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Research on Dual-Mode Parallel Mechanism for New Energy Vehicle Battery Recycling Based on Evolutionary Game Theory

Aimin Liu

Jiangnan University, Wuxi, China
6220910035@stu.jiangnan.edu.cn

Abstract: The rapid development of the new energy vehicle (NEV) industry has brought about the challenge of power battery recycling, which has become a key issue for the industry's sustainable development. This paper applies evolutionary game theory to establish a dynamic game model involving the government, manufacturers, and consumers, and proposes an incentive mechanism combining deposit and credit schemes. By simulating different scenarios, the study explores the interaction between policies and behaviors. The results indicate that dynamic balanced regulation is essential for the stability of the recycling system; the complementarity between deposit and credit schemes can resolve conflicts between short-term and long-term interests; and consumer behavior is influenced by net recycling benefits, which requires guidance through incentives and constraints to promote participation in formal recycling. The simulation results show that under high incentives and moderate regulation, the system tends toward a balanced state between environmental and economic benefits. This study provides theoretical support for power battery recycling and offers practical references for policy optimization and supply chain governance.

Keywords: Power Battery Recycling, Evolutionary Game Theory, Dual-Mode Parallel Mechanism, Incentive Mechanism, Scenario Simulation

1. Introduction

1.1. Research Background

With increasing global attention to environmental protection and sustainable development, NEVs, as low-carbon and environmentally friendly transportation tools, have been widely promoted and adopted. However, the rapid proliferation of NEVs has introduced a series of new challenges, particularly in the area of power battery recycling and reuse [1]. According to a report by the International Energy Agency (IEA), global electric vehicle sales reached 10 million units in 2022, representing a 55% year-on-year increase. This figure is expected to further grow to over 30 million units by 2030 [2]. As these vehicles reach the end of their service life, a large number of used power batteries will enter the market. If not properly handled, they will impose significant environmental and resource pressures [3].

In China, the NEV industry has shown significant growth momentum. In 2022, domestic NEV sales reached 6.887 million units, accounting for 68.9% of the global total. The Chinese government

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places great importance on power battery recycling and reuse, having introduced a series of policies and regulations aimed at establishing a comprehensive recycling system to promote the industry's sustainable development. For example, the Interim Measures for the Management of the Recycling and Utilization of New Energy Vehicle Power Batteries, issued by the Ministry of Industry and Information Technology in 2018, clearly defines the responsibilities and obligations of vehicle manufacturers, battery manufacturers, and recycling service networks, thereby providing an institutional guarantee for power battery recycling and reuse [4–6].

1.2. Domestic and International Research Status

In recent years, the rapid development of the NEV industry has triggered widespread global attention toward power battery recycling and reuse. Researchers both domestically and internationally have explored this issue from various dimensions, including policy design, technological pathways, economic incentives, and multi-stakeholder collaboration, providing significant theoretical support for the establishment of a sustainable recycling system.

Domestic research has primarily focused on optimizing policy tools and improving supply chain efficiency. At the policy level, numerous studies have highlighted that the Extended Producer Responsibility (EPR) system is key to building a recycling system. Economic measures such as financial subsidies and tax incentives can significantly enhance manufacturers' willingness to participate in recycling. However, over-reliance on government subsidies may undermine policy sustainability [7]. For instance, studies analyzing the recycling context under carbon trading frameworks have found that moderate recycling volume subsidies can balance the costs and benefits for vehicle manufacturers, but a dynamic regulatory mechanism is necessary to prevent market distortion [8]. Furthermore, comparative studies on dual-channel recycling models (e.g., "deposit system" and "trade-in system") have shown that policy design needs to dynamically match the actual operational costs of enterprises, as a single model is insufficient to meet the diverse demands of the market [9].

International research has focused more on multi-stakeholder collaboration and the design of circular economy frameworks [10–12]. For example, multi-tier closed-loop supply chain models incorporating carbon regulation constraints have demonstrated that the coordinated efforts of governments, manufacturers, and recyclers can significantly reduce lifecycle carbon emissions [13]. The European Union’s new Battery Regulation sets clear targets for material recycling rates, and related studies have further examined the interaction between recycling rates and tax incentives. In recent years, the United States has increased investment in direct recycling technologies, which research has shown can significantly reduce energy consumption; however, large-scale implementation still requires policy guidance and market cultivation [14]. In terms of incentive mechanisms, international studies have proposed a hybrid "deposit-credit" model, noting that the deposit system relies on consumer behavior and delivers short-term benefits, while the credit system emphasizes corporate compliance but requires government credit backing. The complementarity between these two approaches requires dynamic policy adaptation [15]. Additionally, the issue of information asymmetry has also received widespread attention. Some studies suggest that building data-sharing platforms could reduce decision-making costs for game participants and enhance the transparency and efficiency of the recycling system [16–17].

2. Theoretical Basis of the Dual-Mode Parallel Battery Recycling Mechanism

2.1. Problem Description

The current recycling system for new energy vehicle (NEV) power batteries faces three major challenges: First, there is a prominent conflict between environmental pressure and recycling

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efficiency. A single recycling model struggles to balance large-scale recycling demand with the carrying capacity of resources and the environment. Although the deposit model can quickly improve the recycling rate, it tends to trigger market resistance. In contrast, the credit model faces high initial promotion costs and lacks flexibility during the early stages of implementation. Second, there is a significant conflict in the distribution of interests and responsibilities among key stakeholders—namely the government, vehicle manufacturers, and consumers. Vehicle manufacturers prioritize short-term profits and tend to favor the low-cost deposit model. Consumers, when recycling benefits are insufficient, are more inclined to dispose of used batteries through informal or illegal channels. Meanwhile, the government must balance environmental benefits with regulatory costs, making it difficult for a single model to achieve a win-win outcome for all parties. Finally, there is a notable imbalance between policy rigidity and market dynamics. Existing policies often rely on static incentive mechanisms, which struggle to adapt to market uncertainties, such as technological iterations in battery manufacturing and fluctuations in raw material prices. When the residual value of batteries decreases, the deposit model tends to increase the risk of consumer default. On the other hand, the credit model depends on stable policy support, and delays in policy adjustments may weaken its effectiveness. Therefore, establishing a dual-mode parallel mechanism that integrates the advantages of both the deposit and credit models is key to resolving these conflicts.

2.2. Applicability of the Evolutionary Game Model

The applicability of evolutionary game theory in the dynamic multi-stakeholder interaction of the power battery recycling system is reflected in three main aspects: First, its assumption of bounded rationality and strategy learning aligns with real-world decision-making processes. The government, vehicle manufacturers, and consumers all adjust their strategies through a process of trial and error. For example, the government may adjust the intensity of its regulations in response to environmental degradation, manufacturers may switch between different recycling models based on profitability, and consumers may choose recycling methods according to their net returns [19]. Second, the theory captures dynamic feedback and path dependence effects. The nonlinear interaction of the three parties' strategies creates a feedback loop. For instance, stricter government regulation increases manufacturers' compliance costs, which may motivate manufacturers to improve recycling technologies. This, in turn, enhances consumers' net benefits from formal recycling, forming a positive feedback cycle [20]. Finally, the evolutionary game model provides multi-scenario simulation and policy prediction capabilities. By adjusting model parameters, it can simulate the evolutionary trajectory of the system under different policy scenarios, offering a quantitative basis for dynamic policy optimization [21]. In conclusion, the evolutionary game model can reveal the dynamic stability conditions of the dual-mode parallel mechanism, providing a solid theoretical foundation for the subsequent model construction and policy design.

3. Model Construction: Dual-Mode Parallel Decision-Making Model Based on Evolutionary Game Theory

3.1. Model Assumptions and Game Participants

This study constructs a three-party evolutionary game model involving the government (G), vehicle manufacturers (E), and consumers (C), based on the following assumptions:

1. Bounded Rationality: All three game participants adjust their strategies through trial-and-error learning, seeking local rather than global optimization.
2. Dynamic Interaction: Strategy selection is influenced by the behavior of other participants and external environmental factors, forming a feedback loop.

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3. Strategy Diversity: The government, manufacturers, and consumers each have multiple strategic choices, which exhibit different advantages and disadvantages under different scenarios, increasing the complexity and diversity of the game.
4. Incomplete Information: Due to the complexity and uncertainty of the market environment, participants often face incomplete information when making decisions and must adjust their strategies based on limited information.

The definitions of related parameters are shown in Table 1:

Table 1: Coefficient Definitions

Coefficient	Definition	Coefficient	Definition
α	Environmental benefit coefficient	β	Tax contribution coefficient
γ	Subsidy cost coefficient	r	Battery recycling rate
x	Regulatory intensity	T	Tax revenue
δ	Regulatory cost coefficient	C_m	Regulatory cost
S	Subsidy expenditure	r_r	Deposit return coefficient
D	Deposit amount	C_d	Deposit management cost
P_s	Sales profit	η	Credit value coefficient
y	Manufacturer's deposit model weight	k	Additional management cost coefficient
CPI	Total issued credits	L	Loss from abnormal credit transactions
C_r	Recycling cost	C_C	Credit management cost
C_i	Violation risk cost	z	Formal recycling rate
R_i	Grey income		

3.2. Strategy Space and Payoff Functions

1.Government Strategy

As the policymaker and regulator, the government plays a guiding and supporting role in the game. Its strategy choices directly influence the decision-making of manufacturers and consumers.

The government's payoff function is as follows:

$$U_G = \alpha \cdot r \cdot z + \beta \cdot T - \gamma \cdot S - \delta \cdot C_m(x)$$

Where $C_m(x) = C_{base} + k_m x^2$ implies that regulatory costs increase nonlinearly with the intensity of regulation, reflecting the growing administrative burden and enforcement challenges as regulatory intensity rises.

2. Manufacturer Strategy

As producers and promoters of new energy vehicles, manufacturers seek to enhance technological innovation, reduce costs, and increase market share. Their strategic choices are influenced by government policies and consumer demand.

The manufacturer’s payoff function consists of two components: the deposit model and the credit model:

$$U_{E1} = D(1 - r_r) + P_s - C_d$$
$$U_{E2} = P_s - C_C - \eta \cdot CPI$$

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According to the "Action Plan for Improving the Power Battery Recycling System for New Energy Vehicles" approved by the State Council in February 2025, manufacturers are expected to adopt a dual-mode parallel strategy combining deposits and credits. Thus, the manufacturer's integrated payoff function becomes:

$$U_E = yU_{E1} + (1-y)U_{E2} - ky(1-y)$$

3. Consumer Strategy

As the final users of new energy vehicles, consumers' strategy choices are influenced by personal preferences, purchasing power, and environmental awareness. Their decisions also generate feedback that affects the strategies of the government and manufacturers.

The consumer's payoff function is as follows:

$$U_C = z[yDr_r + (1-y)\eta CPI - C_r] + (1-z)(R_i - C_i)$$

3.3. Dynamic Evolution Equations

In the dynamic evolution equations, let x,y,zx, y, zx,y,z represent the strategic choice variables of the government, manufacturers, and consumers, respectively. The specific definitions and constraints are shown in Table 2:

Table 2: Definitions of Related Variables

Variable	Agent	Meaning	Value Range
x	Government	Proportion of adopting the "strict regulation" strategy	0≤x≤1
y	Manufacturer	Proportion of adopting the "deposit model" strategy	0≤y≤1
z	Consumer	Proportion of adopting "legal recycling" behavior	0≤z≤1

Based on the defined strategy space and payoff functions, this study constructs a three-party dynamic evolutionary model involving the government, automobile manufacturers, and consumers. The government's evolutionary model reveals the dynamic mechanism by which the government adjusts between "strict regulation" and "relaxed regulation." This adjustment is influenced by the government's expected payoffs under different strategies and the proportion of strategy adoption. The manufacturer's evolutionary model demonstrates the dynamic switching process between the "deposit model" and the "credit model." This process is also driven by the manufacturer's expected payoffs and the proportion of strategy adoption. The consumer's evolutionary model describes the dynamic shift between "legal recycling" and "illegal disposal." This shift is influenced by the consumer's expected net benefits and the proportion of legal recycling behavior.

Thus, the dynamic evolutionary equations for the three-party game can be derived as:

$$\mathrm{F(x)} = \frac{dx}{dt} = x(1-x)(\alpha r \frac{\partial z}{\partial x} - \delta \cdot 2k_m x)$$

$$\mathrm{F(y)} = \frac{dy}{dt} = y(1-y)[|U_{E2} - U_{E1}| - k(1-2y)]$$

$$\mathrm{F(z)} = \frac{dz}{dt} = z(1-z)[yDr_r + (1-y)\eta CPI - C_r - (R_i - C_i)]$$

3.4. Equilibrium Point Solution

The Jacobian matrix of the three-party evolutionary game system is given by:

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$$J = \begin{vmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{vmatrix} = \begin{vmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{vmatrix}$$

In the evolutionary game process, each participant continually optimizes and adjusts their strategies based on their vested interests until a dynamic equilibrium state (i.e., Evolutionarily Stable Strategy, ESS) is reached. When x, y, and z take the values of 0 or 1, by applying the Jacobian matrix eigenvalue analysis method and setting F(x)=0, F(y)=0, and F(z)=0, eight pure strategy equilibrium points are identified within the context of the evolutionary game system, specifically: E1(0,0,0),E2(0,1,0),E3(0,0,1),E4(0,1,1),E5(1,0,0),E6(1,1,0),E7(1,0,1),E8(1,1,1). Finally, based on Lyapunov's first method (indirect method), ESS is determined. After calculation, it is concluded that E4 is a saddle point, while the others are unstable points.

In the three-party game scenario corresponding to the saddle point E4(0,1,1), the government chooses weak regulation, the manufacturers rely entirely on the deposit model, and consumers engage in all legal recycling. This state is essentially a short-term pseudo-equilibrium, whose instability arises from the dynamic conflict of strategies among the three parties.

Government's Regulatory Deficiency Conflict: Although weak regulation can temporarily reduce administrative costs, it leads to a gradual decline in environmental benefits due to lack of supervision. When environmental degradation triggers public pressure or policy assessments, the government is forced to shift to strong regulation, forming a positive feedback loop that escapes the saddle point.

Manufacturers' Deposit Model Vulnerability:
Although the deposit model profits in the short term through unreturned deposits, long-term reliance on deposit income will lead to consumer resistance (e.g., demands for higher return rates). Additionally, under weak regulation, the black market will proliferate, eroding the residual value of manufacturers' earnings, pushing them to introduce a credit point system.

Consumers' Behavior Reversal Risk:
Consumers choose legal recycling when the deposit refund benefits are significantly higher than the net benefits of illegal disposal. However, under weak regulation, the probability of enforcement is close to zero, leading to an increase in actual gains from illegal channels. As a result, consumers collectively shift towards illegal disposal, completely dismantling the equilibrium.

Thus, the stability of the saddle point E4(0,1,1) relies on unrealistic static assumptions. Any minor adjustment in the strategy of one party will trigger a chain reaction through the game network, ultimately leading to a more sustainable interior equilibrium.

The interior equilibrium E(x∗,y∗,z∗) reflects the balance in the multi-party dynamic game. This conclusion is consistent with the real-world phenomena of gradual policy adjustments, flexible responses by enterprises, and gradual changes in consumer behavior. The existence condition for the interior equilibrium is:

$$\begin{cases} |U_{E2} - U_{E1}| < k, \text{Moderate Coordination Cost for Manufacturers} \\ R_i - C_i \approx C_r, \text{Balanced Consumer Benefits} \\ \alpha r \frac{\partial z}{\partial x} - \delta \cdot 2k_m x, \text{Government Cost} - \text{Benefit Alignment} \end{cases}$$

4. Simulation Analysis

In this section, the paper describes how the simulation is conducted to illustrate the evolution of strategy choices by the three parties under different parameter conditions. Using Python software,

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parameters that influence the decision-making of the government, manufacturers, and consumers are simulated to analyze the dynamics of their choices in different scenarios. The data for these simulations are sourced from various reports and guidelines such as the "Annual Report on the Development of China's New Energy Vehicle Industry," "Points Trading Management Measures," "Environmental Benefits Assessment of New Energy Vehicles," "2023 White Paper on Power Battery Recycling," and "Interim Measures for the Management of Power Battery Recycling Deposits." Here are the parameter settings for the different scenarios mentioned in the paper:

Table 3: Parameters for All Three Scenarios

Variable	Value	Variable	Value
T	100	L	5
P_S	80	C_C	15
CPI	200	C_i	2
C_{base}	10	β	0.4
k_m	0.5	γ	0.3
C_d	8	η	0.5
k	0.1		

Table 4: Parameters for Scenario 1

Variable	Value	Variable	Value
α	0.6	r	0.5
δ	0.2	R_i	15
x	0.2	r_r	0.7
D	50	C_r	12
R_i	25	S	30
C_C	15	L	5

Table 5: Parameters for Scenario 2

Variable	Value	Variable	Value
x	0.8	r	0.7
δ	0.4	R_i	15
S	40		

Table 6: Parameters for Scenario 3

Variable	Value	Variable	Value
α	0.8	C_r	10
r_r	0.9	R_i	10
D	70	S	50

In Scenario 1, the existing policy framework exhibits moderate regulatory intensity, lower recycling efficiency, and a moderate deposit refund coefficient. Given that the net gain from illegal recycling is significantly higher than from legitimate recycling, consumers show a strong inclination towards illegal disposal. From the perspective of the evolution of strategies between the three parties, under weak regulatory conditions, the government's environmental benefits are limited by low recycling efficiency, but regulatory costs are relatively low. The government may gradually

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strengthen regulation to improve environmental outcomes. For car manufacturers, the deposit system provides significantly higher profits compared to the points system, which leads them to lean towards the deposit system. Consumers, with only a small difference between the net gains of illegal disposal and legitimate recycling, show fluctuating behavior, with their participation in legitimate recycling hovering around 0.5. System stability analysis shows that although the saddle point (0,1,1) may temporarily exist as a pseudo-equilibrium, the motivation for consumers to engage in illegal disposal continues (as indicated by a decreasing z value), which ultimately leads the system to degrade to a state with low recycling efficiency. This scenario reveals the structural imbalance facing the legitimate recycling system under the current policy framework, providing an important benchmark for the optimization of future policies. The evolution path is shown in Figure 1.

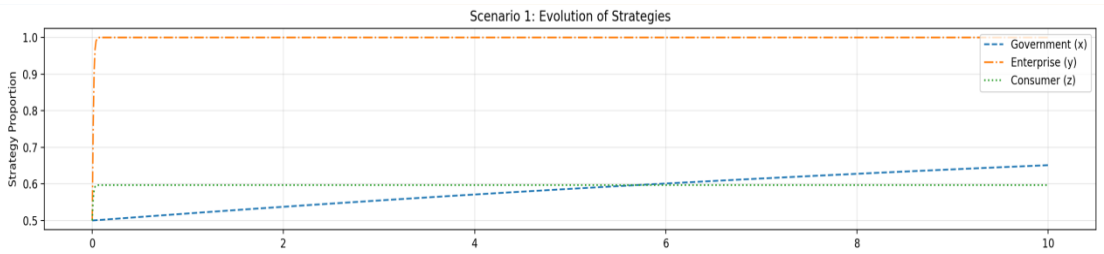

Figure 1: Evolution Path for Scenario 1

In Scenario 2, the government adopts a strict regulatory strategy. By increasing regulatory intensity and optimizing the recycling system's parameters, this significantly changes the dynamic evolution path of the battery recycling system. In this scenario, the regulatory cost increases significantly, leading to a trade-off between environmental benefits and regulatory costs for the government. If environmental benefits do not cover regulatory costs, the government may lean toward reducing regulatory intensity. On the car manufacturing side, despite the points system, the deposit system still provides significant profit advantages. However, high regulatory intensity forces manufacturers to increase compliance investments (such as expanding recycling channels), which may lead to a shift toward the points system in the long term (resulting in a decrease in y). Consumer behavior shows high stability: the net benefit from illegal disposal is significantly lower than from legitimate recycling, pushing the z value to approach 1. The system evolution shows a bidirectional feedback mechanism: the consumer’s legitimate recycling ratio ($z \approx 1$) and the car manufacturer’s deposit system ($y \approx 1$) form a positive reinforcement cycle. However, the high regulatory cost pressure faced by the government may trigger policy adjustments, ultimately leading the system toward an interior equilibrium (x*, y*, z*), reflecting the dynamic balance between policy intensity and market behavior. The evolution path is shown in Figure 2.

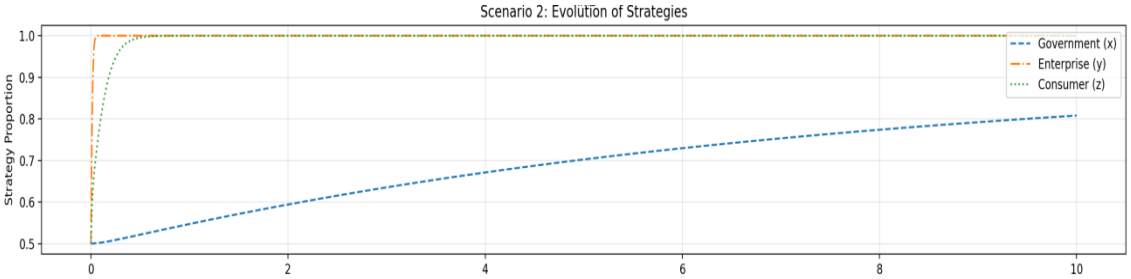

Figure 2: Evolution Path for Scenario 2

In Scenario 3, the policy boosts the deposit refund coefficient, increases the deposit amount, and reduces the legitimate recycling cost, alongside measures to suppress grey income and enhance

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environmental benefits, reconstructing the evolution path of the battery recycling system. At the government level, the balance between environmental benefits and subsidy costs demonstrates strong sustainability, supported by tax revenue. Car manufacturers maintain their profit advantages from the deposit system, but high deposit amounts may trigger consumer resistance, forcing them to balance market acceptance with compliance costs (resulting in a slight decline in y). Consumer behavior quickly trends toward complete compliance ($z \approx 1$) due to the significant difference between the net benefit of legitimate recycling and illegal disposal. The system evolution presents a stability characteristic dominated by consumer behavior: the high compliance rate ($z \approx 1$) and the car manufacturer's deposit system ($y \approx 1$) create a virtuous interaction. Combined with the dynamic matching of government environmental benefits and costs, the system ultimately moves toward a sustainable interior equilibrium ($x^*, y^*, z^* \approx 1$), reflecting the effectiveness of incentive policies in guiding market behavior and improving system stability. The evolution path is shown in Figure 3.

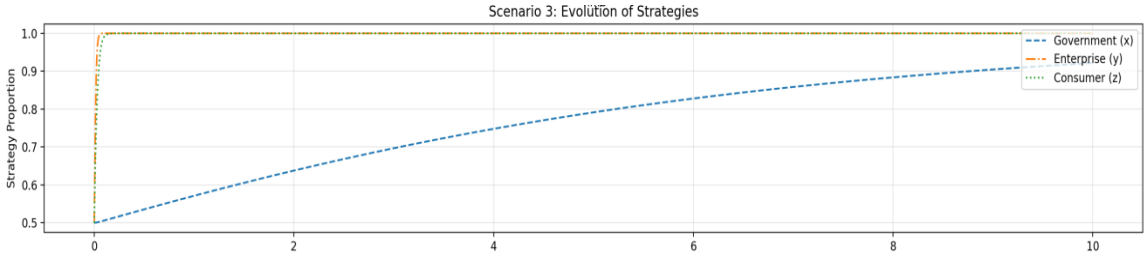

Figure 3: Evolution Path for Scenario 3

A comprehensive comparison is shown in Table 7:

Table 7: Comprehensive Comparison of Scenarios

Scenario	Advantages	Disadvantages	Applicable Stage
Scenario 1	Low regulatory costs, high short-term profits for car manufacturers	Low environmental benefits, high illegal disposal by consumers	Early stage of policy exploration
Scenario 2	Significant improvement in environmental benefits	Excessive regulatory costs, unsustainable policies	Environmental crisis or pressure from public opinion
Scenario 3	High consumer compliance, stable system	Car manufacturer's deposit system may face market resistance	Mature policy phase or long-term objectives

5. Conclusion and Recommendations

5.1. Conclusion

This study constructs an incentive mechanism decision model based on evolutionary game theory and thoroughly analyzes the dynamic strategic interactions among the government, automobile manufacturers, and consumers in the new energy vehicle battery recycling system. The research findings are as follows:

(1) Dynamic Balance between Policy Strength and Market Behavior

There is a complex dynamic feedback mechanism between government regulatory intensity, automobile manufacturers' recycling model choices, and consumers' recycling behaviors. Under different policy scenarios, the strategies of the three parties exhibit significant differences. When government regulation is weak, the system is prone to fall into a low-recycling efficiency pseudo-

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equilibrium state (e.g., Scenario 1), while overly stringent regulation may lead to policy unsustainability (e.g., Scenario 2). Only in scenarios with high recycling incentives and moderate regulation (Scenario 3) can the system approach a stable and sustainable equilibrium point, achieving a balance between environmental benefits and economic costs.

(2) Complementarity of Deposit and Points Systems

In the process of choosing between the deposit model and the points model, the automobile manufacturers' decisions are influenced by various factors, including regulatory intensity, deposit refund coefficients, and recycling costs. The study points out that the deposit model shows higher revenue advantages in the short term; however, in the absence of regulation, this model may trigger consumer resistance and lead to market failure. In contrast, the points model focuses more on long-term compliance and market stability but requires government policy support and regulatory assurance. Therefore, these two models are not mutually exclusive but can complement each other under specific conditions, jointly promoting the sustainable development of the battery recycling system.

(3) Key Role of Consumer Behavior

Consumers' choice behavior has a significant impact on the stability of the battery recycling system. When the profit from illegal disposal exceeds that from legal recycling, consumers are more likely to opt for illegal disposal, severely undermining the sustainability of the recycling system. Only when the net benefits from legal recycling are significantly higher than those from illegal disposal will consumers actively participate in formal recycling. Thus, improving consumer acceptance and participation in formal recycling is key to the healthy development of the battery recycling system.

(4) Effectiveness of Incentive Policies

Incentive mechanisms such as increasing the deposit refund coefficient, raising the deposit amount, reducing recycling costs, and strengthening the environmental benefit coefficient can effectively guide the behavior of consumers and automobile manufacturers, promoting the stable operation of the battery recycling system. However, the implementation of these incentive policies must be carried out within a government regulatory framework to ensure their sustainability and market acceptance.

5.2. Recommendations

Based on the above conclusions, the following policy recommendations are proposed:

(1) Dynamic Optimization of the Regulatory Mechanism

Establish a "flexible regulation" framework to dynamically adjust regulatory intensity based on real-time data on environmental benefits and regulatory costs (e.g., dynamically setting the value of x), to avoid the cost waste or regulatory failure that could result from a one-size-fits-all policy.

Introduce digital regulatory tools (e.g., blockchain traceability systems) to reduce regulatory costs (e.g., decreasing C_m), improve the efficiency of identifying violations, and reduce gray area profits (e.g., lowering R_i).

(2) Improvement of the Dual System for Deposit and Points

Deposit System: Enhance consumer motivation to return deposits by increasing the deposit refund coefficient (r_r) and the deposit amount (D); at the same time, require automobile manufacturers to disclose how the deposits are used to alleviate market trust issues.

Points System: Optimize the points value coefficient (η) and total issuance (CPI), allowing points to be traded between different companies or redeemed for diversified benefits (e.g., charging discounts), thus increasing the participation enthusiasm of both automobile manufacturers and consumers.

(3) Strengthening Consumer Incentives and Constraints

Implement a stacking reward mechanism to promote compliant recycling behaviors, such as tax reductions or insurance discounts, to increase the net benefits of formal recycling (e.g., z items);

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simultaneously, impose strict penalties on illegal disposal behaviors to raise the risk cost of violations (C_i).

Enhance environmental awareness through public education campaigns to reduce consumer resistance to the deposit model, thus forming a positive feedback loop of "high compliance rates—high environmental benefits."

(4) Promoting Collaborative Governance of the Industry Chain

Establish a data-sharing platform for the government, automobile manufacturers, and recycling enterprises to reduce information asymmetry (alleviating the assumption of incomplete information), thus optimizing battery residual value assessment and recycling channel layout.

Encourage automobile manufacturers and battery producers to cooperate in the research and development of low-cost recycling technologies (e.g., reducing C_r), leveraging economies of scale to share compliance costs, and improving the long-term sustainability of the deposit model.

(5) Stage-by-Stage Policy Adaptation

Policy Initial Stage (Scenario 1): In the process of exploring market responses, regulatory costs should be kept low while simultaneously establishing the infrastructure for both the deposit and points systems to avoid path dependency.

Environmental Crisis Period (Scenario 2): In the short term, strengthen environmental regulation to curb the trend of environmental deterioration, while also introducing corresponding fiscal subsidy policies (e.g., increasing T or α) to alleviate government cost pressures in environmental governance.

Mature Stage (Scenario 3): In the phase dominated by incentive policies, promote system stability toward an interior equilibrium state through a combination of high deposit refunds, low recycling costs, and other measures.

6. Conclusion

In the process of achieving the "dual carbon" goals, the recycling of new energy vehicle power batteries plays a crucial role. The construction of its incentive mechanism must comprehensively consider the dynamic game processes of all stakeholders. This study uses an evolutionary game model and scenario simulation methods to reveal the complex interactions between policy parameters and stakeholder behaviors, providing a theoretical foundation and practical guidance for constructing a sustainable power battery recycling system. Looking ahead, future research could further incorporate variables such as heterogeneous agents and regional differences to enhance the model's ability to describe the complexities of the real world.

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