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Governance strategies for end-of-life electric vehicle battery recycling in China: A tripartite evolutionary game analysis

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End-of-life (EOL) electric vehicle (EV) batteries have both economic and environmental benefits if recycled in an environmentally friendly manner while they may cause environmental pollution if treated improperly. China is currently working hard to promote the development of a circular economy by EOL EV battery recycling. However, conflicts of interest among electric vehicle manufacturers (EVMs), consumers, and the government often hinder efficient recycling. This study constructs a tripartite evolutionary game model under the condition of bounded rationality, analyzes the evolutionary stability strategy of three participants, and combines with numerical simulation to explore the feasible governance strategies of EOL EV battery recycling. The results show that four evolutionary stable strategies (ESSs) correspond to the three stages of the EOL EV battery recycling industry: early stage, development stage, and maturity stage. In the early stage, the punishment strategy is more critical to motivate EVMs and consumers to actively participate in battery recycling. The subsidy mechanisms can influence the strategic choices of the three participants, but the excessive subsidy is not conducive to the sustainable development of the EOL EV battery industry. In addition, when the industry matures, the government will gradually decrease intervention, thereby realizing the development path of EOL EV battery recycling from exogenous government supervision to endogenous profit drive.

KEYWORDS

governance strategies, evolutionary game, electric vehicle (EV), battery recycling, EOL EV batteries

1 Introduction

In recent years, in order to curb global warming, countries around the world have worked together to achieve the goals of carbon neutralization and carbon peak. Electric vehicles (EVs), which are powered by batteries, can reduce carbon emissions and are spreading rapidly around the world (Tang et al., 2013; Zhu et al., 2019). According to Canalys, the global cumulative sales volume of EVs in 2021 is nearly 6.5 million, an increase of 109% over 2020. Driven by policies and capital, China's EVs have developed rapidly in recent years (He et al., 2019). The data show that by the end of 2020, the number of EVs reached 4.92 million, and the sales volume of EVs reached 3.5 million in 2021. With the development of the EV industry, the peak period of EV battery retirement is coming. It is expected that the cumulative number of EOL EV batteries in China will be close to 800,000 tons by 2025 Yao, 2021. EOL EV battery recycling has attracted wide attention from society due to its potential environmental pollution and economic benefit (Du et al., 2018; Albertsen et al., 2021). Precious metals such as lithium, nickel, cobalt, and manganese contained in EOL EV batteries can be reused through environment-friendly recycling, which can alleviate resource consumption (Gu et al., 2018; Yang et al., 2020). However, since batteries contain toxic liquids and heavy metals, discarding or non-compliant disposal will cause environmental pollution and resource wastage (Qiao et al., 2020). Therefore, it is urgent and necessary to collect and recycle EOL EV batteries.

China, the country with the largest production and ownership of EVs, faces the pressure of potential environmental pollution and resource waste from EOL EV batteries. Therefore, China vigorously develops circular economy and includes the recycling of EOL EV batteries as a key project. The Ministry of Industry and Information Technology (MIIT) pointed out that electric vehicle manufacturers (EVMs) should assume the main responsibility for EOL EV batteries and cooperate with upstream and downstream enterprises to establish a recycling system. At the same time, relevant financial and fiscal policies have been issued to support the development of the EOL EV battery recycling industry. In 2018, the MIIT identified the first batch of formal recycling enterprises including GEM, BRUNP, and GHTECH; by 2021, the number of formal recycling enterprises reached 47. In addition, these EVMs and formal recycling enterprises have set up nearly 10,000 collection service outlets. However, only 30% of EOL EV batteries in China are recycled through formal channels in 2021. The main reason for the low recycling rate is the existence of a large number of informal recycling organizations. Furthermore, these informal enterprises have little investment in environmental protection when dismantling and disposing EOL EV batteries and are often willing to pay higher purchase prices (Kang et al., 2013). In contrast, due to the negative externality of EOL EV battery recycling, formal recyclers have to spend higher environmental disposal costs, putting them at a competitive disadvantage in the market with informal recyclers. As a result, consumers with weak environmental awareness will sell retired batteries to informal recyclers to obtain higher returns and further form a recycling market of "bad money drives out good money."

To effectively address the aforementioned challenges, the Chinese government has introduced relevant administrative measures to encourage and regulate the recycling of EOL EV batteries, for instance, Administrative Measures for Echelon Utilization of Power Batteries of New Energy Vehicles (2021) and Interim Measures for the Administration of Recycling and Utilization of Power Batteries for New Energy Vehicles (2018). Specifically, the government calls for the implementation of an extended producer responsibility system. A comprehensive utilization enterprise access certification system should be set up. Meanwhile, in order to encourage enterprises to actively recycle EOL EV batteries, some local governments have introduced subsidy policies. However, due to the imperfect regulation system, these norms and incentive policies are difficult to implement effectively. Therefore, facing the increasingly severe challenge of EOL EV battery recycling, what kind of governance strategies should the government make? That is, how should the government's reward and punishment measures be implemented to effectively promote the green and sustainable development of the EOL EV battery recycling industry? This is the common concern of the government and scholars.

The effective governance strategies can be regarded as the long-term game result between the government's regulatory decision and whether EVMs fulfill the recovery responsibility. In addition, the decision of whether consumers can provide their retired batteries to formal recycling channels will also affect the outcome of the game. EVMs, consumers, and the government, as the main stakeholders in the EOL EV battery recycling industry, will play games and make different decisions according to their own interests. For the study on the governance strategy of recycling recyclable waste products, scholars often use the game theory (Chen et al., 2021; Liu et al., 2022). However, the traditional game theory regards the participants as the economic man with complete rationality and focuses on the result of game equilibrium. In fact, affected by information asymmetry and complex relationships, EVMs, consumers, and the government all have the characteristics of bounded rationality, so they will constantly adjust and improve their behavior strategies in the game process. The evolutionary game theory (EGT) only requires players to be bounded rationally and emphasizes the dynamic process of strategy choice behavior instead of static equilibrium (Newton, 2018). Therefore, compared with other methods, the EGT is more appropriate to solve the governance strategy problem of EOL EV battery recycling.

Hence, the primary goal of this study is to develop a detailed analysis of the governance strategies in the Chinese EOL EV battery recycling industry by constructing a tripartite evolutionary game model consisting of EVMs, consumers, and the government, thereby providing guidance and suggestions for improving EOL EV battery recycling. The contributions of this paper are as follows: 1) Compared with the existing literature which focuses on the discussion of the recycling regulatory game between the government and EVMs, we incorporate consumers into the evolutionary game model and analyze the interaction between the three stakeholders to better understand the governance strategies. 2) Different from the existing literature which mainly uses the classical game theory to study governance strategy issues, we lie in the utilization of the EGT to systematically analyze the interaction and evolution pattern of the three stakeholders on the EOL EV battery recycling problem. 3) We analyze the tripartite evolutionary stability strategy in different stages of the EOL EV battery recycling industry and explore the governance strategies to achieve the ideal stable equilibrium state through numerical simulation.

2 Literature review

Our research is closely related to the literature on EOL EV battery recycling, the government's governance in the EOL EV battery recycling industry, and the application of the EGT.

The academic research about EOL EV battery recycling mainly focuses on the recycling status, recycling economic benefits, and environmental impacts. At present, China faces the reality of the low recovery rate of EOL EV batteries. Hu and Wen (2015) and Gu et al. (2017) found that a large number of consumers sell batteries to informal recycling channels such as small workshops, which brings potential environmental pollution. Zeng et al. (2015) argued that improving the EOL EV battery recycling network system and the recycling technology level is the key to solve the low enthusiasm of vehicle enterprises to participate in recycling. He and Sun (2022) found that raising the battery buyback price by small workshops is one of the main factors that interferes with consumer participation in formal recycling. Dong and Ge (2022) found that consumers have negative views on EOL EV battery recycling due to the impact of the chaotic recycling market, low recycling compensation, and poor recycling channels. EOL EV batteries can obtain economic benefits through two recycling modes: recovery utilization and cascade utilization. EV batteries contain lithium, nickel, manganese, cobalt, and other valuable metal materials, and the recovery of these materials has great potential in gaining economic benefits (Babbitt et al., 2014; Kamath et al., 2020). Cascade utilization is an important way to increase the economic efficiency before material recovery (Omrani and Jannesari, 2019). Specifically, Jiang et al. (2021) evaluated the cost-benefit of EOL EV battery recycling in China and concluded that cascade utilization for energy storage will create more economic benefits than that for material recovery solely.

Since the governance system is inadequate, the decision behaviors of the government play a key role in guiding the development of the EOL EV battery industry. Although the government in many countries regards the promotion of EVs as a policy direction to get rid of fossil energy, EVs are not a panacea without side effects. EOL EV battery recycling is crucial to protecting the environment and alleviating resource pressure. In fact, many countries have introduced relevant governance policies to promote the recycling of EOL EV batteries. For example, Japan has formulated a series of relevant laws and subsidized battery manufacturers to regulate the recycling of batteries. In the United States, government regulation and deposit systems are used to motivate consumers to return batteries to recycling companies. Germany mainly implemented the recycling fund policy to promote battery manufacturers to share the recycling network and promote efficient recycling of batteries. In terms of governance strategies regarding EOL EV batteries, scholars mostly use the game theory method. Li and Mu (2018) analyzed the joint recycling decision and coordination of a three-echelon battery closed-loop supply chain, and found that the recycling alliance can stimulate consumers' willingness to participate in formal recycling by reducing recycling costs and increasing recycling prices. Tang et al. (2018) built a game model analysis that setting a reasonable minimum collection rate as a reward and punishment standard can effectively motivate EVMs to implement recycling. Yang et al. (2021) built a game model of EOL EV battery recycling and found that the government regulation mechanism can better promote EVMs to actively fulfill the responsibility of recycling than the subsidy mechanism.

The idea of the EGT originated from biology, which examines the evolutionary trend of group behavior based on the assumption of bounded rationality (Friedman, 1991). In the 1960s, ecologists began to use the ideas of the evolutionary game theory to study ecological problems. In recent years, the EGT has been applied to various strategy problems of economics (Debnath et al., 2018; Zhao et al., 2019; Wang et al., 2019) and management (Sun et al., 2021; Wang et al., 2021; Wang and Wang, 2021). The field of recycling involves multi-agent participation, and the strategy choice of agents changes with the external environment of the game. The evolutionary game method has been applied to study the participation strategy selection of stakeholders in waste electrical and electronic equipment recycling (Wang et al., 2019; Wang et al., 2021), cooperative mechanism of construction waste disposal (Du et al., 2020; Shao et al., 2022), incentive and supervision mechanism of recycling (Long et al., 2019; Ma and Zhang, 2020), *etc.*

Inspired by previous works, this study seeks to investigate the behavioral strategies of three participants, namely, EVMs, consumers, and the government, in the process of EOL EV battery recycling through the evolutionary game method, and combines numerical simulation to analyze the influence of key factors on the evolution path and results, thereby providing guidance and suggestions for improving EOL EV battery recycling.

3 Construction of the evolutionary game model

3.1 Problem description

According to the practice situation in China, the EOL EV battery recycling industry chain includes EVMs, battery

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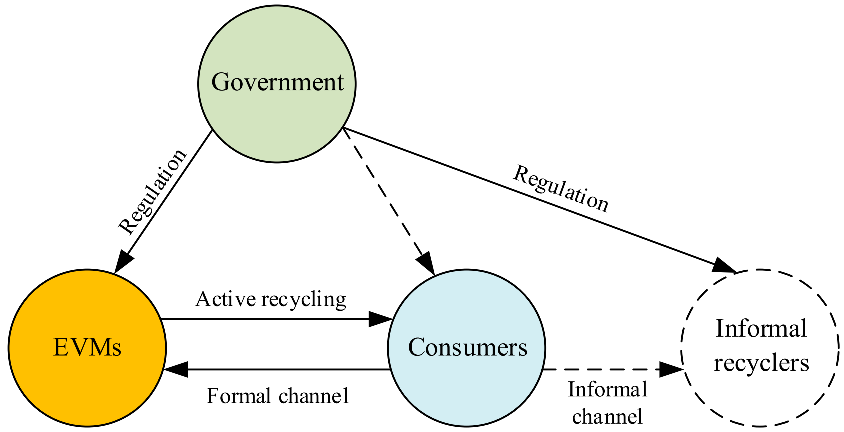

FIGURE 1
Relationship among the participants in EOL EV battery recycling.

manufacturers, and third-party recycling enterprises. However, the Chinese government requires that EVMs should bear the main responsibility of recycling, the collection of EOL EV batteries, and hand over the batteries to downstream recycling enterprises for disposal. For example, BYD, an electric vehicle manufacturer, cooperates with third-party recycling enterprise GEM to carry out EOL EV battery recycling. Therefore, this study takes EVMs as the main body of the EOL EV battery recycling industry chain to build the game model.

EVMs, consumers, and the government play an important role in recycling, supply, and regulation, respectively, in the process of battery recycling. In the evolutionary game model, the relationship between EVMs, consumers, and the government is shown in Figure 1. The government provides subsidies or penalties to EVMs according to whether they fulfill the recycling responsibility. Meanwhile, the government will also strictly supervise informal recycling enterprises and regulate the EOL EV battery recycling market. As the core enterprise in the battery recycling chain, EVMs not only reflect the produce and production of EVs but also extend to collect batteries from consumers. At the same time, consumers choose whether to sell batteries to EVMs or informal recyclers based on maximizing the revenue. The coordination of the three participations is the key to promoting the effective recycling of EOL EV batteries.

3.2 Assumptions of the game

Considering the practice of current EOL EV battery recycling in China, this paper makes the following assumptions.

3.2.1 Game subject

The participants of the game are composed of three decision-making subjects: EVMs, consumers, and the government. The three participants are all bounded rational in the game. EVMs make recycling decisions with the goal of maximizing profits, which is the demand side of EOL EV batteries. Consumers make decisions with the goal of utility maximization and are the suppliers of EOL EV batteries. The government advocates the recycling of EOL EV batteries with the goal of environmental protection and carbon emission reduction and is the maker of regulatory policies. Due to the information asymmetry and the complexity of the environment, none of the three participants in the game can obtain the optimal strategy through a single game. Instead, they need to continuously learn and improve their past strategy through multiple rounds of the game, so as to formulate the behavioral decision that best matches their current situation.

3.2.2 Strategy set of the game subject

3.2.2.1 Electric vehicle manufacturers

Following the principle of extended producer responsibility (EPR), EVMs need to fulfill the main responsibility for the collection and recycling of batteries. At the same time, in order to maintain the brand image, some EVMs choose to actively carry out EOL EV battery recycling. For example, BYD has actively carried out centralized recycling of batteries by establishing recycling service outlets. However, due to the high investment cost of recycling service outlet construction, low level of recycling technology, and profit difficulties, some EVMs will choose to respond negatively. The strategy set of EVMs is [active recycling (AR), negative recycling (NR)], assuming that the probability of choosing the AR strategy is x, and the probability of choosing the NR strategy is $1 - x$.

3.2.2.2 Consumers

Informal recycling enterprises have almost no investment in environmental protection and safe treatment during EOL EV battery recycling, so they can purchase batteries from consumers at a higher price. Consumers with a strong awareness of environmental protection will choose to sell retired batteries to EVMs, while those with poor awareness of environmental protection will choose to sell retired batteries to informal recycling enterprises to obtain higher benefits. The strategy set of the consumers is {formal channel (FC), informal channel (IC)}, assuming that the probability of choosing the FC strategy is y, and the probability of choosing the IC strategy is $1 - y$.

3.2.2.3 Government

Facing the possible negative externalities caused by EOL EV batteries, the government comprehensively considers the social and environmental benefits and regulatory costs and decides whether to implement the recycling regulation. The strategy set of the government is {strict regulation (SR), loose regulation (LR)}, assuming that the probability of adopting the SR strategy is z, and the probability of adopting the LR strategy is $1 - z$.

3.2.3 Parameters and descriptions

Assume that the cost of EV active recycling is C_m, including recycling service outlet construction investment, environmental protection treatment cost, and transportation cost. If consumers choose the FC strategy, the revenue of echelon utilization and recycling for EVMs is βR_{mr}, where β indicates the recycling technology level.

Assume that the revenue of consumers choosing the FC strategy is R_c. If EVMs actively recycle, it can ensure the formal treatment of EOL EV batteries and reduce the damage to the environment caused by harmful substances such as heavy metals. Therefore, consumers can obtain environmental benefits. αH, α indicate consumers' environmental awareness. If consumers choose the IC strategy, they will sell batteries to informal recycling enterprises and obtain revenue R_{cn}. Since informal recyclers do not carry out environmental treatment of waste materials, they can buy back EOL EV batteries from consumers at a higher price; therefore, assume $R_{cn} > R_c$. When EVMs choose the AR strategy, due to the positive externalities of formal recycling, the benefits of consumers choosing the FC strategy are higher than those of choosing the IC strategy; therefore, assume $R_c + \alpha H > R_{cn}$.

When adopting the SR strategy, on one hand, the government punishes the EVMs with negative recycling, and the penalty is F; on the other hand, the government severely supervises the behavior of informal recycling enterprises and increases its recovery cost, which results in the benefits of consumers choosing the IC strategy, which is $(1 - \lambda)R_{cn}$, where λ indicates the government's supervision of informal channels. Assume that the subsidy cost that the government pays to support the EVMs to actively recycle is S. The cost of strict regulation for the government is C_g,; meanwhile, it can obtain revenue R_g, such as the improvement of government credibility. If EVMs choose the AR strategy, the government will obtain environmental benefits R_e. If EVMs choose the NR strategy and consumers choose the IC strategy, EOL EV batteries flow into informal recycling channels which results in environmental pollution and waste of resources. The government's environmental governance cost is C_i. The relevant parameters and description are given in Table 1.

3.3 Payment matrix

According to the aforementioned basic assumptions and descriptions, the expected payoffs of the three participants in EOL EV battery recycling are calculated in the game tree as shown in Figure 2.

4 Analysis of the evolutionary game model

4.1 Strategy stability and evolution path analysis of EVMs

Based on the payment matrix, we calculate the replicator dynamic equation of each stakeholder. Let U_{m1} and U_{m2} denote the expected revenues of the EVMs who choose the AR strategy and NR strategy, respectively, and let $\bar{U}_m$ denote the average expected revenues of the EVMs. Then, the expected revenues and average expected revenues of the EVMs ' recovery efforts are as follows:

$$U_{m1} = zy(\beta R_{mr} - C_m + S) + z(1 - y)(-C_m) + (1 - z)y(\beta R_{mr} - C_m) - (1 - z)(1 - y)C_m, \quad (1)$$

$$U_{m2} = zy(-F) + z(1 - y)(-F), \quad (2)$$

$$\bar{U}_m = xU_{m1} + (1 - x)U_{m2} = Sxyz + \beta R_{mr}xy + Fxz - C_m x - Fz. \quad (3)$$

The replicator dynamic equation of the EVMs to choose active recycling is as follows:

$$F_m(x) = \frac{dx}{dt} = x(U_{m1} - \bar{U}_m) = x(x - 1)(C_m - \beta R_{mr}y - Syz - Fz). \quad (4)$$

According to the stability theorem of differential equations, the stable point of the replicator dynamic equation should satisfy two conditions: $F(x) = 0$, and $dF(x)/dx < 0$.

Taking the derivative of $F_m(x)$, we can obtain the following equation from Eq. 4:

$$\frac{dF_m(x)}{dx} = (2x - 1)(C_m - \beta R_{mr}y - Syz - Fz). \quad (5)$$

Set $z_0 = \frac{C_m - \beta R_{mr}y}{Sy+F}$, while $z = z_0$, and$F_m(x) \equiv 0$. It means that it is in a stable state no matter what value x takes; thus, any probability of EVMs who choose active recycling is the evolutionarily stable strategy (ESS).

While $z > z_0$, $\frac{dF_m(x)}{dx}|_{x=0} > 0$ and $\frac{dF_m(x)}{dx}|_{x=1} < 0$,; thus, it can be deduced that $x = 1$ is the ESS.

TABLE 1 Parameters and description.

Parameters	Description
Electric vehicle manufacturers	
C_m	Cost under the AR strategy
R_{mr}	Recycling revenue when consumers choose the FC strategy
β	Recycling technology level
Consumers	
R_c	Revenue when consumers choose the FC strategy
R_{cn}	Revenue when consumers choose the IC strategy
H	Environmental benefits when EVMs choose the AR strategy
α	Consumers' environmental awareness
Government	
C_g	Cost under the SR strategy
R_g	Revenue under the SR strategy
F	Penalty to EVMs who choose the NR strategy
S	Subsidy to EVMs who choose the AR strategy
R_e	Environmental benefits when EVMs choose the AR strategy
C_i	Environmental governance cost when EVMs choose the NR strategy
λ	Government's supervision of informal recycling channels
Probability	
x	Probability of EVMs choosing the AR strategy
y	Probability of consumers choosing the FC strategy
z	Probability of the government adopting the SR strategy

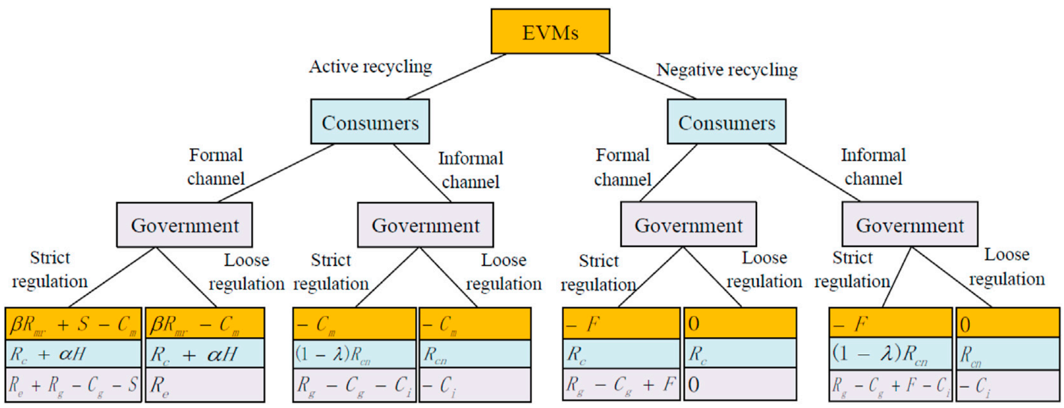

FIGURE 2
Game tree of the three participants.

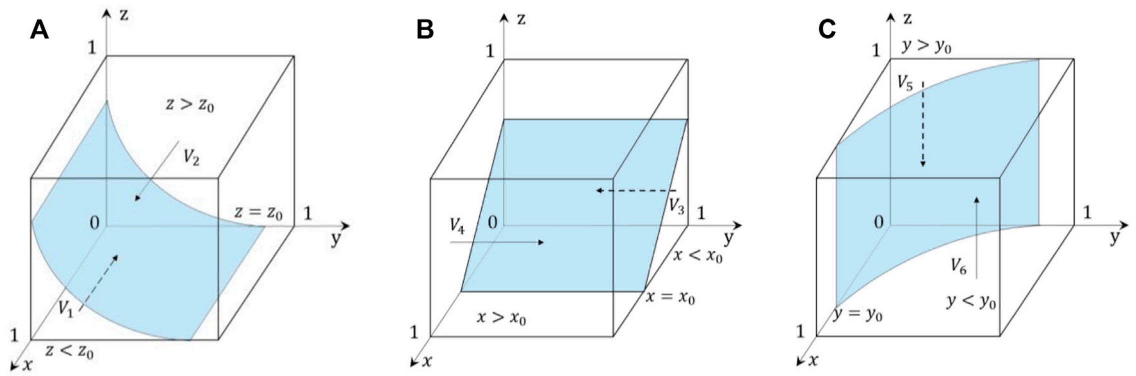

FIGURE 3
Dynamics trend schematic diagram of EVMs, consumers, and the government.

While $z < z_0$, $\frac{dF_m(x)}{dx}|_{x=0} < 0$ and $\frac{dF_m(x)}{dx}|_{x=1} > 0$,; thus, it can be deduced that $x = 0$ is the ESS.

Based on the analysis of the evolutionarily stable strategy of EVMs, we can draw the dynamics trend schematic diagram of EVMs, as shown in Figure 3A. We can observe that the entire feasible region is divided into two parts, V_1 and V_2 , by the intersection space of y and z. When the values of β, S , and F gradually increase, the value of z_0 will gradually decrease. At this time, the volume of V_2 increases, indicating that the probability of EVMs choosing the AR strategy increases. When the values of C_m gradually increase, the value of z_0 will gradually increase; thus, the volume of V_2 decreases, indicating that the probability of EVMs choosing the AR strategy decreases.

4.2 Strategy stability and evolution path analysis of consumers

Similarly, the replicator dynamic equation of consumers to choose participation in formal recycling is as follows:

$$\begin{aligned} F_c(y) &= \frac{dy}{dt} = y(U_{c1} - \bar{U}_c) \\ &= y(1-y)(\alpha Hx + \lambda R_{cn} z + R_c - R_{cn}), \end{aligned} \tag{6}$$

where U_{c1} denotes the expected revenues of consumers who choose the FC strategy and $\bar{U}_c$ denotes the average expected revenues of consumers.

Taking the derivative of $F_c(y)$, we can obtain the following equation from Eq. 6:

$$\frac{dF_c(y)}{dy} = (1-2y)(\alpha Hx + \lambda R_{cn} z + R_c - R_{cn}). \tag{7}$$

Set $x_0 = \frac{R_{cn} - R_c - \lambda R_{cn} z}{\alpha H}$, while $x = x_0$, and $F_c(y) \equiv 0$. It means that it is in a stable state no matter what value y takes; thus, any probability of consumers choosing the FC strategy is the ESS.

While $x > x_0$, $\frac{dF_c(y)}{dy}|_{y=0} > 0$ and $\frac{dF_c(y)}{dy}|_{y=1} < 0$,; thus, it can be deduced that $y = 1$ is the ESS.

While $x < x_0$, $\frac{dF_c(y)}{dy}|_{y=0} < 0$ and $\frac{dF_c(y)}{dy}|_{y=1} > 0$,; thus, it can be deduced that $y = 0$ is the ESS.

Based on the analysis of the evolutionarily stable strategy of consumers, we can draw the dynamics trend schematic diagram of consumers, as shown in Figure 3B. We can observe that the entire feasible region is divided into two parts, V_3 and V_4 , by the intersection space of x and z. When the values of α, R_c, λ , and H gradually increase, the value of x_0 will gradually decrease. At this time, the volume of V_4 increases, indicating that the probability of consumers choosing the FC strategy increases. When the values of R_{cn} gradually increase, the value of x_0 will gradually increase; thus, the volume of V_4 decreases, indicating that the probability of consumers choosing the FC strategy decreases.

4.3 Strategy stability and evolution path analysis of the government

The replicator dynamic equation of the government to choose strict regulation is as follows:

$$\begin{aligned} F_g(z) &= \frac{dz}{dt} = z\left(U_{g1} - \bar{U}_g\right) \\ &= z(z-1)\left(Sxy + Fx + C_g - F - R_g\right), \end{aligned} \tag{8}$$

where U_{g1} denotes the expected revenues of the government to choose strict regulation and $\bar{U}_g$ denotes the average expected revenues of the government.

Taking the derivative of $F_c(y)$, we can obtain the following equation from Eq. 8:

$$\frac{dF_g(z)}{dz} = (2z-1)\left(Sxy + Fx + C_g - F - R_g\right). \tag{9}$$

Set $y_0 = \frac{R_g+F-C_g-Fx}{Sx}$, while $y = y_0$, and $F_g(z) \equiv 0$. It means that it is in a stable state no matter what value z takes; thus, any probability of the government adopting the SR strategy is the ESS.

While $y > y_0$, $\frac{dF_g(z)}{dz}|_{z=0} < 0$ and $\frac{dF_g(z)}{dz}|_{z=1} > 0$,; thus, it can be deduced that $z = 0$ is the ESS.

While $y < y_0$, $\frac{dF_g(z)}{dz}|_{z=0} > 0$ and $\frac{dF_g(z)}{dz}|_{z=1} < 0$,; thus, it can be deduced that $z = 1$ is the ESS.

Based on the analysis of the evolutionarily stable strategy of the government, we can draw the dynamics trend schematic diagram of the government, as shown in Figure 3C. We can observe that the entire feasible region is divided into two parts, V_5 and V_6, by the intersection space of x and y. When the values of R_g and F gradually increase, the value of y_0 will gradually increase. At this time, the volume of V_6 increases, indicating that the probability of the government adopting the SR strategy increases. When the values of C_g and S gradually increase, the value of y_0 will gradually decrease; thus, the volume of V_6 decreases, indicating that the probability of the government adopting the SR strategy decreases.

4.4 System evolution strategy stability analysis

Let $F_m(x) = 0$, $F_c(y) = 0$, and $F_g(z) = 0$; then, we obtain eight pure strategy equilibrium points, namely, $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$、, $E_6(1,0,1)$, $E_7(0,1,1)$, and $E_8(1,1,1)$. However, it is necessary to further judge whether the equilibrium point is an evolutionary stability strategy (ESS) Ritzberger and Weibull, 1995. According to Lyapunov's indirect method, the asymptotic stability of a three-dimensional dynamical system at the equilibrium point can be judged by the three eigenvalues of the Jacobian matrix. If all eigenvalues of the Jacobian matrix are negative, the corresponding equilibrium point is the ESS (Friedman, 1998). The Jacobian matrix can be obtained by joint replication dynamic Eqs 4, 6, 8 as follows:

$$J = \begin{bmatrix} \partial F_m(x)/\partial x & \partial F_m(x)/\partial y & \partial F_m(x)/\partial z \\ \partial F_c(y)/\partial x & \partial F_c(y)/\partial y & \partial F_c(y)/\partial z \\ \partial F_g(z)/\partial x & \partial F_g(z)/\partial y & \partial F_g(z)/\partial z \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix}, \tag{10}$$

where

$$\begin{cases} J_{11} = (2x-1)(C_m - \beta R_{mr} y - Fz - Syz) \\ J_{12} = x(x-1)(-\beta R_{mr} - Sz) \\ J_{13} = x(1-x)(F+Sy) \\ J_{21} = y(1-y)\alpha H \\ J_{22} = (1-2y)(\alpha Hx + \lambda R_{cn} z + R_c - R_{cn}). \\ J_{23} = y(1-y)\lambda R_{cn} \\ J_{31} = z(z-1)(F+Sy) \\ J_{32} = z(1-z)xS \\ J_{33} = (2z-1)(Sxy + Fx + C_g - F - R_g) \end{cases} \tag{11}$$

The equilibrium points should be brought into the Jacobian matrix and solved for the eigenvalues corresponding to each point. According to the basic assumptions $R_{cn} > R_c$, $R_c + \alpha H > R_{cn}$ analyzes the stability of the equilibrium solution, as shown in Table 2.

Because there are positive eigenvalues in equilibrium points $E_2(1,0,0)$, $E_3(0,1,0)$, $E_6(1,0,1)$, and $E_7(0,1,1)$, they cannot be the ESS. The stability of the remaining four equilibrium points can be discussed through the following four situations.

Situations 1: When $R_c < R_{cn}$ and $C_g > F + R_g$, the equilibrium point $E_1(0,0,0)$ is asymptotically stable. In this situation, EVMs choose the AR strategy, consumers choose the FC strategy, and the government adopts the LR strategy. The negative behavior of the three stakeholders will lead to a large number of batteries flowing into informal recycling channels and causing environmental pollution risks.

Situations 2: When $C_m > F$, $R_c < (1-\lambda)R_{cn}$, and $C_g < F + R_g$, the equilibrium point $E_4(0,0,1)$ is asymptotically stable. The first inequality $C_m > F$ indicates that EVMs prefer the NR strategy if the cost is higher than the penalties. The second inequality $R_c < (1-\lambda)R_{cn}$ means that consumers prefer the IC strategy if the revenue from choosing the FC strategy is less than that from the IC strategy. As seen from the third inequality $C_g < F + R_g$, the government adopts the SR strategy when the net revenue of strict regulation outweighs the cost. In this situation, EVMs choose the NR strategy, consumers choose the IC strategy, and the government adopts the SR strategy. The government advocates the recycling of EOL EV batteries with the goal of environmental protection and carbon emission reduction. However, due to the imperfect regulation mechanism, it is difficult to improve the motivation of EVMs and consumers.

Situations 3: When $\beta R_{mr} > C_m$, $R_c + \alpha H > R_{cn}$, and $C_g + S > R_g$, the equilibrium point $E_5(1,1,0)$ is asymptotically stable. The first inequality $\beta R_{mr} > C_m$ indicates that EVMs prefer the AR strategy when the recycling revenue is higher than the cost. The second inequality $R_c + \alpha H > R_{cn}$ shows that consumers prefer the FC strategy if the sum of revenue and environmental benefits is higher than that in the IC strategy. As seen from the third inequality $C_g + S > R_g$, the government adopts the LR strategy when the sum of the cost and subsidy from adopting the SR strategy exceeds the revenue. In this situation, with the improvement of recycling technology and consumer environmental awareness, EVMs will make profits through recycling and consumers are willing to hand over retired batteries to formal recycling channels. As the recycling industry matures, the government will gradually reduce intervention. The development of the EOL EV battery recycling industry will be changed from policy-driven to economic-driven.

TABLE 2 Eigenvalues and stability of the game equilibrium point.

Equilibrium point	Eigenvalue 1	Eigenvalue 2	Eigenvalue 3	Positive or negative	Stability
$E_1\,(0,0,0)$	$-C_m$	$R_c - R_{cn}$	$R_g - C_g + F$	$(-,-,N)$	ESS
$E_2\,(1,0,0)$	C_m	$R_c - R_{cn} + \alpha H$	$R_g - C_g$	$(+,+,N)$	Unstable
$E_3\,(0,1,0)$	$\beta R_{mr} - C_m$	$R_{cn} - R_c$	$R_g - C_g + F$	$(N,+,N)$	Unstable
$E_4\,(0,0,1)$	$-C_m + F$	$R_c - (1-\lambda)R_{cn}$	$C_g - R_g - F$	$(N,-,N)$	ESS
$E_5\,(1,1,0)$	$C_m - \beta R_{mr}$	$R_{cn} - R_c - \alpha H$	$R_g - C_g - S$	$(N,-,N)$	ESS
$E_6\,(1,0,1)$	$C_m - F$	$R_c - (1-\lambda)R_{cn} + \alpha H$	$R_g - C_g$	$(N,+,N)$	Unstable
$E_7\,(0,1,1)$	$\beta R_{mr} - C_m + S + F$	$(1-\lambda)R_{cn} - R_c$	$C_g - R_g - F$	$(N,+,N)$	Unstable
$E_8\,(1,1,1)$	$C_m - \beta R_{mr} - S - F$	$(1-\lambda)R_{cn} - R_c - \alpha H$	$C_g - R_g + S$	$(N,-,N)$	ESS

The symbol "N" indicates that the positive and negative values of eigenvalues are uncertain.

Situations 4. When $\beta R_{mr} + S + F > C_m$, $R_c + \alpha H > (1-\lambda)R_{cn}$, and $R_g > C_g + S$, the equilibrium point $E_8\,(1,1,1)$ is asymptotically stable. The first inequality $\beta R_{mr} + S + F > C_m$ means that EVMs tend to choose the AR strategy when the net revenue from choosing the AR strategy is higher than the cost. The second inequality $R_c + \alpha H > (1-\lambda)R_{cn}$ indicates that consumers prefer the FC strategy if the sum of revenue and environmental benefits from choosing the FC strategy is higher than that from the IC strategy. The third inequality $R_g > C_g + S$ indicates that the government prefers the SR strategy if the difference between the revenue and cost of strict regulation is greater than the subsidies. In this situation, under the background of China's implementation of the "dual carbon" target strategy, the government actively promotes EVs. In order to achieve sustainable development of the EV industry, the government has a strong incentive to strictly regulate the EOL EV battery recycling market. At this time, the government strengthens the subsidy and penalty mechanism, which can effectively encourage EVMs to choose active recycling and consumers to choose formal recycling channels.

Based on the aforementioned four situations and the reality of EOL EV battery recycling in China, we divide the evolution path of the EOL EV battery recycling industry into three stages: early stage, development stage, and mature stage. At present, China is in the early stage of EOL EV battery recycling, due to the imperfect regulatory system, immature recycling technology, and low environmental awareness, and the negative behavior of the three parties resulted in a large number of retired batteries unable to be formally recycled. Situation 1 and Situation 2 are consistent with this reality. Situation 4 is the development stage, indicating that the reward and punishment policies drive the gradual improvement and development of the recycling industry. Situation 3 is the mature stage, indicating that the industry has entered a benign stage driven by the market mechanism.

5 Numerical analysis of governance strategies

According to the evolutionary game analysis in the previous section, the tripartite game's strategy combination may evolve into two ideal stable states: (AR, FC, and LR) or (AR, FC, and SR). However, the tripartite game's strategy combination may also be (NR, IC, and LR) or (NR, IC, and SR). In this part, we use the MATLAB R2021a software to conduct a numerical study to explore the behavioral strategy selection of the three stakeholders at each stage of the EOL EV battery recycling industry, so as to optimize the government's governance strategies and accelerate the construction of a multi-agent collaborative EOL EV battery recycling system.

According to the survey data of Guohai Securities on the EOL EV battery recycling market, let the initial parameters be $C_m = 8$, $R_{mr} = 10$, $R_c = 3$, $R_{cn} = 5$, $F = 2$, $S = 2$, $H = 3$, $R_g = 8$, $C_g = 5$, $\lambda = 0.3$, $C_i = 4$, and $R_e = 4$. The initial values of x, y, and z are $\{0.5, 0.5, 0.5\}$, respectively. Furthermore, we assume that $\beta = 0.5$ and $\alpha = 0.4$, which indicates that recycling technology and consumer environmental awareness are at a low level. In the following section, we will analyze the realization path from the *status quo* of recycling to the ideal state by adjusting the relevant parameters.

5.1 The impact of the punishment strategy on system evolution

In the early stage, the government advocates the recycling of EOL EV batteries with the goal of environmental protection and carbon emission reduction and will formulate incentive and punishment policies for EOL EV battery recycling. However, due to the imperfect regulation mechanism, it is difficult to improve the motivation of EVMs and consumers. Therefore, at this stage, the government needs to establish a strict

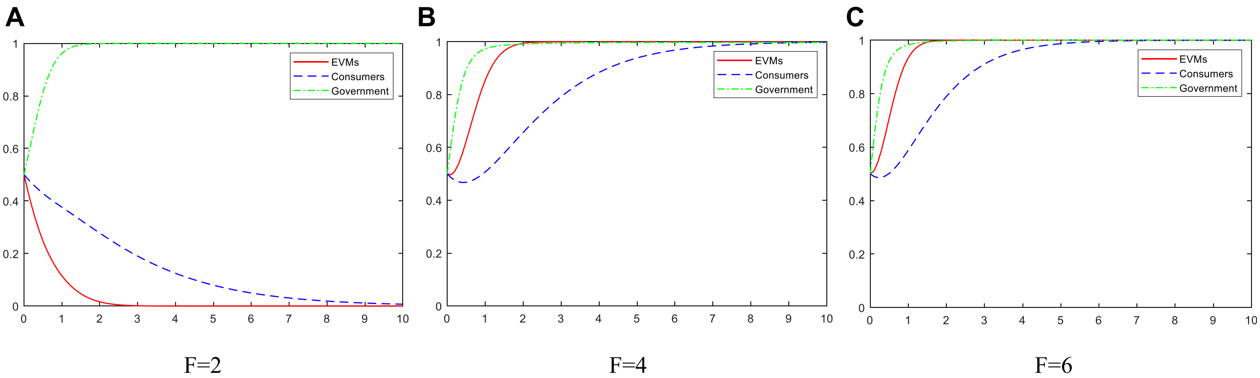

FIGURE 4
Impact of different values of penalty on the evolutionary process.

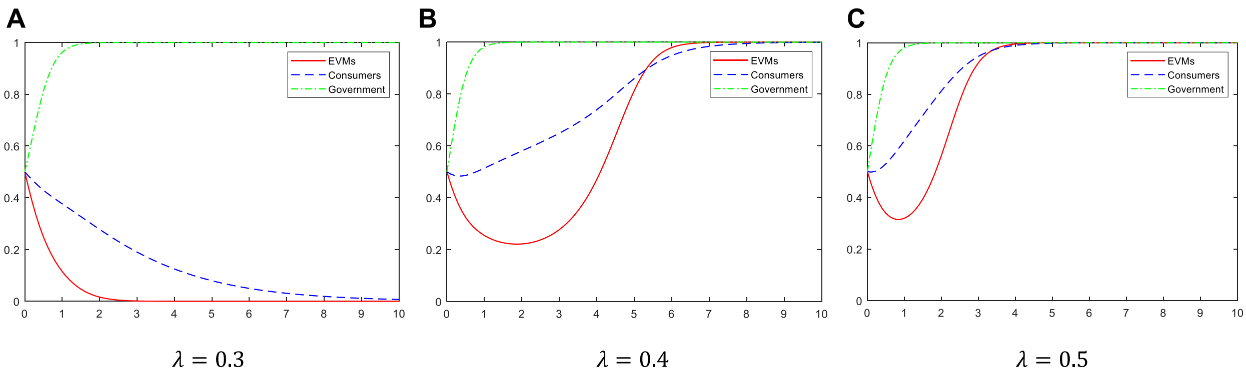

FIGURE 5
Impact of different values of supervision on the evolutionary process.

punishment mechanism, including a penalty for negative recycling by EVMs and the supervision of informal recycling channels. We set the values of F as 2, 4, and 6, which, respectively, correspond to a low, medium, and high scenario of the government's penalty on EVMs who choose the negative recycling strategy. As the penalties increase, the impact on the evolution path of three participants is shown in Figure 4.

In Figure 4A, EVMs choose the NR strategy and consumers choose the IC strategy when $F = 2$, which shows that lower penalties cannot effectively restrain the speculation of EVMs. In Figure 4B, when the penalty increases to 4, the excessive penalty results in EVMs choosing the AR strategy and consumers choosing the FC strategy. Furthermore, in Figure 4C, when $F = 6$, the evolution time of both EVMs who choose the AR strategy and consumers who choose the FC strategy is shortened. It indicates that increasing the penalty can promote EVMs to recycle EOL EV batteries. At this time, EVMs will increase the construction of recycling service sites and strengthen environmental protection awareness promotion, which is conducive to increase the enthusiasm of consumers to participate in formal recycling.

In the same way, we set the values of λ as 0.3, 0.4, and 0.5, which, respectively, correspond to a low, medium, and high scenario of the supervision for informal recycling channels. The government's supervision on the informal recycling channels will directly affect the system evolution result. As the supervision increases, the impact on the evolution path of three participants is shown in Figure 5.

In Figure 5A, EVMs choose the NR strategy and consumers choose the IC strategy when $\lambda = 0.3$, which indicates that the government's lax supervision of informal channels will lead to chaos in the recycling market. In Figure 4B, when the supervision increases to 0.4, the strict supervision results in EVMs choosing the AR strategy and consumers choosing the FC strategy. Furthermore, in Figure 5C, when $\lambda = 0.5$, the evolution time of both EVMs who choose the AR strategy and consumers who

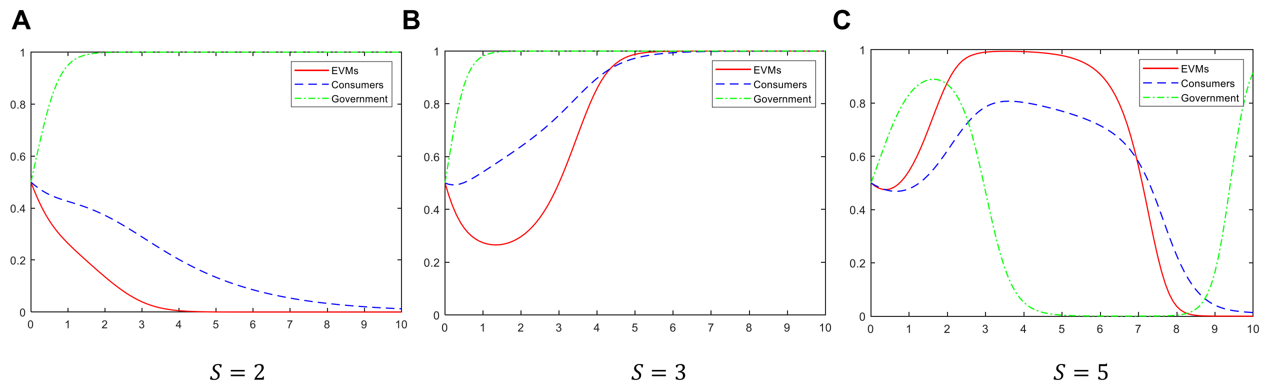

FIGURE 6
Impact of different values of the subsidy on the evolutionary process.

choose the FC strategy is shortened. We also observe that the active recycling probability curve of EVMs is U-shaped, which indicates that government supervision first affects the supply-side consumers and then transmits from the supply-side to the demand-side EVMs. It indicates that the government's strengthening of the supervision of the informal recycling market can promote more consumers to choose formal channels, thus, further improving the enthusiasm of EVMs to recycle batteries. It can be concluded that the punishment strategy can effectively promote the collaborative participation of EVMs and consumers in EOL EV battery recycling.

5.2 The impact of the subsidy strategy on system evolution

In China, the state has issued a series of incentive policies to encourage and support the recycling of EOL EV batteries. For example, in Shenzhen, Hefei, Shanghai, Guangxi, and other provinces and cities, the local governments have issued subsidy policies to support the recycling of EOL EV batteries. We assume the values of S equal 2, 3, and 5, respectively, and investigate the impact of the subsidy strategy on the behavioral strategies of tripartite participants. As the subsidies increase, the impact on the evolution path of tripartite participants is shown in Figure 6.

It can be seen from Figure 6A that EVMs choose the NR strategy and consumers choose the IC strategy when $S = 2$, which shows that a lower subsidy cannot play a positive incentive role. Figure 6B shows when the subsidy increases to 3, the higher subsidy encourages EVMs to choose the AR strategy and consumers to choose the FC strategy. However, Figure 6C shows that as the subsidy increases and exceeds the threshold, when $S = 5$, the tripartite evolution system will have oscillations and cannot reach a stable state. The aforementioned results show that appropriate increase of the subsidy can effectively enhance the willingness of EVMs choosing the AR strategy and consumers choosing the FC strategy. In contrast, the high subsidy will aggravate the government's financial burden and reduce the government's willingness to regulate, which is not conducive to the sustainable development of the EOL EV battery recycling industry.

5.3 The impact of recycling technology and consumer environmental awareness on system evolution

Set the values of β as 0.5, 0.7, and 0.9, which correspond to a low, medium, and high scenario of the recycling technical level, respectively. Similarly, the values of α are set as 0.4, 0.6, and 0.8, which correspond to a low, medium, and high scenario of consumer environmental awareness, respectively. Figure 7 draws the impact of the changes of β and α on behavioral strategies of the three stakeholders.

Figure 7A shows that EVMs choose the NR strategy, consumers choose the IC strategy and the government adopts the SR strategy when $\beta = 0.5$ and $\alpha = 0.4$. Figure 7B shows that when $\beta = 0.7$ and $\alpha = 0.6$, EVMs choose the AR strategy, consumers choose the FC strategy, and the government adopts the SR strategy. Furthermore, Figure 7C shows that when $\beta = 0.9$ and $\alpha = 0.8$, EVMs choose the AR strategy and consumers choose the FC strategy. The probability of the government adopting the SR strategy first rises and then falls, and finally evolves to the LR strategy. Simulation analysis indicates that under the strict regulation of government departments, in order to improve the economic benefits of EOL EV battery recycling, EVMs will increase the investment in technological innovation. The probability of EVMs choosing the AR strategy will gradually increase. At the

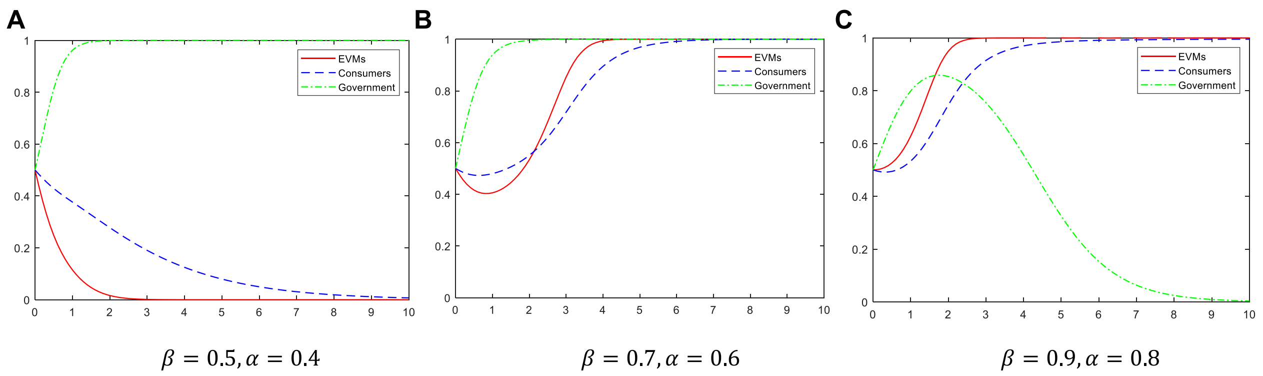

FIGURE 7
Impact of β and α on the evolutionary process.

same time, with the gradual improvement of environmental protection awareness, the probability of consumers choosing the FC strategy will also increase, which will increase the supply of EOL EV batteries for EVMs. Therefore, through the increase of the recycling scale on the supply side and the improvement of recycling technology on the demand side, EVMs will eventually gradually improve the profitability of recycling, thereby promoting the sustainable development of EOL EV battery recycling. Meanwhile, when the recycling industry matures, the government's strict regulation mechanism can be gradually withdrawn.

6 Discussion

EOL EV battery recycling is of great significance to ensure the security of national resources and promote the realization of carbon peaking and carbon neutrality. In the initial stage, due to backward recycling technology and equipment, the recycling cost of formal enterprises is high. Consumers' lack of environmental awareness and imperfect regulatory systems have led to a large number of EOL EV batteries flowing into informal channels. As a result, the current Chinese EOL EV battery recycling market is chaotic and the formal collection ratio is low, which needs to be solved urgently. Focusing on this, this study brings consumers into the analysis and constructs a tripartite evolutionary game model to explore the governance strategies for end-of-life electric vehicle battery recycling in China.

Different from the one-time equilibrium in these studies (Tang et al., 2018; Yang et al., 2021), this research pays more attention to explore the learning, imitation, and trial-and-error process of the three participants, and further analyze the influencing factors of this process. Compared with the existing literature (Guo et al., 2022; He and Sun, 2022), in addition to the traditional income-related variables and cost-related variables, this paper considers the influence of EVMs' recycling technology level and consumers' environmental awareness preference behavior, so the research is more in-depth and comprehensive. Furthermore, the article analyzes the governance strategies at different stages of the industry based on the current situation of China's EOL EV battery recycling industry and the industry life cycle theory. Therefore, this research is a supplement and improvement of the existing achievements and can also provide useful enlightenment and suggestions for promoting the effective recycling of EOL EV batteries.

Through systematic analysis, we found that the punishment strategy and subsidy strategy can effectively promote EVMs and consumers to choose positive behaviors. However, the excessive subsidy is not conducive to the sustainable development of the EOL EV battery industry. On one hand, excessive subsidies will increase the government's financial burden, which is not conducive to the government's sustainable supervision of the recycling market. On the other hand, high subsidies may lead to opportunistic behavior of enterprises to defraud subsidies. This finding partly explains why only a few local governments in China have introduced battery recycling subsidy policies. The reward and punishment mechanism is only the governance strategies at the early stage of recycling, while technological innovation and green consumption are the leverage to promote the sustainable development of the EOL EV battery industry.

7 Conclusion and implications

Through tripartite evolutionary game analysis, we obtain the following conclusions. 1) For the evolutionary system, there exist four evolutionary stable strategies. Moreover, based on the different levels of recycling technology and consumer awareness of environmental protection, four evolutionary stable strategies correspond to the three stages in the Chinese EOL EV battery recycling: early stage, development stage, and maturity stage. 2) Simulation analysis shows that government strict regulation on both sides of the supply and demand is critical to motivate EVMs and consumers to actively participate in recycling in the early stage. Subsidy mechanisms can influence the strategic choices of the three parties. However, when the subsidy is too high, the three participants will have behavior shock, which is not conducive to the sustainable development of the EOL EV battery recycling industry. 3) As battery recycling technology matures and consumers' environmental awareness increases, a high probability of EVMs choose the active recycling strategy and consumers choose the formal channel strategy. When the recycling industry matures, the government will gradually decrease interventions and finally adopt loose regulation.

Based on the current situation of EOL EV battery recycling in China, we propose the following policy recommendations.

At present, China's EOL EV battery recycling industry has just started, recycling technology is not mature, coupled with the lack of public awareness on the environmental recovery of retired batteries, resulting in insufficient enthusiasm of EVMs to recycle. At this time, the government should adopt strict supervision measures of "carrot and stick" and establish a clear reward and punishment mechanism. On one hand, it is necessary to establish a recycling system with wider coverage to solve the problem that batteries cannot be collected. The government should support the construction of a battery life cycle management traceability system and strictly supervise the flow of EOL EV batteries. On the other hand, the government needs to innovate incentive policies and measures to guide EVMs to cooperate with the upstream and downstream of the industry chain to build an EOL EV battery recycling system and simultaneously provide subsidies or tax incentives to EVMs according to the number of EOL batteries recycled.

In the long run, it is necessary to realize the sustainable development of the EOL EV battery recycling industry through technological progress and green consumption. First, the government should invest resources to support the research and development of core technologies for battery recycling and reuse by improving the recovery rate of valuable metal materials in retired batteries to increase recycling profits. Second, the government needs to strengthen the publicity of the environmental safety risks of waste batteries, actively advocate the concept of green and low-carbon consumption, and enhance the environmental protection awareness of the whole society. When the benign external environment of the EOL EV battery recycling industry is formed, the difficult profit dilemma of the industry will be fundamentally solved, so as to realize the development path of the EOL EV battery recycling industry driven by enterprise profit from government exogenous regulation.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

LW and C-XW were responsible for the methodology and solution method; LW wrote the original draft; and Y-QL was responsible for collecting data.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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