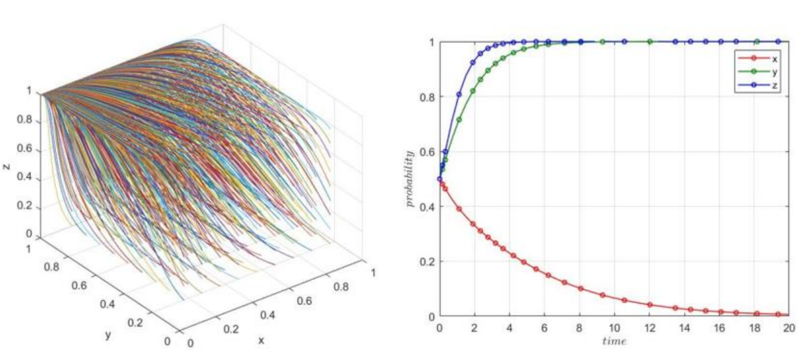

Figure 15 System evolution process in the maturity stage of EVBR industry

Parameter Sensitivity Analysis at the Maturity Stage

This section analyzes the impact of two key parameters on EVBMs' decisions: the deployment cost of blockchain technology, C_1 and the core competitiveness gain H_2 from its application. Additionally, the joint variation between environmental gains E_1 from successful formal recycling and health losses H_3 from negative recycling on consumer strategy choices is explored.

Firstly, this study sets the blockchain deployment cost parameter C_1 at 4.0, 4.5, 5.0, and 5.5 to investigate the impact of cost fluctuations on NEVMs' strategy choices, as shown in Figure 16.

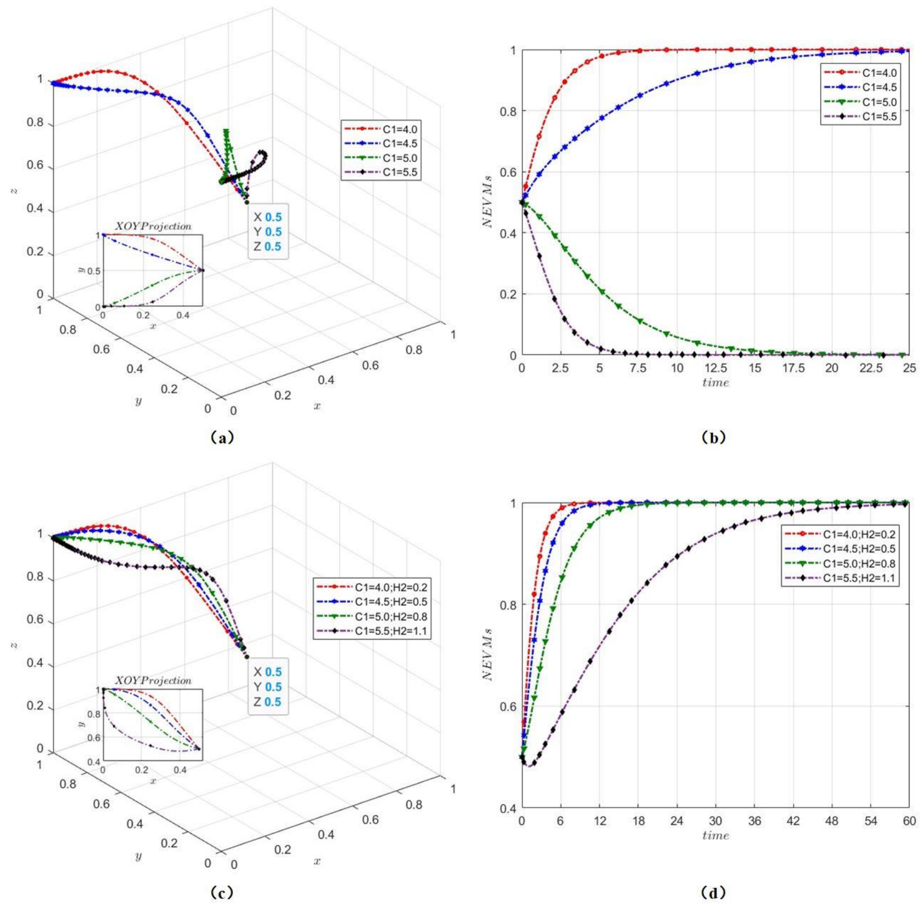

Figure 16 The impact of C_1 and H_2 on the evolutionary process of NEVMs' behavioral strategies

The two subfigures (a) and (b) of Figure 16 shows a significant decline in the adoption rate of the BA strategy as C_1 increases, and when C_1 exceeds a critical threshold, the diminishing return on investment triggers NEVMs' suppression of technology adoption. On this basis, this study further examines the impact of changes in H_2 on NEVMs' decision-making, as shown in Figure 16 (c) and (d). As the value of H_2 increases, NEVMs gradually overcome cost pressures and are more inclined to proactively adopt blockchain technology. This phenomenon suggests that, compared to the cost burden of technological innovation, NEVMs focus more on enhancing core competitiveness and increasing market share.

Moreover, technological advancements have driven significant breakthroughs in NEVMs' battery recycling while also spurring innovations in battery materials. Although these new materials improve battery endurance, they make the battery processing progress more professional-needed, which, if processed improperly, will cause severe damage to the environment. Moreover, as the EVBR industry enters its maturity stage, the overall rise in environmental awareness across society is expected to generate widespread normative social influence effect, encouraging more consumers to opt for formal recycling channels. Based on these considerations, this study introduces a dynamic mechanism to capture the impact of relevant variables on the evolution of consumer strategies, thereby systematically analyzing how evolving environmental awareness contributes to the long-term stability and sustainability of the power battery recycling system. Here, the dynamic environmental benefit is adjusted to $E_1^* = zE_1$, and the dynamic environmental damage is revised to $H_3^* = (1 - z)H_3$. Accordingly, the Replication dynamic equation for consumers is updated as follows:

$$F^*(z) = z(1-z)\left(R_3 - P + x\alpha_1 F + (1-x)\alpha_2 F + yL_1 + zE_1 + (1-z)H_3\right) \tag{15}$$

This study sets the values of E_1^* (0.13, 0.43, 0.73, 1.03) and H_3^* (0.15, 0.25, 0.35, 0.45) to represent the environmental benefits of consumer participation in recycling and the environmental pollution caused by battery innovation, respectively. In addition, this study further explores the impact of increased consumer environmental awareness on strategy choices under the same environmental variables, as shown in Figure 17. The results show that, with a fixed level of environmental awareness, consumers' risk aversion preference drives their strategies to favor PP strategies; when environmental variables remain constant, a higher initial probability of consumers choosing active recycling accelerates the evolution of their strategy towards the PP direction. When $E_1^* = 0.13$ and $H_3^* = 0.15$, the increase in consumers' initial probability makes their strategies change from NP to PP strategies. This suggests that after the EVBR industry has entered the maturity stage, increasing consumer environmental awareness becomes a key endogenous driving force for its development. Under the combined effects of improved environmental policies, ongoing technological advances, and optimized market mechanisms, the environmental benefits of formal recycling are becoming increasingly prominent, while effective regulation of informal channels is gradually raising their environmental costs, which, in turn, encourages consumers to rationally shift toward more sustainable recycling practices.

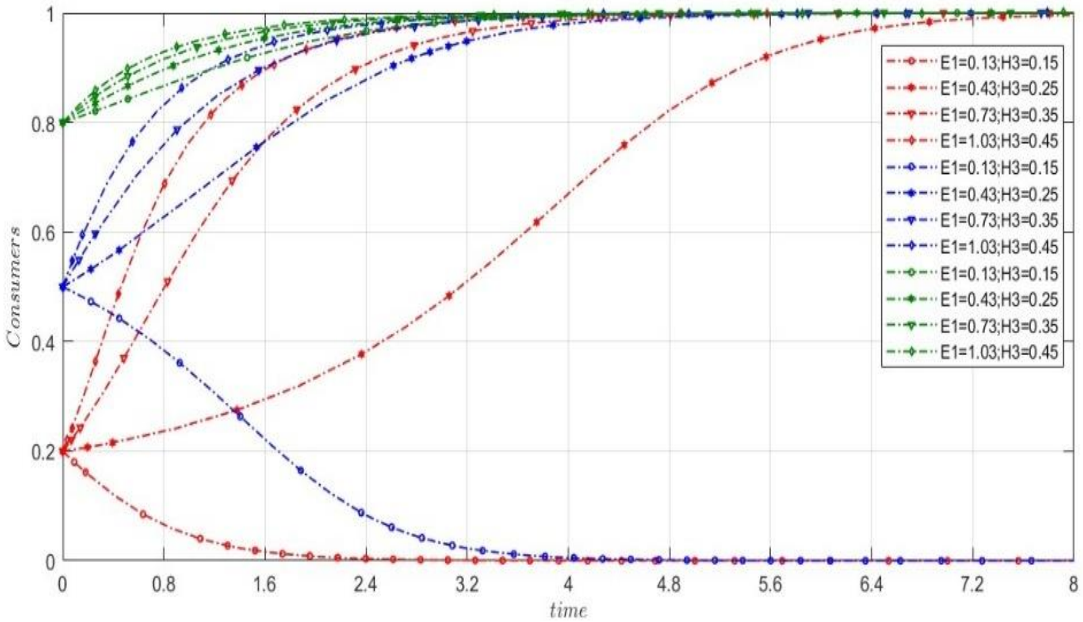

Figure 17 The impact of E_1 and H_3 on the evolutionary process of consumers' behavioral strategies under different initial probabilities

DISCUSSION

In the sustainable transformation of EVBR, stakeholders' strategies are influenced by both self-interests and a sense of responsibility, evolving dynamically across different stages. Building on project lifecycle theory, this paper develops an analytical framework for the sustainable development of EVBR, identifies the key factors influencing its optimal evolution at each stage, and performs a sensitivity analysis of the core parameters. The results suggest that EVBR's sustainable development depends not only on individual stakeholders' decision-making but also on the interactions and synergies among various parties. As development progresses, its sustainable benefits increase over time. However, due to differences in stakeholders' perceptions of social responsibility, economic goals, and policy constraints, their roles and strategic choices shift at different stages. Drawing on the above analysis, the paper proposes a collaborative governance mechanism for the sustainable development of EVBR and constructs an optimized path from a lifecycle perspective, as shown in Figure 18, providing theoretical support and practical guidance for the long-term stable development of EVBR.

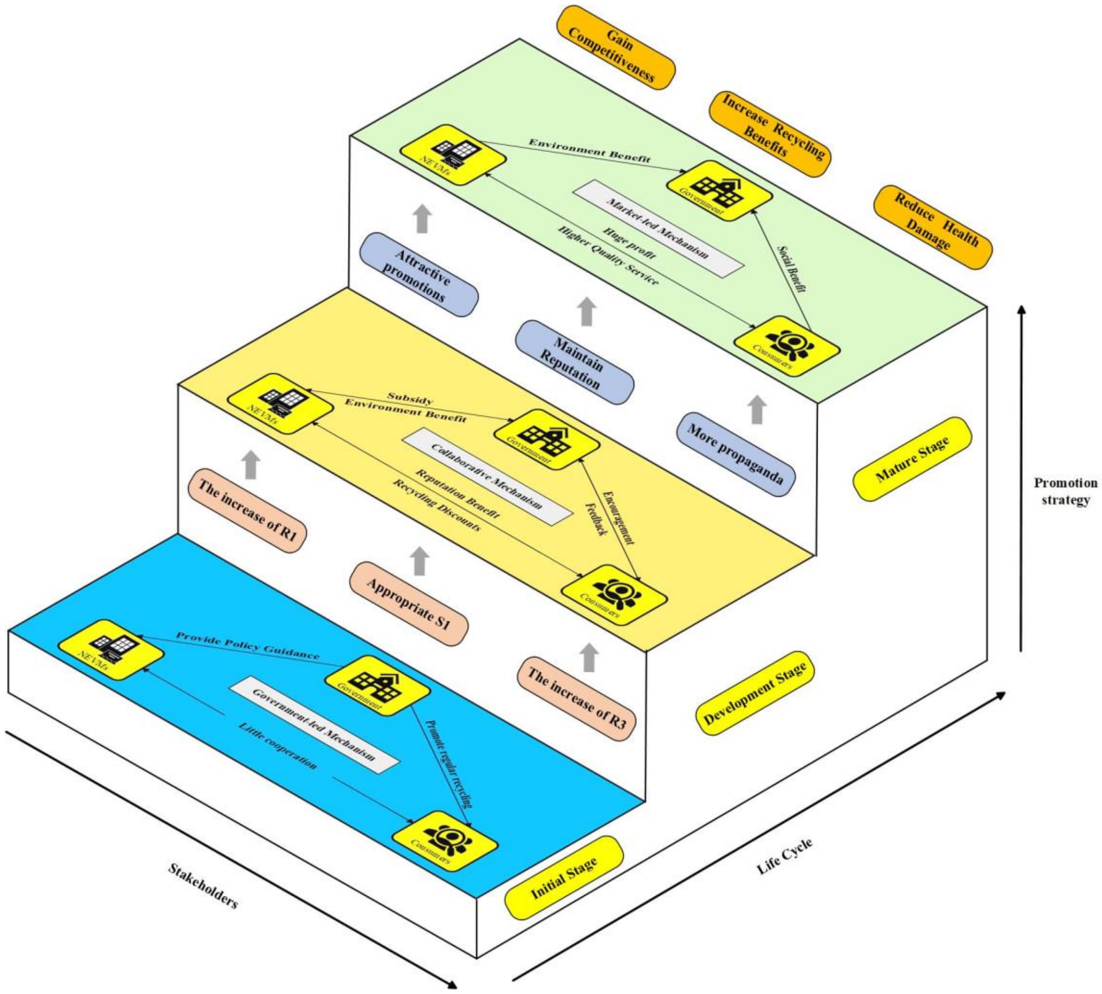

Figure 18 Promotion mechanisms for sustainable development in the EVBA industry

In the initial stage of EVBR, the government's role extends beyond policy implementation, as it proactively guides the development direction of EVBR through resource allocation and market guidance, driven by the dual considerations of social responsibility and economic development. Due to the lack of significant economic benefits, NEVMs face great cost pressure in promoting technological innovation. To incentivize their technological upgrading, the government should offer appropriate fiscal subsidies, tax incentives, and special funding to alleviate the financial burden of NEVMs. Additionally, the government needs to introduce policies to promote the development of market-based trading platforms, ensuring that NEVMs receive fair returns from the battery recycling process and facilitating economies of scale from blockchain technology, thereby enhancing their drive for technological innovation and sustainability. In the early stage of EVBR, irregular market pricing leads to formal recycling channels offering lower prices than informal recyclers, causing consumers to favor informal channels in pursuit of higher returns, which severely undermines the sustainable development of EVBR. Therefore, the government must implement price guidance policies to increase consumer benefits in formal recycling, while improving transparency and fairness to strengthen consumer trust.

In the EVBR development stage, with the improvement of government policies and the enhancement of consumers' environmental awareness, a new pattern of synergistic development among the government, NEVMs and consumers is gradually taking shape. The enhancement of the government's social image relies not only on the rationality and fairness of its decisions but also on the collaboration between NEVMs and consumers in co-creating a green and efficient recycling system. For NEVMs, building a green recycling system requires advanced technologies, equipment, and the integration of resources from various stakeholders. This goal cannot be achieved by NEVMs alone and requires active participation from the government and consumers. The government should offer policy subsidies to ease the operational pressures on NEVMs, providing strong support for their initiatives. For consumers, the overall environmental awareness of society and the convenience of participating in green recycling are key factors that influence their strategy choices. At this stage, the decisions made by all stakeholders serve their own interests while simultaneously promoting the sustainable development of the EVBR industry, Creating a triple-win outcome.

In the mature stage of EVBR, with the ongoing improvement of market mechanisms, NEVMs further solidified their dominant position in the industry by expanding economies of scale, the industry gradually shifted to a market-driven structure. During this process, NEVMs significantly improve resource management efficiency through technological innovation and optimization of recycling processes. Consumers, increasingly aware of the long-term health benefits of environmental protection, are more inclined to choose formal recycling channels. Although the government's leading role in the EVBR market has diminished, it still needs to continue to play a regulatory role to prevent Short-term speculation and unfair competition, maintaining the stability and standardization of EVBR industry.

CONCLUSION

From the perspective of stakeholder involvement, this study aims to explore the key factors affecting behavioral strategies and to analyze the selection process of stakeholders. By solving the replication dynamic equation, the evolutionary stability strategy of the system under different conditions is investigated. Based on the industry life cycle theory, this study further analyzes stakeholder behavioral strategies and their interactions during the early, growth, and mature stages of the EVBR industry under three mechanisms: government-led, collaborative participation, and market-oriented models. Finally, numerical simulations were conducted using MATLAB R2024b to analyze the impact of parameter variations on the evolutionary trajectories of stakeholder strategies. The main conclusions of this study are drawn as follows:

During the development of the EVBR industry, the government, NEVMs and consumers play different roles at different stages and are guided by their respective mechanisms. In the government-led initial stage, the government actively promotes the development of green recycling systems by NEVMs through policy incentives and encourages consumer participation. However, constrained by short-term cost pressures, NEVMs lack sufficient motivation to develop recycling systems, and consumers, due to limited information and insufficient incentives, show low enthusiasm for engaging with formal recycling channels. As EVBR enters the development stage, NEVMs begin to increase investment in green recycling technologies, contributing to greater recycling efficiency and streamlined processes. Simultaneously, with the improvement of environmental awareness, consumers exhibit a more proactive attitude toward recycling participation. At this stage, the government assumed a pivotal role by consistently offering policy support and guiding market development, which facilitated effective coordination among stakeholders. In the mature stage, the dominant role of market mechanisms in the recycling system becomes increasingly evident. NEVMs continuously enhance recycling efficiency and industrial chain integration through technological innovation, while consumer participation becomes more proactive and widespread. Under the macro-level guidance of the government, stakeholders jointly contribute to the sustainable development of the EVBR industry.

Variations in key factors exert differentiated influences on the strategic behavior of stakeholders. From the perspective of governmental policy guidance, a moderate increase in support and subsidies for green recycling can effectively promote NEVMs to accelerate technological innovation and system construction. Nevertheless, excessive fiscal spending may pose budgetary pressures, so a balance needs to be struck between incentives and regulation. For NEVMs, the cost and return on investment of environmental programs are important factors influencing their decision-making. While pursuing corporate interests, NEVMs are required to evaluate the allocation of resources toward recycling technologies and infrastructure to optimize the operational efficiency of green recycling initiatives. Consumers' willingness to engage in green recycling is closely influenced by policy guidance, recycling convenience, and incentive mechanisms, with government-led public education and NEVMs' promotional activities playing an essential role in this process. The joint efforts of the government, NEVMs, and consumers have facilitated the sustainable development of the green recycling industry for power batteries, creating a triple-win outcome for all stakeholders involved.

Finally, based on the changes in stakeholder strategies across different stages of industry development, this study constructs a collaborative governance framework for the sustainable development of EVBR and proposes strategies to promote its sustainability, including the establishment of price regulation mechanisms, reasonable subsidy policies, and incentives for consumer participation. However, this study primarily focuses on the main factors currently influencing stakeholder decisions, while overlooking other potential variables that may also affect these decisions. As society and technology continue to evolve, emerging factors and shifts in stakeholder dynamics will inevitably shape the future trajectory of the EVBR industry, which should be a focal point for future research.

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