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Game evolution and simulation analysis of power battery recycling in China under conflicting supply and demand of critical metals

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A great demand for lithium, cobalt, nickel, and other critical metals by power batteries has been increasing with the explosive development of the new energy industry, which further exacerbated the contradiction between the supply and demand of critical metals. In addition, two key factors, including an imbalance of government reward and punishment and a low degree of cooperation between manufacturers and recycling enterprises, have hindered the recovery and utilization of critical metals in power battery with the expansion of the power battery recycling market. A three-party evolutionary game model, including power battery manufacturers, third-party recycling enterprises, and the government, was constructed in this study to analyze the evolutionary stability of the strategy selection of each participant. Also, the influence of each factor on the three-party strategy selection and verifying the reliability of the results through simulation were also discussed. The results show that 1) both government incentives and punishments are beneficial for promoting cooperation between power battery manufacturers and recycling enterprises. The cost of cooperation will be the key factor affecting power battery recycling. 2) Increasing the probability of cooperation is an effective way to ensure the increase in income of both parties after cooperation. Further suggestions, including the establishment of a dynamic reward and punishment mechanism by the government and strengthening the cooperation to cope with the continued tight supply of critical metals by the manufacturers and recyclers, were also put forward in this research.

KEYWORDS

critical metals, recycling, cooperation, tripartite evolutionary game model, simulation analysis

Introduction

The development of energy vehicles (EVs) is an effective way to achieve carbon emission reduction and carbon neutrality (Li et al., 2022). As an important component of EVs, power batteries are crucial to the manufacturing and development of EVs. Critical metals such as lithium, cobalt, and nickel, as essential constituents of active cathode materials and anode active materials of power batteries, have become indispensable raw materials in power battery manufacturing (Gu et al., 2017). By 2030, China's lithium-ion battery (LIB) demand for lithium, cobalt, and nickel will be 11 times, 9 times, and 62 times higher than that in 2020, respectively (Shafique et al., 2022), and the tight supply and demand situation for critical metals in China is expected to intensify in the future. Power battery will enter the end-of-life stage after their capacity decays to a certain level, and recycling of retired power batteries can effectively increase the supply of key materials and reduce the initial production cost of power batteries (Idjis and Costa, 2017). In addition, battery recycling and reusing will achieve a win-win situation for both resource recovery and environmental protection impact, compared to new battery manufacturing (Gu et al., 2018). It will become increasingly important as lithium batteries increase (Alipanah et al., 2021). It is expected that by 2025, recycled lithium in China will account for 9% of the total lithium supply from lithium batteries and cobalt will account for nearly 20% (Pagliaro and Meneguzzo, 2019), which will go some way to alleviating the tight supply and demand for critical metals in power battery production.

Government supervision plays a major role in power battery recycling. On the one hand, a rational design of the layout, pricing strategy, and utilization to the power battery recycling industry is the key to realizing the efficient use of recycled power batteries (Lyu et al., 2021). On the other hand, supervision and subsidies for power battery recycling, gradient utilization, and resource reuse recycling systems are important to realize resource recycling (Tang et al., 2019; Liu and Wang, 2021; Wang, 2022). Lack of supervision will lead to the occurrence of corporate fraud and other situations. The Chinese government has introduced a series of regulations to guide and regulate the recycling of used batteries (Sun et al., 2021). Nevertheless, there are still phenomena such as regulatory imbalances and unsound recycling networks, which seriously hinder the healthy development of recycling market and incur huge environmental governance costs (He and Sun, 2022).

The cooperation cost is also one of the factors that both production enterprises and recycling enterprises must be considered when cooperating. Although extended producer responsibility (EPR) policies hold producers responsible for the entire life cycle of their products (Lindhqvist, 2000), especially the recycling and disposal of products designated by consumers as no longer useful (Gaur et al., 2022), producers usually cannot completely rely on their own power to achieve waste recycling. According to Gu et al. (2016), subjects involved in waste recovery can be divided into hawkers, collection stations, distributors, and middlemen, of which middlemen are second-level recyclers, and the other three are directly connected with consumers and belong to first-level recyclers (Chi et al., 2011). Although the number of recycling enterprises is very large, most of which are small and medium-sized enterprises, no special recycling network has been formed (Wang and Wu, 2017). Both power battery manufacturers and recycling enterprises need to pay a certain cost to seek recycling cooperation. For recycling enterprises, capabilities with high dismantling capabilities and strong technical have to pay less such costs. Power battery manufacturers can achieve win-win cooperation by signing risk-equivalent contracts and establishing advantages in the recycling power battery recycling market (Zhu and Yu, 2019). For recyclers, the amount of investment under different investment models and the recycling rate will also influence its decisions (You et al., 2014).

There are many studies on various aspects of power battery recycling, such as policies and regulations on power battery recycling (Xu et al., 2017; Choi and Rhee, 2020; He and Sun, 2022), power battery recycling subjects (Schultmann et al., 2003), recycling channels (Chuang et al., 2014; Tang et al., 2018), and recycling mode (Hong and Yeh, 2012). Game theory is simulated decision interactions among rational decision-makers by using mathematical methods and has many applications in political science, economics, and sociology (Fang et al., 2021). Compared with traditional engineering methods, game theory pays more attention to the social and personal behaviors of stakeholders (Yuan et al., 2022). Luo et al. (2019) used a dynamic game to optimize subsidy policy for autonomous vehicles. Gu et al. (2021) constructed a game model of the impact of government subsidies on the utilization of electric vehicle batteries from the perspective of the closed-loop supply chain. Li X. et al. (2020) conducted an evolutionary game analysis on the behavior of the main participants in the electric vehicle battery deposit refund scheme launched by the Shenzhen Municipal Government of China. Li J. et al. (2020) built a non-cooperative game model that considers the battery recycling rate and consumers' environmental awareness and includes three game subjects, namely, EVs manufacturers, fuel vehicle manufacturers, and the government, and further verify the efficiency of dual credit policy over subsidy one. Using an evolutionary game model among consumers, EVs manufacturers, and the government under the EPR system, He and Sun (2022) found that the government's dynamic reward and punishment mechanism encourage consumers and 97% of EVs enterprises to participate in power battery recycling; the cost of recycling is the biggest influencing factor that hinders the recycling of power batteries by EVs manufacturers, and the change of recycling price of third-party recycling enterprises will affect the development of recycling industry.

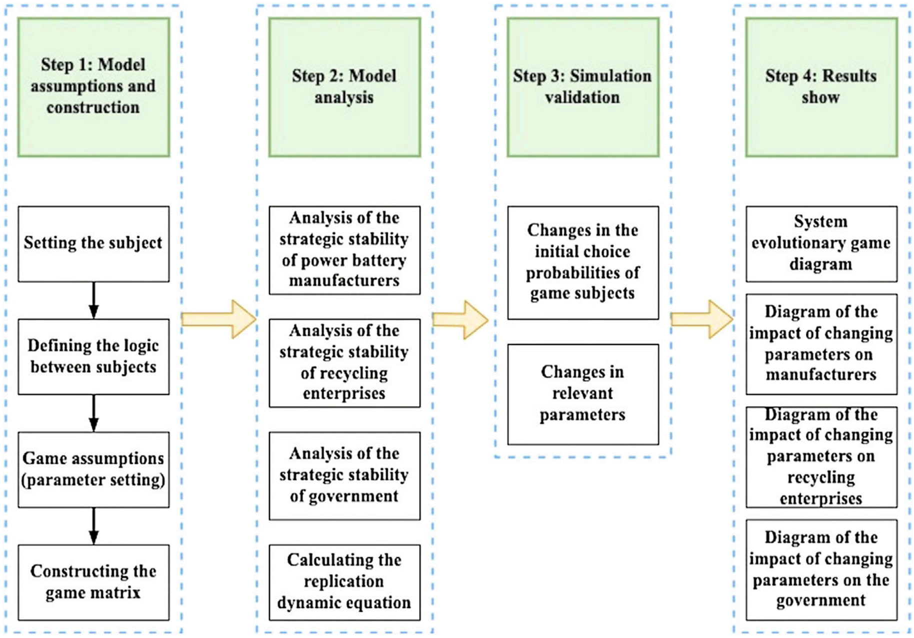

FIGURE 1
Framework for studying the evolution of a tripartite game for recycling critical metals in power batteries.

There are many literatures on government policy research, but there is a lack of research on the design of power battery recycling network at the enterprise level (Wang et al., 2020). In order to improve the efficiency of power battery recycling and the utilization rate of recycled power batteries, it seems difficult to rely only on the government, and the roles and interactions between different players must be considered (Kong et al., 2020). Specifically, the cooperation between recycling enterprises and power battery stakeholders can promote a mutually beneficial win-win situation (Ding and Zhong, 2018; Sopha et al., 2022). Therefore, it is necessary to study the cooperation between interest groups in the battery recycling industry in China (Zhou et al., 2007).

In summary, this study structures an evolutionary game model of three responsible parties in the power battery recycling chain to address 1) the influence of the initial selection probability of production enterprises, recycling manufacturers, and the government on the evolutionary game process and results in power battery recycling. 2) The impact on the game subject is analyzed from the perspectives of cooperation cost, supervision cost, and the amount of rewards and penalties; furthermore, the mitigation effect of power battery recycling on the supply shortage of critical metal resources is analyzed. Compared with previous studies, the model scenario of this study is more practical and the analysis of the scenario is richer. First, this study considers the participation willingness of both power battery manufacturers and recycling enterprises; second, the model of three-party game is introduced to analyze the evolution process of the three-party game under the reward and punishment mechanism. Third, this study introduces the optimization behavior of the dynamic reward and punishment mechanism for the three game subjects. Finally, this study analyzes the influence of key factors on group behavior and provides policy suggestions for power battery recycling to alleviate the supply shortage of critical metals. This can help policy makers to make better policies and help alleviate the tight supply and demand situation of critical metals. The rest of the article is structured as follows: *Section 2* constructs a three-party evolutionary game model, *Section 3* provides a stability analysis of the game subjects, *Section 4* conducts simulations, and the last section gives conclusions and policy recommendations.

Tripartite evolutionary game modeling

Research framework

This study adopts the evolutionary game method for research, and the specific research framework (Figure 1) can be obtained as follows: first, the game model is hypothesized based on the actual situation, including determining the game subject, setting the game relationship between the subjects and the parameters in the game relationship, and constructing the pure strategy game matrix.

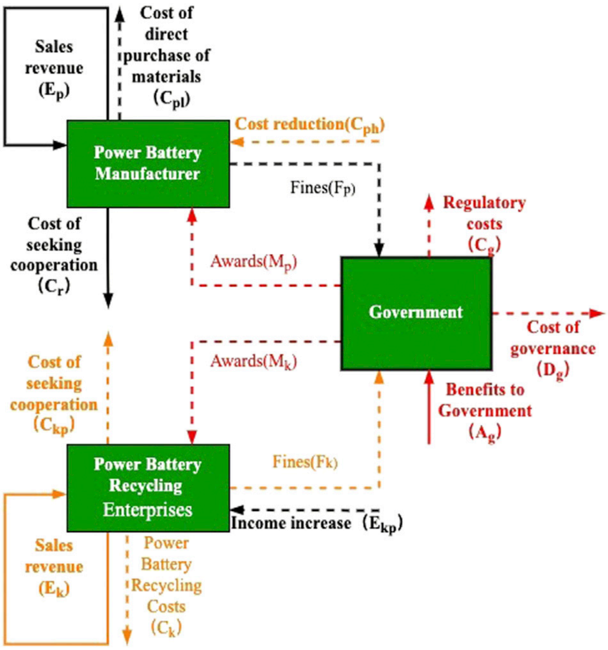

FIGURE 2
Evolutionary game model among power battery manufacturers, recycling enterprises, and government.

Second, we analyzed the stability of game models and evolutionary stable strategy (ESS), including the calculation of the dynamic replication equation under different pure game strategies, phase diagram of strategy evolution, and Jacobian matrix of the stable system. Third, the model parameters are assigned to the actual situation, and a simulation analysis is carried out to observe the influence of the change in the initial selection probability of the subject and the change in related parameters on the evolution process of all parties in the evolutionary game. Finally, the related results are described by images.

Game model assumption

The reduction in the supply of critical metals has exacerbated the tension of the contradiction between supply and demand, resulting in increased production costs for power battery manufacturers. The government has strengthened its supervision of power battery recycling enterprises, which makes it difficult for them to sell recycled power batteries to unqualified enterprises. Under the guidance of the government, power battery manufacturers and third-party recycling enterprises are willing to cooperate and spend some cost to seek cooperation. Therefore, the government, power battery manufacturers, and recycling enterprises are the main participants of power in battery recycling.

Based on the aforementioned scenarios, this study constructs a three-party evolutionary game system (Figure 2) and puts forward the following reasonable assumptions:

Assumption 1: The power battery manufacturer is participant 1, the third-party recycling enterprise is participant 2, and the government regulatory department is participant 3. The three parties are rational subjects with limited participation, and the choice of strategy gradually evolves over time and stabilizes at the optimal strategy. This study only considers the scenario that power battery manufacturers and recycling enterprises cooperate to recycle power batteries. Power battery manufacturers are not directly involved in power battery recycling. Third-party recycling enterprises do not include manufacturers.

Assumption 2: The strategy space for power battery manufacturers is $\alpha = (\alpha_1, \alpha_2) =$ (using recycled power batteries, not using recycled power batteries), the probability of choosing α_1 is x, and the probability of choosing α_2 is $1-x$, $x \in [0,1]$. The strategy space for the third-party recycling enterprises is $\beta = (\beta_1, \beta_2) =$ (cooperation, non − cooperation), the probability of choosing β_1 is y, and the probability of choosing β_2 is $1-y$, $y \in [0,1]$. The strategic space for the government regulatory department is $\gamma = (\gamma_1, \gamma_2) =$ (strict supervision, loose supervision), the probability of choosing γ_1 is z, and the probability of choosing γ_2 is $1-z$, $z \in [0,1]$.

Assumption 3: The production cost of power battery manufacturer is C_{pl}. Power battery manufacturers can choose to cooperate with third-party recycling enterprises and purchase their recycled power batteries from third-party recycling enterprises through cooperation. The cost of power battery manufacturers seeking cooperation is C_r. The cost of recovering critical metals from the recycled power battery is lower than the cost of buying from the market, and the use of recycled power batteries reduces the production cost of power battery manufacturers to a certain extent. This part of the cost is C_{ph}. The operating income of the power battery manufacturer is E_p. Under the strict supervision of the government, the power battery manufacturer actively seeks to cooperate with third-party recycling enterprises, the government will reward M_p. Otherwise, the negative behavior of power battery manufacturers will be punished, and the punishment amount is F_p.

Assumption 4: The cost of the third-party recycling enterprises is C_k, and the income is E_k. If under the guidance of government policies, the additional income obtained by the resale of recycled waste power batteries to power battery manufacturers for processing is E_{kp}, and the government award is M_k. If they are handed over to unqualified enterprises or hoarded and disturbed market prices, they will be fined F_k by the government.

Assumption 5: When the government regulates recycling behavior, the regulatory cost that the government pays is C_g. When power battery manufacturers and third-party recycling enterprises reach cooperation, the market price remains stable,

TABLE 1 Game matrix of mixed strategies.

		Third-party recycling agency	Government regulator	
			Strict supervision z	Loose supervision 1-z
Power battery manufacturer	Use recycled power batteries (x)	Intention to cooperate (y)	$E_p - C_{pl} + C_{ph} - C_r + M_p$	$E_p - C_{pl} + C_{ph} - C_r$
			$E_k - C_k + C_r + M_k$	$E_k - C_k + C_r - C_{kp} + E_{kp}$
			$-C_{kp} + E_{kp}$	A_g
			$-C_g - M_p - M_k + A_g$	
		Intention not to cooperate (1-y)	$E_p - C_{pl} - C_r$	$E_p - C_{pl} - C_r$
			$E_k - C_k - F_k$	$E_k - C_k$
			$F_k - D_g - C_g$	A_g
	No recycled power batteries are used (1-x)	Intention to cooperate (y)	$E_p - C_{pl} - F_p$	$E_p - C_{pl}$
			$E_k - C_k$	$E_k - C_k$
			$F_p - D_g - C_g$	A_g
		Intention not to cooperate (1-y)	$E_p - C_{pl} - F_p$	$E_p - C_{pl}$
			$E_k - C_k - F_k$	$E_k - C_k$
			$F_k + F_p - D_g - C_g$	A_g

the recycling industry develops healthily, the contradiction between the supply and demand of critical metals will be alleviated, and the government will gain social benefits A_g. Otherwise, any party is unwilling to cooperate, the contradiction between the supply and demand of critical metals in the market will further intensify, and the price of power battery will continue to rise. The government needs to consume manpower and material resources to renovate the market, and the cost of this part of governance is D_g. When the government loose supervision, if the power battery manufacturer and the third-party recycling enterprises do not reach cooperation, because the government cannot know the strategic choice information of the enterprise and the third-party recycling enterprises, the government regulatory department will not reward or punish. The means of government regulation mainly include setting up supervision agencies, setting recovery prices, public financial subsidies, penalties, rewards, sales tax, production tax, and setting up licensing systems.

According to the aforementioned assumptions, the mixed strategy game matrix of the power battery manufacturer, third-party recycling enterprises, and government can be obtained, as shown in Table 1.

Evolution model construction and stability analysis

In this section, we calculate the mathematical expectations and probabilities of the strategic choices of power battery producers, recycling enterprises, and governments, and the factors that influence the evolution of the game between the parties can be obtained and analyzed.

Strategy stability analysis of power battery manufacturers

The mathematic expectation that power battery manufacturers using recycled power batteries E_{11}, the mathematic expectation that power battery manufacturers not using recycled power batteries E_{12} and the average mathematic expectation $\overline{E_1}$ are as follows:

$$\begin{aligned} E_{11} &= yz\left(E_p - C_{pl} + C_{ph} - C_r + M_p\right) + y(1-z)\left(E_p - C_{pl} + C_{ph} - C_r\right) \\ &+ (1-y)z\left(E_p - C_{pl} - C_r\right) + (1-y)(1-z)\left(E_p - C_{pl} - C_r\right), \end{aligned} \tag{1}$$

$$\begin{aligned} E_{12} &= yz\left(E_p - C_{pl} - F_p\right) + y(1-z)\left(E_p - C_{pl}\right) \\ &+ (1-y)z\left(E_p - C_{pl} - F_p\right) + (1-y)(1-z)\left(E_p - C_{pl}\right), \end{aligned} \tag{2}$$

$$\overline{E_1} = xE_{11} + (1-x)E_{12}. \tag{3}$$

The dynamic replication equation of the power battery manufacturer's strategy selection is as follows:

$$F(x) = \frac{dx}{dt} = x\left(E_{11} - \overline{E_1}\right) = x(x-1)\left[\left(M_p y + F_p\right)z + C_{ph}y - C_r\right]. \tag{4}$$

The first derivative of x can be obtained by the following:

$$\frac{d(F(x))}{dx} = (1-2x)\left[\left(M_p y + F_p\right)z + C_{ph}y - C_r\right], \tag{5}$$

making

$$G(y) = \left(M_p y + F_p\right)z + C_{ph}y - C_{gr}. \tag{6}$$

According to the stability theorem of the ordinary differential equation, the probability of power battery production enterprises choosing to use recycled batteries in a stable state must satisfy $F(x) = 0$ and $\frac{d(F(x))}{dx} < 0$. $\frac{\partial G(y)}{\partial y} = M_p z + C_{ph} > 0$, so $G(y)$ is a monotonically increasing function with respect to y. When $y = y^* = \frac{C_r - F_p z}{z M_p + C_{ph}}$, $G(y) = 0$, $\frac{d(F(x))}{dx} \equiv 0$, unable to determine stabilization strategy; when $y < y^*$, $G(y) < 0$, $\frac{d(F(x))}{dx}|_{x=0} < 0$, $x = 0$ is ESS; when $y > y^*$, $G(y) > 0$, $\frac{d(F(x))}{dx}|_{x=1} < 0$, $x = 1$ is ESS.

As shown in Figure 3, V_1 represents the willingness of the power battery manufacturers to use the recycled power battery, and the probability that the power battery manufacturers are unwilling to use the recycled power battery can be expressed as V_2. The volumes of V_1 and V_2 are calculated as follows:

$$V_2 = \int_0^1 \int_0^1 \frac{C_r - F_p z}{z M_p + C_{ph}} dz dy = -\frac{F_p}{M_p} + \left[\frac{C_r}{M_p} + \frac{F_p C_{ph}}{M_p^2}\right] ln\left(1 + \frac{M_p}{C_{ph}}\right), \tag{7}$$

$$V_1 = 1 - V_2 = 1 + \frac{F_p}{M_p} - \left[\frac{C_r}{M_p} + \frac{F_p C_{ph}}{M_p^2}\right] ln\left(1 + \frac{M_p}{C_{ph}}\right). \tag{8}$$

Corollary 1: The willingness of power battery manufacturers to use recycled power batteries V_1 is negatively correlated with the benefits brought by using recycled power batteries C_{ph}, positively correlated with government rewards M_p and punishments F_p, and negatively correlated with the cost of seeking cooperation C_r.

Proof 1: Calculate the first partial derivative of each influencing factor according to the formula V_1. It is possible to obtain $\frac{\partial V_1}{\partial C_r} < 0$, $\frac{\partial V_1}{\partial M_p} > 0$, $\frac{\partial V_1}{\partial C_{ph}} > 0$, $\frac{\partial V_1}{\partial F_p} > 0$. Therefore, an increase in M_p, C_{ph} and F_p or a decrease in C_r will increase the probability that power battery manufacturers will seek to use recycled batteries.

Corollary 1 shows that it is important to ensure that manufacturers can make enough profit from using recycled power batteries. The government can increase the reward amount M_p and the punishment amount F_p to increase the willingness of the producer enterprises to use recycled power batteries V_1. The cost of seeking cooperation with recycling enterprises C_r restricts the willingness of power battery manufacturers to use recycled power batteries V_1.

Stability analysis of third-party recovery enterprises

The mathematic expectation that third-party recycling enterprises intend to cooperate with power battery manufacturers E_{21}, the mathematic expectation that third-party recycling enterprises unintended to cooperate with power battery manufacturers E_{22} and the average mathematic expectation $\overline{E_2}$ are as follows:

$$\begin{aligned} E_{21} &= xz(E_k + C_r + M_k - C_k - C_{kp}) + x(1-z)(E_k + C_r - C_k - C_{kp}) \\ &+ (1-x)z(E_k - C_k - C_{kp}) + (1-x)(1-z)(E_k - C_k - C_{kp}), \end{aligned} \tag{9}$$

$$\begin{aligned} E_{22} &= xz(E_k - C_k - F_k) + x(1-z)(E_k - C_k) \\ &+ (1-x)z(E_k - C_k - F_k) + (1-x)(1-z)(E_k - C_k), \end{aligned} \tag{10}$$

$$\overline{E_2} = yE_{21} + (1-y)E_{22}. \tag{11}$$

The dynamic replication equation of the power battery manufacturer's strategy selection is as follows:

$$F(y) = \frac{dy}{dt} = y\left(E_{21} - \overline{E_2}\right) = y(1-y)\left[(M_k x + F_k)z + C_k x - C_{kp}\right]. \tag{12}$$

The first derivative of y can be obtained by the following:

$$\frac{d(F(y))}{dx} = (1-2y)\left[(M_k x + F_k)z + C_k x - C_{kp}\right], \tag{13}$$

making

$$J(z) = (M_k x + F_k)z + C_k x - C_{kp}. \tag{14}$$

According to the stability theorem of ordinary differential equations, the probability of the third-party recycling enterprises choosing cooperation in a stable state must meet $F(y) = 0$ and $\frac{d(F(y))}{dy} < 0$. $\frac{\partial J(z)}{\partial x} = E_{zk} z + E_{k2} > 0$, so $J(z)$ is a monotonically increasing function with respect to x. When $z = z^* = \frac{C_{kp} - C_k x}{F_k + x M_k}$, $J(z) = 0$, $\frac{d(F(y))}{dy} \equiv 0$, it is unable to determine the stabilization strategy; when $z < z^*$, $J(z) < 0$, $\frac{d(F(y))}{dy}|_{y=0} < 0$, $y = 0$ is ESS, and when $z > z^*$, $J(z) > 0$, $\frac{d(F(y))}{dy}|_{y=1} < 0$, $y = 1$ is ESS.

As shown in Figure 4, V_1 represents that recycling enterprises are unwilling to cooperate with power battery manufacturer, and the probability of cooperation can be expressed as V_2, calculate the volumes of V_1 and V_2 as follows:

$$V_1 = \int_0^1 \int_0^1 \frac{C_{kp} - E_{kp} x}{F_k + x M_k} dx dz = -\frac{E_{kp}}{M_k} + \left[\frac{C_{kp}}{M_k} + \frac{E_{kp} F_k}{M_k^2}\right] \ln\left(1 + \frac{M_k}{C_{kp}}\right), \tag{15}$$

$$V_2 = 1 + \frac{E_{kp}}{M_k} - \left[\frac{C_{kp}}{M_k} + \frac{E_{kp} F_k}{M_k^2}\right] \ln\left(1 + \frac{M_k}{C_{kp}}\right). \tag{16}$$

Corollary 2: The probability of third-party recycling enterprises choosing cooperation V_2 is positively correlated with government rewards M_k, punishments F_k and increased benefits of cooperation E_{kp}, negatively correlated with the cost of seeking cooperation C_{kp}.

Proof 2: Calculate the first partial derivative of each influencing factor according to the formula. V_1. It is possible to obtain $\frac{\partial V_1}{\partial C_{kp}} < 0$, $\frac{\partial V_1}{\partial M_k} > 0$, $\frac{\partial V_1}{\partial E_{kp}} > 0$, $\frac{\partial V_1}{\partial F_k} > 0$. Therefore, an increase in M_k, E_{kp} and F_k or a decrease in C_{kp} will lead to a rise in the probability of third-party power battery recycling enterprises seeking cooperation.

Corollary 2 indicates that the government should play the role of bridge and build a cooperation platform between power battery manufacturers and third-party recycling enterprises through the guidance of the government. The government should increase the rewards M_k and punishments F_k for third-party recycling enterprises, that is, to reward the

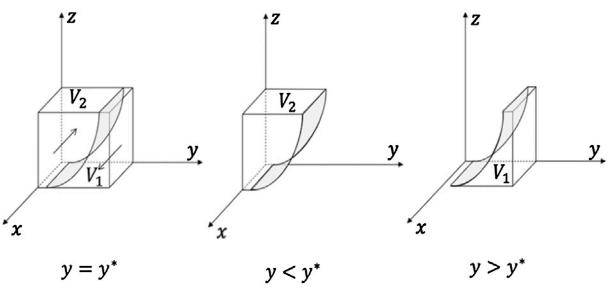

FIGURE 3
Phase diagram of power battery manufacturing enterprises strategy evolution.

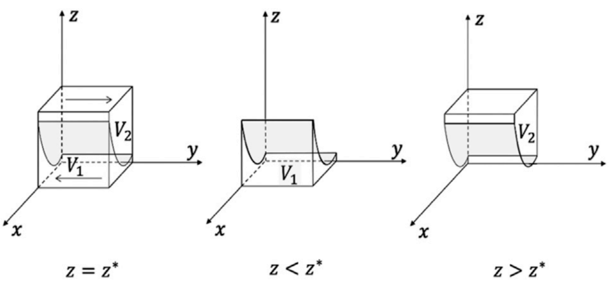

FIGURE 4
Phase diagram of recycling enterprises strategy evolution.

recycling enterprises that carry out recycling cooperation according to law and increase the punishments for the illegal behaviors of the recycling enterprises, so as to increase the willingness of third-party recycling enterprises to cooperate V_2. Power battery manufacturers should adopt the strategy of high price recycling to increase the cooperation income of recycling enterprises E_{kp}. The cost of recycling enterprises in seeking cooperation with manufacturing enterprise C_{kp} restricts their willingness to cooperate V_2.

Stability analysis of government

The mathematic expectation that power battery manufactures using recycled power batteries E_{31}, the mathematic expectation that power battery manufactures not using recycled power batteries E_{32}, and the average mathematic expectation $\overline{E_3}$ are as follows:

$$\begin{aligned}E_{31} &= xy\left(-C_g - M_p - M_k + A_g\right) + x(1-y)\left(F_k - D_g - C_g\right)\\ &+(1-x)y\left(F_p - D_g - C_g\right) + (1-x)(1-y)\left(F_p + F_k - D_g - C_g\right),\end{aligned} \tag{17}$$

$$E_{32} = xy\left(A_g\right) + x(1-y)\left(-D_g\right) + (1-x)y\left(-D_g\right) + (1-x)(1-y)\left(-D_g\right), \tag{18}$$

$$\overline{E_3} = zE_{31} + (1-z)E_{32}\,. \tag{19}$$

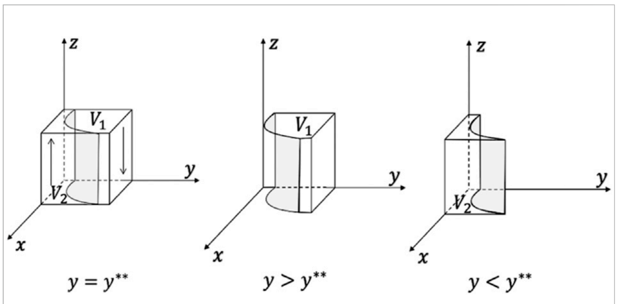

FIGURE 5
Phase diagram of government strategy evolution.

The dynamic replication equation of the power battery manufacturer's strategy selection is as follows:

$$\begin{aligned}F(z) = \frac{dz}{dt} = z\left(E_{11} - \overline{E_1}\right) = z(1-z),\\ \left\{\left[\left(D_g - M_k - M_p\right)x - F_k\right]y + F_p x + F_p - D_g + F_k - C_g\right\}.\end{aligned} \tag{20}$$

The first derivative of z can be obtained:

$$\frac{d(F(z))}{dz} = (1-2z)\left\{\left[\left(D_g - M_k - M_p\right)x - F_k\right]y + F_p x + F_p - D_g + F_k - C_g\right\}, \tag{21}$$

making

$$H(y) = \left[\left(D_g - M_k - M_p\right)x - F_k\right]y + F_p x + F_p - D_g + F_k - C_g\,. \tag{22}$$

According to the stability theorem of ordinary differential equations, the probability of strict government supervision in a stable state must meet $H(y) = 0$ and $\frac{d(F(z))}{dz} < 0$. $\frac{\partial H(y)}{\partial y} = (D_g - M_k - M_p)x - F_k < 0$, $H(y)$ is a monotonically decreasing function with respect to y, when $y = y^{**} = \frac{F_p + F_k - F_p x - C_g}{x(M_p + M_k) + F_k}$, $H(y) = 0$, $\frac{d(F(z))}{dz} \equiv 0$, unable to determine stabilization strategy; when $y < y^{**}$, $H(y) < 0$, $\frac{d(F(z))}{dz}|_{z=1} < 0$, $z = 1$ is ESS; when $y > y^{**}$, $H(y) > 0$, $\frac{d(F(y))}{dy}|_{z=0} < 0$, $z = 0$ is ESS.

As shown in Figure 5, V_2 represents the probability of government strengthening supervision, the probability of loose supervision can be expressed as V_1, and the volumes V_1、V_2 are calculated as follows:

$$\begin{aligned}V_2 = \int_0^1\int_0^q \frac{F_k + F_p - F_p x - C_g}{x\left(M_p + M_k\right) + F_k}dxdz = -\frac{F_p}{M_p + M_k}\\ +\left[\frac{F_k + F_p - C_g}{M_p + M_k} + \frac{F_K F_p}{\left(M_p + M_k\right)^2}\right]\ln\left(1 + \frac{M_p + M_K}{F_K}\right),\end{aligned} \tag{23}$$

$$V_1 = 1 + \frac{F_p}{M_p + M_k} - \left[\frac{F_k + F_p - C_g}{M_p + M_k} + \frac{F_K F_p}{\left(M_p + M_k\right)^2}\right]\ln\left(1 + \frac{M_p + M_K}{F_K}\right). \tag{24}$$

Corollary 3. The probability of the government's strict supervision V_2 is positively correlated with the amount of the

TABLE 2 Stability analysis of equilibrium points of the three-party evolutionary game system.

equilibrium	Eigenvalues of the Jacobian		Stability conclusion	Conditions
	$\lambda_1, \lambda_2, \lambda_3$	Symbol		
$E_1 = (0,0,0)$	$-C_{kp}, -C_r, F_k + F_p - C_g$	$(-,-,\times)$	Not sure	A
$E_2 = (1,0,0)$	$C_r, E_{kp} - C_{kp}, F_k - C_g$	$(+,+,-)$	Instability point	
$E_3 = (0,1,0)$	$C_{kp}, C_{ph} - C_r, F_p - C_g$	$(+,+,-)$	Instability point	
$E_4 = (0,0,1)$	$F_k - C_{kp}, F_p - C_r, C_g - F_k - F_p$	$(\times,\times,-)$	Not sure	B
$E_5 = (1,1,0)$	$C_r - C_{ph}, C_{kp} - E_{kp}, -C_g - M_p - M_k$	$(-,-,-)$	ESS	C
$E_6 = (1,0,1)$	$C_r - F_p, C_g - F_k, E_{kp} - C_{kp} + F_k + M_k$	$(\times,\times,+)$	Instability point	
$E_7 = (0,1,1)$	$C_{kp} - F_k, C_g - F_p, C_{ph} - C_r + F_p + M_p$	$(\times,\times,+)$	Instability point	
$E_8 = (1,1,1)$	$C_r - C_{ph} - F_p - M_p, C_{kp} - E_{kp} - F_k - M_k, C_g + M_p + M_k$	$(-,-,+)$	Instability point	

(A: $F_k + F_p < C_g$, B: $F_k < C_{kp}$, $F_p < C_r$, C: $C_r < C_{ph}$, $C_{kp} < E_{kp}$, $\times$ indicates symbol uncertainty).

TABLE 3 Parameter values for each stage in the evolutionary game model.

Parameters	C_{pl}	C_{ph}	E_p	C_r	F_p	M_p	C_k	E_k	E_{kp}	M_k	F_k	C_{kp}	C_g	A_g	D_g
Value	130	60	150	30	50	15	8	30	11	2	3	5	20	30	10

government's rewards M_p and punishments F_p for power battery manufacturers; it is positively correlated with the reward amount M_k and punishment amount F_k of third-party recycling enterprises; it is negatively correlated with government rewards for power battery manufacturers and third-party recycling enterprises $(M_p + M_k)$ and negatively correlated with government regulatory costs C_g.

Proof 3: Calculate the first partial derivative of each influencing factor according to the formula of V_1, $\frac{\partial V_1}{\partial (M_p+M_k)} < 0$, $\frac{\partial V_1}{\partial F_p} > 0$, $\frac{\partial V_1}{\partial C_g} < 0$, $\frac{\partial V_1}{\partial F_k} > 0$. An increase in F_k, F_p and $(M_p + M_k)$ or a decrease in C_g will increase the probability that a power battery manufacturer will seek to use recycled batteries.

Corollary 3 shows that the greater the punishment degree of the government to manufacturer F_p and recycling enterprises F_k, the more conducive to government supervision. The greater the reward degree of the government to the production enterprises M_p and the greater the reward degree of the recycling enterprises M_k, the more unfavorable the implementation of government supervision. The government needs to strictly control the cost of supervision C_g, which is not conducive to the implementation of government supervision.

Stability analysis of ESS

According to Lyapunov's first rule: all eigenvalues of the Jacobian matrix have negative real parts, then the equilibrium point is asymptotically stable. If at least one of the eigenvalues of the Jacobian matrix has a positive real part, the equilibrium point is not stable. Make $F(x) = 0$, $F(y) = 0$, $F(z) = 0$, the equilibrium point of the system can be obtained: $E_1 = (0,0,0)$, $E_2 = (1,0,0)$, $E_3 = (0,1,0)$, $E_4 = (0,0,1)$, $E_5 = (1,1,0)$, $E_6 = (1,0,1)$, $E_7 = (0,1,1)$, $E_8 = (1,1,1)$. The stability analysis of the Jacobian matrix and equilibrium point of the three-party evolutionary game system (Table 2) is shown as follows:

$$J = \begin{bmatrix} J_1 & J_2 & J_3 \\ J_4 & J_5 & J_6 \\ J_7 & J_8 & J_9 \end{bmatrix} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix},$$
$$= \begin{bmatrix} (1-2x)\left[(M_p y + F_p)z + C_{ph} y - C_r\right], & x(1-x)(M_p z + C_{ph}), & x(1-x)(M_p y + F_p), \\ y(1-y)(M_k z + E_{kp}), & (1-2y)\left[(M_k x + F_k)z + C_k x - C_{kp}\right], & y(1-y)(M_k x + F_k), \\ z(1-z)\left[(D_g - M_k - M_p)y + F_p\right], & z(1-z)\left[(D_g - M_k - M_p)x - F_k\right], & \begin{matrix}(1-2z)\{\left[(D_g - M_k - M_p)x - F_k\right]y \\ + F_p x + F_p - D_g + F_k - C_g\},\end{matrix} \end{bmatrix} \tag{25}$$

Corollary 4: When $C_r < C_{ph}$ and $F_{p'} C_{kp} < E_{kp}$ and $F_{k'}$ $(F_k + F_p) > C_g$, there is only one ESS in the system: $E_5 = (1,1,0)$; when $F_k < C_{kp'} F_p < C_{r'} (F_k + F_p) < C_g$, there are three ESS in the system: $E_1 = (0,0,0)$, $E_4 = (0,0,1)$ and $E_5 = (1,1,0)$.

Corollary 4 shows that when the following conditions are met, the evolution of the strategy combination is stable at E_5 (using recycled power battery, cooperation, loose supervision): (1) the cost reduced by the manufacturer when using recycled power battery C_{ph} is greater than the cost of the power battery manufacturer seeking joint renting C_r; (2) the punishment

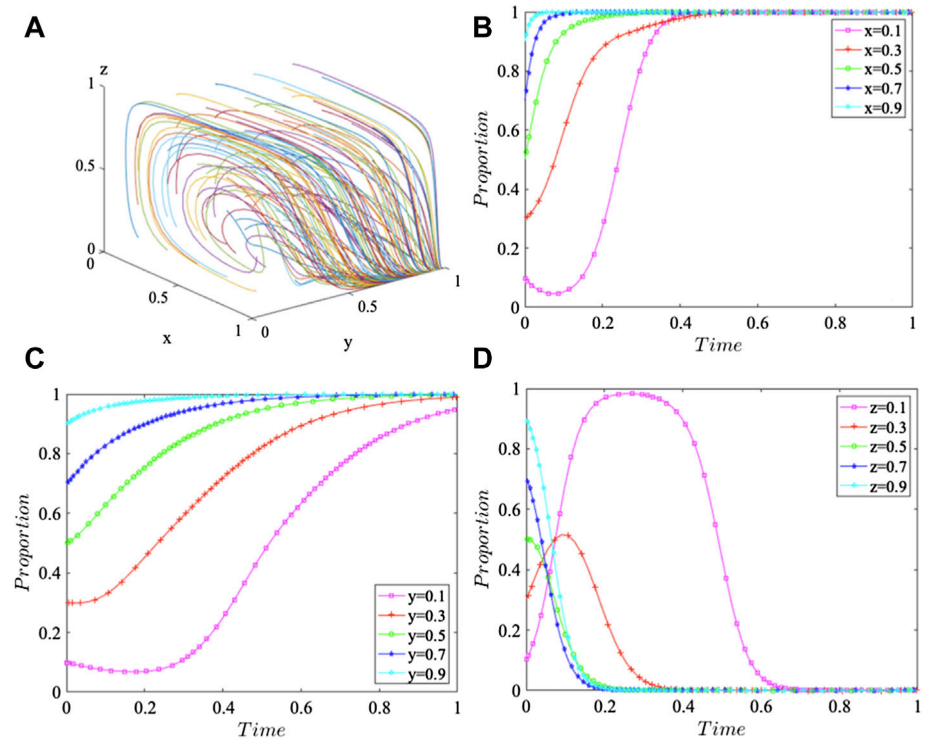

FIGURE 6
Results of three parties with different initial selection probabilities. **(A)** Results of ESS with different initial selection probabilities, **(B)** evolutionary game results of power battery manufacturers under different initial selection probabilities, **(C)** evolutionary game results of recycling enterprise under different initial selection probabilities, **(D)** evolutionary game results of government under different initial selection probabilities.

imposed by the government on the manufacturer F_p is greater than the cost of the power battery manufacturer seeking joint renting C_r; (3) when the third-party recycling enterprises cooperate with power battery manufacturers, the increase of enterprise income E_{kp} is greater than the cost of third-party recycling enterprises seeking external cooperation C_{kp}; (4) when the third-party recovery agencies do not cooperate, the government's punishments F_k is greater than the cost of the third-party recovery agencies seeking cooperation C_{kp}; (5) the sum of fines imposed by the government on power battery manufacturers and third-party recycling enterprises $F_k + F_p$ is greater than the cost of government supervision C_g.

Simulation analysis

In order to intuitively observe the dynamic evolution of the behavior of the three stakeholders in the power battery recycling model and verify the validity of the aforementioned analysis, the model parameters were assigned and simulated based on Corollary 4. The parameters are assigned according to Lander et al. (2021) and the actual situation. Table 3 illustrates the initial game values of the three stakeholders.

Each parameter value in Table 2 satisfies the stability conditions, and 50 groups of different initial strategy points of x, y and z are randomly generated to verify that the equilibrium point $E_5 = (1, 1, 0)$ is the stable equilibrium point in the dynamic system. The different colored lines in Figure 6A show the evolutionary process of the three-way evolutionary game. They finally converge to E_5. The results of the evolutionary game show that no matter what the initial strategies of each party are, when the constraint conditions of Inference four are satisfied, $E_5 = (1, 1, 0)$ is the ESS of the system, which effectively validates the analysis results mentioned before. Regardless of whether the government strictly regulates or not, power battery manufacturers and recycling enterprises will cooperate on power battery recycling as the supply and demand contradiction of critical metals continues to intensify.

Compared with the evolution process of power battery manufacturers and third-party recycling enterprises, it takes a long time for third-party recycling enterprises to reach E_5 with the same initial probability selection. For both production

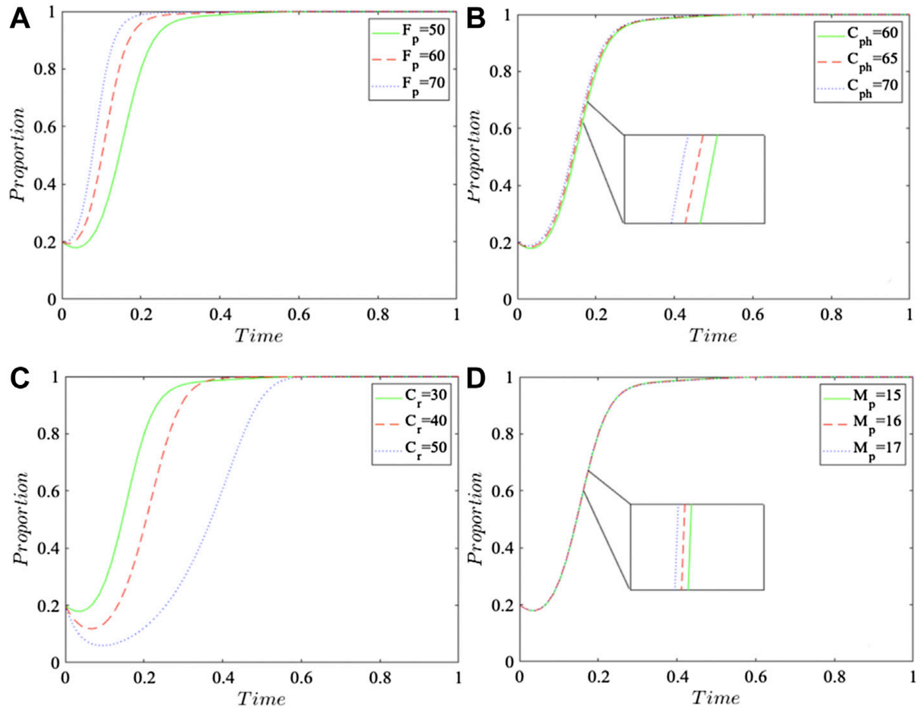

FIGURE 7
Influence of changing parameters on power battery manufacturers. **(A)** Impact of changes in the amount of punishment, **(B)** impact of changes in profits from using power batteries, **(C)** impact of changes in collaboration costs, **(D)** impact of changes in the amount of reward.

enterprises and recycling enterprises, the increase in initial selection probability will speed up the process to reach E_5 (Figures 6B,C). For the government, it can be observed that when the probability of choosing strict supervision is 0.1 and 0.3, the initial evolution direction changes toward strict supervision and then becomes loose supervision. After the initial probability exceeds 0.3, the evolution direction continues to evolve in the direction of loose supervision (Figure 6D).

To analyze the cost saved by enterprises, the government's rewards and punishments for enterprises, and the impact of cooperation cost changes on power battery manufacturers, assign 50, 60, and 70 to F_p; assign 60, 65, and 70 to C_{ph}; assign 30, 40 and 50 to C_r; assign 15, 16 and 17 to M_p, observation of the replication dynamics equations of production firms evolving 50 times over time under the same initial selection probability.

With the amount of government reward M_p, the punishment F_p and the use of recycled power batteries to reduce costs for enterprises C_{ph}, the process for the evolutionary game to reach E_5 becomes faster (Figures 7A,B,D), which indicates that power battery manufacturers are more willing to use recycled power batteries. The change in power battery use intention F_p has a stronger effect on the change. The increase in cooperation cost of power battery manufacturers C_r has a restraining effect on the willingness to use power battery, which is shown as with the increase in cooperation cost C_r, the process for the probability curve to reach E_5 becomes slower and presents a trend of continuous expansion (Figure 7C). This indicates that the inhibiting effect of increasing the cost of cooperation C_r on producers' willingness to use recycled power batteries is more pronounced than the promoting effect of increasing the fine F_p on producers' willingness to use recycled power batteries. Therefore, higher cooperation costs C_r are the main obstacle to the cooperation between production enterprises and recycling enterprises.

To analyze the increased sales revenue after cooperation, the government's rewards and punishments, and seek the impact of changes in cooperation costs on recycling enterprises, assign 5, 6, and seven to C_{kp}; assign 2, 4, and six to M_k; assign 11, 12, 13 to E_{kp}; assign 3, four and five to F_k, observation of the replication dynamic equations of the recycling enterprises evolving 50 times over time under the same initial selection probability.

When the government reward amount M_k, punishment amount F_k and increased revenue from cooperation E_{kp} increase, the process for the probability curve to reach E_5 becomes faster (Figures 8B–D). This means that it takes less time for third-party recycling enterprises to make cooperative decisions. By comparison, it is found that the curve in Figure 8A is more affected by variable changes, indicating that the third-party recycling enterprises pay more attention to the increased income after cooperation E_{kp} when making decisions. As the cost

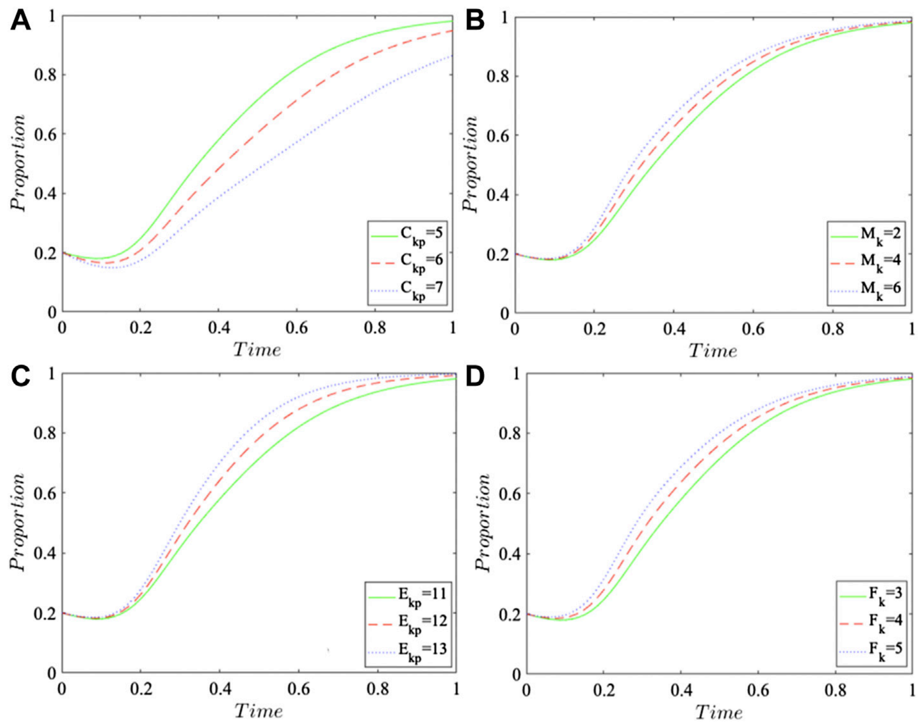

FIGURE 8
Influence of changing parameters on third-party recycling enterprises. **(A)** Impact of changes in collaboration costs, **(B)** impact of changes in the amount of reward, **(C)** impact of changes in profits in increase profits, **(D)** impact of changes in the amount of punishment.

of seeking cooperation C_{kp} increases, the willingness of third-party recycling enterprises to cooperate decreases. Like the graphs of power battery manufacturers, the increase in cooperation cost C_{kp} has a greater impact on the willingness of third-party recycling enterprises to cooperate relatively to the change in other parameters.

To analyze the effects of increasing government regulatory cost C_g, government rewards M_p and punishments F_p for power battery manufacturers, and government rewards M_k and punishments F_k for recycling enterprises on government selection strategies, assign 20, 25 and 30 to C_g; assign 2, four and six to M_k; assign 15, 25 and 35 to M_p; assign 3, six and nine to F_k; assign 50, 60 and 70 to F_p. observation of the replication dynamic equations of the government evolving 50 times over time under the same initial selection probability.

With the increase in M_p, F_p, M_k, and F_k, the probability curve can evolve to E_5 faster and is more obvious in the middle of the game than in the early and late stages (Figures 9B–E). The government's willingness to strictly regulate acts as a disincentive. Especially as government decisions evolve toward lighter supervision, the increase of M_p, F_p, M_k and F_k have an increasingly pronounced effect on the impetus for lenient government supervision. When the government's regulatory cost C_g increases, it has a dampening effect on the government's decision regardless of whether the government's regulatory intention is strict or loose, and the probability curve takes significantly longer to reach E_5. This indicates that changes in government regulatory cost C_g have a greater impact on the government's evolutionary game (Figure 9A).

The aforementioned simulation results show that, under the assignment conditions of Table 2, the system only has one combination of evolutionarily stable strategies (use recycled power battery, cooperation, loose supervision), which is consistent with the conclusion of inference 4. The simulation results are consistent with the analysis results, which have certain practical guiding significance for the development of the critical metal recycling market.

Conclusion and policy recommendations

With the rapid growth of the demand for EVs critical metals and the continuous contradiction between the supply and demand of critical metals, the efficient recycling of power batteries plays an increasingly prominent role in alleviating the tight supply of critical metals and protecting the environment. As stakeholders, the production manufacturers,

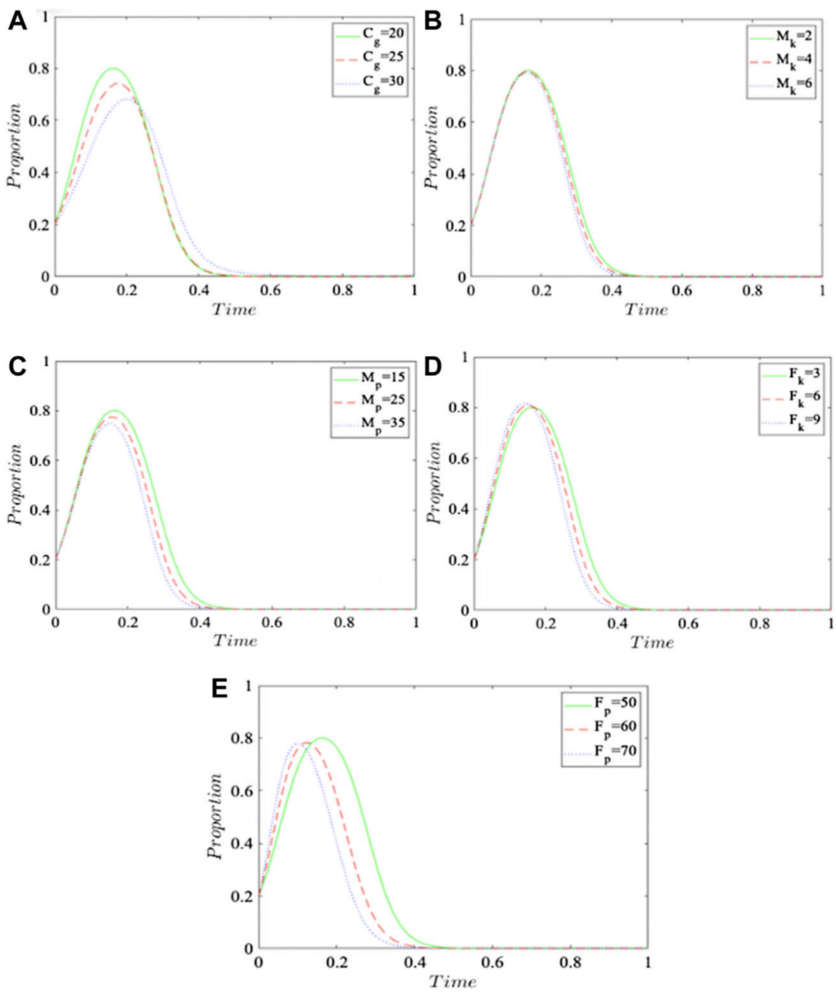

FIGURE 9
Influence of changing parameters on the government. **(A)** Impact of changes in monitoring costs, **(B)** impact of changes in rewards for recycling enterprises, **(C)** impact of changes in rewards for power battery manufacturers, **(D)** impact of changes in punishments for recycling enterprises, **(E)** impact of changes in punishments for power battery manufacturers.

recycling enterprises and the government have a great impact on this process. Therefore, this study considers the impact of recycling cooperation between power battery manufacturers and recycling enterprises under government supervision on the contradiction between the supply and demand of critical metals used in power battery production, and constructs a three-party evolutionary game model between them. The stability of each strategy choice, the system stability, and the influence of each factor on the main body of the game are analyzed. The effectiveness of the results is verified by simulation. The main conclusions and policy recommendations are included as follows:

(1) The initial probability of selection strategy does not change the decision only affects the process of E_5. When the probability of strict supervision is low at the beginning, the government will prefer to change from strict supervision to loose supervision. When the probability of strict supervision is high at the beginning, the willingness for strict supervision will gradually decrease with the increase in the number of games and finally stabilize to loose supervision. Regardless of the initial selection probability, the choice intention of the manufacturer and the recycling institution can evolve toward E_5. Power battery manufacturers are more affected by a tight supply of critical metals than third-party recyclers. Regardless of whether a power battery manufacturer's initial willingness to use recycled batteries is strong, their strategy has evolved to E_5 faster than third-party recycling enterprises. The government should pay more attention to the willingness

of third-party recycling enterprises to cooperate with power battery manufacturers and crack down on their illegal distribution channels, which could improve the supply shortage of critical metals.

(2) The effective way to promote cooperation between power battery manufacturers and recycling enterprises is to ensure an increase in both sides' income after cooperation. In the case of a shortage of critical metals in the power battery production process, power battery manufacturers must increase the use of recycled power battery to reduce the consumption of primary resources to reduce the manufacturing cost of power battery. For production enterprises, it is better to suggest that the government strengthen market supervision rather than spending much on negotiating with third-party recycling enterprises. Recycling enterprises need to appropriately increase recycling efforts and technical input according to their own economic conditions. With the expansion of the recycling scale and the increase in government subsidies, recycling enterprises need to choose appropriate development strategies according to their own conditions. Continuing to increase cooperation is a good development direction for recycling enterprises to increase profits while maintaining the same cost.

(3) Government rewards and punishments are conducive both to promote cooperation between power battery manufacturers and recycling enterprises and to encourage the recovery and utilization of critical metals. The cost of cooperation between both parties will be the key factor affecting the recovery of power battery. The government should pay close attention to the trend of the recycling market, increase the communication between manufacturers and recycling enterprises, and do a good job of publicizing policies to reduce the cost of cooperation so that both sides can gain certain benefits under the cooperation mode. The government needs to pay attention to the cost changes of market supervision and adjust the rewards and punishments mechanism according to the constant changes in the market. Static rewards and punishments mechanism will lead to rigid behavior patterns of participants in power battery recycling. Dynamic rewards and punishments will make power battery manufacturers more actively participate in recycling. Government rewards for power battery manufacturing enterprises cannot be too high, and the optimal battery recycling rate may be reduced by increased government rewards. In both model analysis and simulation analysis, government subsidies for power battery recycling enterprises and third-party recycling enterprises play a positive role in the decision-making of both parties. Relevant studies also show that government subsidies for manufacturers and third-party recycling enterprises promote the closed-loop development of the supply chain of EVs. The intensity of subsidies is the issue that the government needs to focus on when making policies. In the setting of the punishment amount, the punishments for noncooperation of third-party testing enterprises should be higher than that of power battery manufacturers.

Future work

This study only considers the game behavior among the three players of power battery recycling under the premise of bounded rationality and does not consider the influence of consumer behavior and other parameter changes on power battery production. Therefore, expanding the system boundary, combining system dynamics with game theory to draw more quantitative conclusions, and introducing consumers as game subjects will be our next research direction.

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

Conceptualization, SG and GL; methodology, SG and YW; software, SG; validation, SG and GL, and XG; formal analysis, SG; investigation, SG and GL; resources, SG; data curation, SG; writing—original draft preparation, SG; writing—review and editing, SG, GL, and XG; visualization, SG and YW; supervision, GL and XG; project administration, GL; funding acquisition, GL. All authors have read and agreed to the published version of the manuscript.

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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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