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An Evolutionary Game Research on Cooperation Mode of the NEV Power Battery Recycling and Gradient Utilization Alliance in the Context of China's NEV Power Battery Retired Tide

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Abstract: Recycling and gradient utilization (GU) of new energy vehicle (NEV) power batteries plays a significant role in promoting the sustainable development of the economy, society and environment in the context of China's NEV power battery retirement tide. In this paper, the battery recycling subjects and GU subjects were regarded as members in an alliance, and an evolutionary game model of competition and cooperation between the two types of subjects was established. Evolution conditions and paths of the stable cooperation modes between these two were explored. Suggestions were proposed to avoid entering a state of deadlock and promote the alliance to achieve the "win-win" cooperation mode of effective resource recovery and environmental sustainability. The results revealed four types of certain situations, two types of uncertain situations, and one type of deadlock situation for the evolution of alliance cooperation. The factors of the market environment are evident in not only changing the evolution paths and steady-states of the alliance but also in breaking the evolution deadlock. However, the sensitivity of the members in the alliance to different types of parameters varies greatly. It is difficult for the government to guide the formation of an ideal steady-state of cooperation or break the deadlock of evolution by a single strategy, such as subsidies or supervision. The combination of subsidy-and-supervision or phased regulation should be adopted. Only increasing subsidies is likely to weaken the function of the market and have a counterproductive effect.

Keywords: NEV battery recycling; gradient utilization; cooperation mode; evolutionary game

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1. Intruction

With the intensification of global warming and the decline in petroleum resources, the promotion and diffusion of new energy vehicles (NEVs) continue to be an important way for China to coordinate efforts to cope with the pressure of energy security, ecological and environmental protection, and climate change [1,2]. Since 2014, China has entered the rapid promotion period of NEVs. China has ranked first in the world in the production, sales, and ownership of NEVs for five consecutive years. According to the average life of vehicle batteries of 5–8 years, China will experience the first wave of NEV battery retirement after 2020 [3]. According to statistics, retired NEV batteries reached 230,000 tons (24.6 GWh) in 2020, and it is expected to be 800,000 tons by 2025, with an economic scale of over 35.4 billion yuan [4]. Such a large number of retired batteries, if not effectively recycled and reused, is not only a significant waste of resources, but the battery's toxic electrolyte and heavy metals will cause massive pollution to the environment [5,6].

At present, gradient utilization (GU) is an effective means to extend the life cycle of NEV batteries and recognize their value fully [7,8]. GU refers to the retesting, screening, repairing, pairing, and reuse of power batteries that have been retired from NEV (their performance is reduced to less than 80% of initial performance) under relatively mild conditions [9]. Batteries after GU can be disassembled, and they can be recycled (typically when the remaining capacity is less than 30%) to recover cobalt, lithium, and other precious metals to achieve the "win-win" of resource recovery and environmental protection.

The considerable market increment constantly attracts an accelerated layout of capital. NEV battery recycling and GU have become a direction on which the upstream and downstream automobile industry chains have focused [10,11]. According to statistics, at the beginning of 2020, there were more than 9500 battery recycling sites that completed information registration and filing in China [12]. There are many battery recycling and GU cooperation alliances among NEV manufacturers and gradient utilization enterprises (GUEs). With the guidance and support of the Ministry of Industry and Information Technology of China, China Association of Automobile Manufacturers, and China Electric Vehicle Power Battery Industry Innovation Alliance, a series of pilot projects appeared in the fields of "peaking and valley filling" electric energy storage, the standby power supply of communication base stations, low-speed electric vehicles, and other scenarios.

Since 2018, the Chinese government has launched a series of policies to guide the NEV power battery recycling and utilization to guarantee and regulate the development of the industry. Based on the extended producer responsibility (EPR) system, NEV manufacturers should undertake the primary responsibilities for retired battery recycling [13] requiring enterprises such as NEV manufacturers and GUEs to establish recycling service sites by self-construction, co-construction, or authorization [14]. For recycled batteries, it is encouraged to use them for GU first, followed by regenerated utilization through leasing or selling [15,16]. Local governments also actively issued support policies, such as capital subsidies, tax exemptions and exemptions, support platforms, and strengthen supervision, to help the industry maximize economic benefits [17].

Although China's NEV battery recycling and GU industry has received both policy and market support, there are still many difficulties in its development [18]. For example, the standards of the first batch of retired batteries are not unified. The costs of dis-assembly and utilization are high [19]. The evaluation system for decommissioned batteries is not perfect [20]. The key technologies of GU require further breakthroughs [21,22]. Furthermore, there is no mature cooperation mode for NEV manufacturers and GUEs in terms of recycling system construction and GU product rental and sale strategies.

The cooperation mode originates from the strategic choice of the enterprises and determines the economic value of the industry. Under the standard of the current EPR system and relevant management regulations, what are the stable cooperation modes between the recycling subjects and GU subjects? How can the alliance-formed stable "win-win" cooperation model, which contributes to industry development be promoted? To answer these questions, we combine the recycling and GU bodies in a NEV Power battery recycling and GU alliance, and the competition and cooperation game models of alliance are constructed by using evolutionary game theory, the evolutionary stability analysis and numerical simulation are used to discuss the evolutionary conditions and guiding strategies for the formation of ideal steady-state alliance.

According to "For the Continuation of Resources: 2030 New Energy Vehicle Battery Cycle Economy Potential Research Report", which is issued by the international environmental organization Greenpeace and the All-China Environment Federation on the 29 October 2020, more than 2.1 TWh power batteries will be sold globally by 2030. Based on the decommissioning condition of 20% power loss during 5–8 years of service, the total amount of decommissioned power batteries for passenger electric vehicles worldwide will reach 12.85 million tons in 2021–2030 and the market scale of recycle and reuse will exceed 100 billion Yuan [4]. Therefore, the retirement wave of NEV batteries is not only happening in China but is a global phenomenon. Decommissioned power batteries will be either rich energy carriers or heavy environmental burdens depending on how we deal with them.

The European Union, the United States, Japan, and other countries started earlier in the recycling of lead-acid batteries and lithium batteries, and the established recycling system has achieved good results [13]. Therefore, NEV battery recycling and reuse in these countries and regions basically follow their previous experience and the supporting policy system is relatively perfect. Among them, the European Union and the United States have mainly set up battery recycling channels through industry associations or industry alliances, and realize battery registration and compulsory restitution through a deposit system. In Japan, battery manufacturers mainly build recycling channels through reverse logistics and the government provides subsidies [23].

All countries attach great importance to mitigating environmental problems and obtaining extended benefits through traceability and GU of batteries. However, as the battery decommissioning tide is just approaching, demonstration projects and commercial projects of NEV battery GU in many countries have just started and some leading enterprises are gradually starting to form cooperative alliances. Nissan has partnered with Sumitomo to develop home and commercial energy storage projects through battery recycling and GU. In Germany, Bosch and BMW are cooperating to carry out a project of a photovoltaic power station energy storage system. Tesla and the National Renewable Energy Laboratory (NREL) are also working on an energy storage business such as grid-level energy storage applications, home energy storage walls, and solar energy storage [24,25]. Although there are differences in the construction of NEV battery recycling channels in different countries, the emphasis on the GU of NEV batteries is extremely consistent. Therefore, the research and exploration of the cooperation mode between NEV manufacturers and GUEs in this paper can provide both theoretical bases for the establishment and stability of China's GU alliance of NEV batteries and useful references for the management practice of GU alliances in other countries.

The contribution of this study is to reveal four types of certain modes, two types of uncertain modes, and one type of deadlock mode for the evolution of alliance cooperation, and the evolution conditions and intervention strategies of each mode is proposed. It can provide a strategic reference for China's power battery recycling and GU alliance to form a stable "win-win" cooperation mode, and avoid falling into a deadlock of evolution. It can also provide a basis for the government to guide and supervise the development of battery recycling and utilization industry in a timely and effective manner.

The rest of the paper is structured as follows: Section 2 reviews the relevant literature and identifies the research gap with emphasis. Section 3 constructs an evolutionary game model including assumptions and a payment matrix. The evolutionary stable strategies and conditions are analyzed in Section 4. Section 5 presents the numerical experimental simulation of evolutionary processes and the function of related parameters to stabilize evolution or break deadlock. Final conclusions and Management Implications of this study are given in Section 6. The establishment and analysis of the replicated dynamic equations are given in Appendix A.

2. Literature Review

2.1. Environmental and Economic Benefits of NEV Power Battery Recycling and Utilization

NEV power batteries contain a large number of toxic substances that, if not properly handled, will cause serious harm to the ecological environment and human health [5,26,27]. Battery recycling involves primarily physical disassembly, dry and wet recovery, biological recovery, and other technologies to recover precious metals and degrade harmful substances in batteries [28–30]. However, there is an urgent need for more efficient recycling and treatment processes to improve the environment and the economic viability of recycling [31].

Some scholars proposed that although the recycling and reuse of NEV power batteries have significantly promoted environmental benefits, the economic benefits must be verified [32]. For example, Gu et al. analyzed the economic benefits of power battery recycling and reuse by establishing the pricing and decision-making model of a closed-loop supply chain. They demonstrated that battery recycling can reduce the consumption of new battery raw materials and reduce environmental impact, but it may not gain economic benefits [33]. Hao Han et al. compared the energy consumption and greenhouse gas (GHG) emissions of the production of electric vehicles with and without recycling according to the predicted data of China's NEV recycling volume in 2025. The results revealed that recycling some materials, such as steel, aluminum, and battery cathode materials, could effectively reduce pollution emissions and have economic benefits [34].

Although the assessment of the lifecycle emissions of Lithium-Ion Batteries (LIB) manufacturing is complex, it is generally recognized that at least 30–50% of lifecycle GHG emissions from EVs are related to battery manufacturing and mineral extraction [35]. Raw materials account for up to 50% of the cost of a typical LIB. By substituting virgin materials with recycled materials, the total pack cost could be reduced by up to 30% [36]. It is an effective means to obtain economic benefits to prolong the life cycle of the used power battery of NEV and to make further reuse of non-violent scenes [37].

Studies have found that battery GU has certain commercial and environmental benefits and also social value. Moreover, battery cost, government subsidies, and electricity prices are three critical factors that affect the GU value of China's NEV battery [38]. The development of essential technologies, such as battery screening and performance evaluation, and the further enrichment of application scenarios of GU, are the main factors of environmental and economic benefits [39].

2.2. Strategy Optimization of NEV Power Battery Recycling and Utilization

Effectively designing the layout strategy and pricing strategy of NEV power battery recycling sites and the means of utilization after recycling are essential to achieving efficient battery recycling and utilization [40,41]. From the perspective of NEV manufacturers, Lei et al. proposed the optimal design scheme of NEV waste power battery recycling sites and found that transportation cost, carbon tax, and the number of batteries to be recycled are the three major factors affecting the layout of recycling sites [42]. Tang et al. studied the optimal channel selection and battery capacity allocation strategy of EV manufacturers for battery recycling and explored the influence of critical parameters on the equilibrium capacity allocation strategy and the manufacturer's profit through numerical experiments [43]. Hong et al. built a manufacturer-led closed-loop supply chain battery recycling game model, compared the profit and loss of manufacturer recycling, retailer recycling, and third-party enterprise recycling, and found that the retailer recycling method is the optimal economic benefit strategy [44]. Cheng et al. proposed an optimization scheme of battery GU strategy from the perspective of the value chain and discussed the application of battery capacities in different GU scenarios, which is an important basis for gradient pricing [45]. In addition to the further development of critical technologies such as sorting and testing, GU of NEV power batteries should introduce cutting-edge information technology and other means, such as establishing a battery life cycle information storage chain with a consensus mechanism. Such an approach is effective for improving data security and economy, reducing transaction costs and testing costs, and increasing the residual value of batteries [46].

2.3. The Impact of Policies on the Recycling and Utilization of NEV Power Batteries

The enthusiasm among most enterprises for power battery recycling is related to supervision, subsidies, and other incentive measures, and the intensity of government rewards and punishments affects the choice of cooperative partners of manufacturers [47,48]. Wang et al. considered the impact of battery recycling with and without mandatory policies, finding that manufacturers and OEMs were unable to develop a unified plan for battery recycling with the effects of non-mandatory policies [49]. Based on game theory, Shao et al. found that exogenous and endogenous government subsidy policies differ significantly in their influence on the battery recycling strategies of EV manufacturers—environmental awareness by consumers is essential [2]. Gu et al. studied the optimal production decision of NEV manufacturers for government-subsidized battery recycling, revealing that for a small market, manufacturers may prefer a relatively small battery recovery rate. Moreover, battery recycling can offset the adverse effects of loss aversion on the optimal output and expected utility, with a positive impact on the output of NEV manufacturers [1]. Alexandre et al. studied the opportunities and challenges of EV battery recycling and proposed that it is necessary for the government to introduce research and development funds and establish pilot projects and some market-pull measures [6]. Jiang et al. studied the influence of government subsidies on the independent R&D and technology introduction strategy of NEV enterprises, demonstrating the positive effects of subsidy intensity and the success rate of the R&D and innovation environment on the independent R&D strategies of NEV enterprises [50].

According to existing studies, the recycling and utilization of NEV power batteries can extend the battery life cycle, weaken the negative externalities of the environment, and effectively alleviate the pressure on China's energy and environmental protection, which has significant social importance. However, there are still some problems with industrial development, such as core technology breakthroughs and refining and improving the policy system. Furthermore, retired batteries have not yet reached scale, leading to unclear economic benefits in the industry.

Most scholars focus on the optimization strategy of NEV power battery recycling, such as supply chain pricing and profit maximization. They also study how to effectively recycle power batteries from the perspective of NEV manufacturers and battery manufacturers based on the EPR system and how to regulate and subsidize to improve the recovery rate and recovery efficiency from the perspective of the government. The battery recycling subjects and the GU subjects have not been included in a research model, and the competition and cooperation relationship between these two strategies has not been discussed. Moreover, the vital role of the GU subjects in regulating the recycling channel, battery traceability, and secondary recycling of echelon products have not been fully considered.

In October 2020, China issued the New Energy Vehicle Power Battery Gradient Utilization Management Measures (draft), which encourages upstream and downstream enterprises to build cooperative ecological systems to build battery-recycling sites and GUEs to actively adopt business strategies, such as leasing batteries, large-scale utilization, and others to facilitate subsequent recycling [16]. The GUEs should also be included in the battery-recycling channel and undertake the extended responsibility of the producer of power battery recycling and the secondary recycling responsibility of the echelon products.

Therefore, under the guidance of relevant management policies in China, this paper focuses on power battery recycling and GU industry and constructs a game model of competition and cooperation between NEV enterprises and GUEs. Evolutionary game theory is used to explore the Pareto equilibrium for maximizing the benefits of these agents, and a stable cooperation mode of "win-win" was sought for the alliance of power battery recycling and GU. The results are expected to promote the rapid and sustainable development of the NEV power battery recycle and GU industry and also offer references for China's NEV industrial management policies.

3. Evolutionary Game Model

3.1. Problem Description and Basic Assumptions

According to Interim Administration Measures of Recycling and Utilization of New Energy Vehicle Power Battery and Guide to the Construction and Operation of New Energy Vehicle Power Battery Recycling Service Sites, NEV manufacturers enterprises shall bear the main-body responsibility of power battery recycling, and GUEs shall bear the main-body responsibility of power battery GU, GU products tracking and regulation [13,15]. Consequently, in this paper, the two types of subjects are regarded as an alliance of power battery recycling and GU to build a dynamic game model. According to the recommendations of management measures, NEV manufacturing enterprises have two strategies for building recycling service sites: self-constructing and co-constructing with the leadership. Strategy selection is dominated by NEV manufacturers.

In this paper, firms that producing GU products are referred as the GUEs. There are two strategies for GUEs. One is to obtain ownership of the battery. In this situation, GUEs purchase the battery from NEV manufacturers and obtain GU revenue, then recycle the batteries and sell them to other companies after GU. The other is to obtain the right to use the battery by leasing, avoiding battery flush into illegal channels more effectively. In this situation, GUEs sign lease agreements with the NEV manufacturers and pay lease fees only. After the lease expires, the battery will be returned to the NEV manufacturer (usually to the recycling service site). The NEV manufacturer will then sell these batteries to other comprehensive utilization enterprises for regeneration.

The Chinese government and local governments have launched a series of subsidies and regulatory policies to promote China's NEV power battery recycling and GU. For example, the Shenzhen Municipal Government proposed to provide 50% of the power battery recycling subsidies to enterprises that have the provision funds for battery recycling and reuse. The Shanghai Municipality Government promulgated the Interim Measures of Shanghai to Encourage the Purchase and Use of NEV, which provides NEV manufacturers with a subsidy of 1000 Yuan for each set of NEV power batteries recycled. The Tianjin Government proposes to build and improve the regional battery traceability information system based on the national traceability comprehensive management platform for NEV monitoring and power battery recycling [51]. Subsidies and supervision are conducive to lowering the threshold of power battery recycling and GU and forming adequate support for the alliance quickly. However, an approach for guiding the overall development of industry alliances and the final cooperation mode by various subsidies and supervisions remains to be further discussed.

Based on the description above, this paper proposes the following hypotheses.

Hypothesis 1. *In this paper, it is assumed that the NEV manufacturer group and the GUE group form a cooperative alliance, members of which conform to the bounded rationality hypothesis. Individuals in these two groups are interested in cooperating but have not yet found stable cooperation modes. In the process of the game, one member of each group is randomly selected from the two groups repeatedly to conduct the game in order to find the stable cooperation mode of the alliance. Individuals of the two groups will learn and try to maximize their own interests during the evolutionary process of the alliance. When the alliance has evolved to the evolutionarily stable strategy, the two sides in the alliance find the stable cooperation mode.*

Hypothesis 2. *According to the rules of EPR, NEV manufacturers should take primary responsibility for battery recycling. Therefore, NEV manufacturers have a say in the process of establishing recycling service sites. Accordingly, we assume that NEV manufacturers have two strategies to choose from: one is "self-constructing battery recycling sites and the other is "co-constructing battery recycle sites". In case of self-construction, NEV manufacturers bear all construction and operation costs; for co-construction, the alliance shares the construction and operation costs as partners—the NEV manufacturers offer a discount on the price and rent of the batteries to the GUEs. In the process of building recycling service sites, because the NEV manufacturer must take the primary responsibility, its share of construction and operation costs is larger than that of other co-builders.*

Hypothesis 3. *Because the first batch of retired NEV batteries in China's current market does not have a unified standard, their performance is not stable; there are considerable security risks and difficulties in the testing and evaluation of GU batteries. According to the development status of China's NEV battery GU demonstration projects, GUEs have control over how they obtain the batteries. There are two types of strategies to choose from for the GUEs: one is "purchase retired batteries", and the other is "lease retired batteries". When the GUEs choose to purchase, they have the ownership of the batteries, unlike when they choose to lease.*

Hypothesis 4. *According to the strategies of the two types of subjects, there are four modes of cooperation in the alliance: (1) "co-constructing" and "leasing", (2) "co-constructing" and* *"purchasing", (3) "self-constructing" and "leasing", and (4) "self-constructing" and "purchasing". The "co-constructing" and "leasing" mode avoids repeated investment, rationally optimizes the layout, saves social resources, promotes gradient battery supervision, facilitates secondary recycling, and forces GUEs to assume extended responsibilities. Therefore, we use the mode of "co-constructing" and "leasing" as an ideal state for guidance. The "co-constructing" strategy was regarded as the positive strategy of the NEV manufacturers, and the percentage of the groups choosing this strategy was x. The "self-constructing" strategy was regarded as the negative strategy, and the percentage of the groups choosing this strategy was* $1 - x$*. Similarly, the proportion of choosing the positive strategy (i.e., leasing batteries) and negative strategy (i.e., purchasing batteries) in the GUEs is y and* $1 - y$*.* $x,y \in [0,1]$*. Both sides seek a better strategy through trial-and-error until equilibrium is reached.*

3.2. Parameter Setting and Payment Matrix

According to the literature review and the development status of NEV battery GU alliance demonstration projects in China, the cooperation mode between NEV manufacturers and GUEs is mainly influenced by market factors such as battery recovery strategy, cost factors, and pricing strategies, in addition to regulatory factors such as government supervision and subsidy [5,41–43,48]. For NEV manufacturers, the cost factors mainly include costs of establishing battery recycling sites and operating costs such as battery testing. Their revenue mainly includes revenue from selling or leasing batteries to GUEs and revenue from reselling recycled GU batteries when they leased batteries to the GUEs instead of selling them [47]. In the case of GUEs, the costs mainly include the expenditure of purchasing or leasing batteries and the expenses incurred in co-constructing recycling sites, while the incomes mainly include the revenue generated by GU and the income from the resale of batteries after GU if they purchased the batteries instead of leasing them from NEV manufacturers. In addition, contractual factors such as cost sharing and deal discounts also have important influences on the cooperation mode [44]. On this basis, the government's regulatory policies on the GU of NEV batteries and the subsidies for constructing and operating of recycling sites also determine the direction of cooperation mode of the alliance [49]. Therefore, this paper focuses on building a model from the perspective of these parameters and discussing the influence of changing these parameters on the alliance cooperation mode.

According to the above analysis, the following variables are set in this paper to build the game model, as depicted in Table 1.

The business flow chart for the different strategies adopted by the players in the alliance is shown in Figures 1 and 2.

In the cooperation mode of "co-constructing" and "leasing", the NEV manufacturers will provide discounts in battery lease fees to the GUEs. The NEV manufacturers can obtain both the rental income and the revenue from selling to regenerated utilization enterprises after the batteries are returned, but they must pay the construction and operation costs of recycling sites according to the proportion of allocation and share part of the test cost when the batteries are returned from the GUEs. The GUEs can obtain the GU income of the leased batteries while paying the rent fee, sharing the co-construction and cooperation costs and test costs when returning the batteries.

In the cooperation mode of "co-constructing" and "purchasing", NEV manufacturers receive discounted battery sales and pay a share of the co-construction and cooperation costs of recycling sites. The GUEs obtain both the GU income and the revenue from selling batteries after GU to regenerated utilization enterprises and pay the battery purchase costs, apportioned co-construction and co-operation cost.

In the cooperation mode of "self-constructing" and "leasing", the NEV manufacturers can obtain both rental income and revenue from selling to regenerated utilization enterprises after the batteries are returned. However, they must pay for the construction and operation costs of recycling sites. The GUEs can obtain the GU income of the leased batteries while paying the rent fee, secondary recovery costs, and test costs.

In the cooperation mode of "self-constructing" and "purchasing", NEV manufacturers obtain battery sales and pay the construction and operation costs of recycling sites. The GUEs obtain both the GU income and the revenue from selling batteries after gradient use. They should also pay the battery purchase cost and secondary recovery costs. The constructed payment matrix is depicted in Table 2.

Table 1. Model symbol definitions.

Category	Symbol	Definition
Market parameters	π_0	Battery purchase costs that GUEs pay to NEV manufacturers when choosing the "purchasing" strategy.
	$\pi_0{}'$	Battery renting costs that GUEs pay to NEV manufacturers when choosing the "leasing" strategy.
	C_0	Construction costs incurred by NEV manufacturers when they choose the "self-constructing" strategy.
	C_1	Construction costs incurred by NEV manufacturers when they choose the "co-constructing" strategy.
	C_R	Operating costs of battery recycling sites (including costs of recycling, storage, transportation of batteries from consumers, etc.)
	$C_R{}'$	Operation and transportation costs of the secondary recycle of batteries after GU when NEV manufacturers choose "self-construction" strategy.
	C_t	Testing fee of batteries after GU in the mode of "leasing".
	π_1	Income that the GUEs can obtain from the gradient batteries when choosing the strategy of "purchasing".
	$\pi_1{}'$	Income that the GUEs can obtain from the gradient batteries when choosing the strategy of "leasing".
	α	The proportion of costs borne by the NEV manufacturers in the mode of "co-constructing".
	β	The proportion of costs borne by the GUEs in the mode of "co-constructing".
	θ	Preferential discounts that the GUEs can get in the mode of "co-constructing".
	M_0	Revenue generated when the NEV manufacturers resell the leased batteries regenerated utilization enterprises in the mode of "leasing".
	M_1	Revenue generated when the GUEs sell the batteries after GU to regenerated utilization enterprises in the mode of "purchasing".
Government parameters	λ	Government supervision of battery recycling and GU, such as standardizing the recycling channels and improving the battery traceability management system. (Enhancing supervision is beneficial to GUEs to improve income.)
	s_1	Discounts of construction cost of the recycling sites that caused by government subsidies. (Discounts decrease when subsidies increase.)
	s_2	Discounts of operation cost of the recycling sites that caused by government subsidies. (Discounts decrease when subsidies increase.)

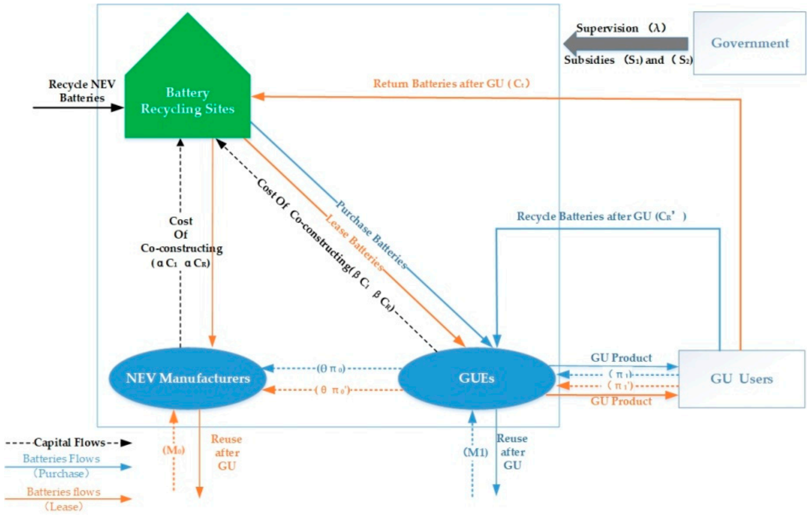


Figure 1. Business flow chart of co-constructing.

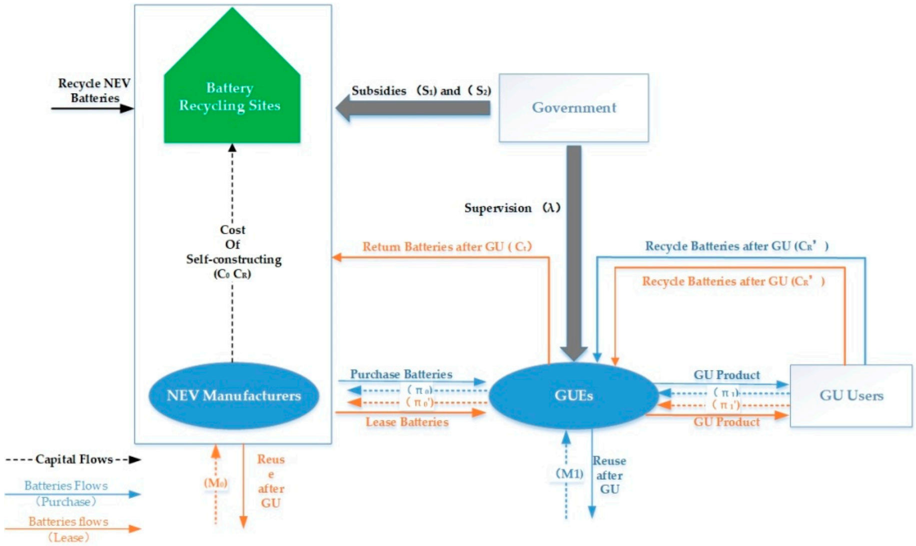


Figure 2. Business flow chart of self-constructing.

Table 2. Game payment matrix between new energy vehicle (NEV) manufacturers and gradient utilization enterprises (GUEs).

		Gradient Utilization Enterprises (GUEs)	
		Leasing Batteries (y)	**Purchasing Batteries ($1-y$)**
NEV Manufacturers	Co-constructing recycling sites (x)	$U_{11} = \theta\pi_0' - \alpha s_1 C_1 - \alpha s_2(C_R + C_t) + M_0$ $V_{11} = \lambda\pi_1' - \theta\pi_0' - \beta s_1 C_1 - \beta s_2(C_R + C_t)$	$U_{12} = \theta\pi_0 - \alpha s_1 C_1 - \alpha s_2 C_R$ $V_{12} = \lambda\pi_1 + M_1 - \theta\pi_0 - \beta s_1 C_1 - \beta s_2 C_R$
	Self-constructing recycling sites ($1-x$)	$U_{21} = \pi_0' - s_1 C_0 - s_2 C_R + M_0$ $V_{21} = \lambda\pi_1' - \pi_0' - C_R' - C_t$	$U_{22} = \pi_0 - s_1 C_0 - s_2 C_R$ $V_{22} = \lambda\pi_1 + M_1 - \pi_0 - C_R'$

4. Analysis of Evolutionary Stable Strategies

According to the game payment matrix in Table 2, the equilibrium of evolutionary game is analyzed (See Appendix A for the detailed analysis) and five local equilibrium points of the alliance system such as (0, 0), (0, 1), (1, 0), (1, 1), (x^*, y^*) are obtained. The local stable point obtained from the replicator dynamics equation is not necessarily a stable fixed point and needs to be further calculated according to the method proposed by Friedman [52]. For a local stable point, if the value of *Det* is positive while the value of *Tr* is negative at the same time, the locale stable point can be identified as a stable fixed point. Through enumeration, we can obtain four types of certain situations, two types of uncertain situations, and one type of deadlock situation for the evolution of alliance cooperation.

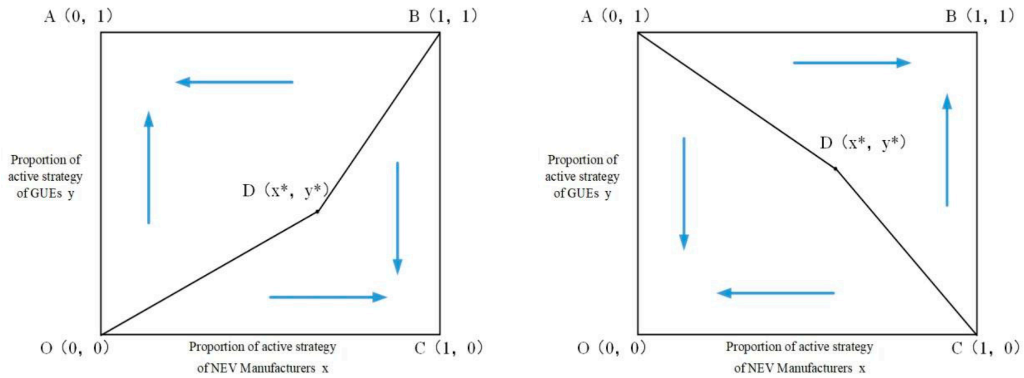
Situation 1: When $(A_1 + A_2) < 0$, $A_2 < 0$ and $(B_1 + B_2) < 0$, $B_2 < 0$ (The parameter A_1, A_2, B_1 and B_2 are explained in Appendix A, similarly hereinafter), (0, 0) is the stable fixed point of replicator dynamics. Regardless of the initial proportion of the two types of subjects that choose positive strategies, the stable cooperation mode of "self-constructing" and "purchasing" will be formed within the alliance. In this situation, the conditions $s_1(C_0 - \alpha C_1) + s_2(1 - \alpha)C_R < \min[(1 - \theta)\pi_0' + \alpha s_2 C_t, (1 - \theta)\pi_0]$ must be met for NEV manufacturers. It means that the cost-added value of the construction and operation of the self-built recycling sites of NEV manufacturers is lower than the reduced income value of the batteries compared with the strategy of joint construction. Simultaneously, for GUE, the condition $\lambda(\pi_1 - \pi_1') + M_1 > \max[(\pi_0 - \pi_0') - C_t, \theta(\pi_0 - \pi_0') - \beta s_2 C_t]$ must be met. It means that the sum value of the incremental benefit from GU and regenerated utilization is more than the added cost of battery acquisition and battery testing. The NEV manufacturers pay more attention to the increased construction and operation costs of battery recycling sites, while the GUEs pay more attention to which battery acquisition method can obtain more profits.

Situation 2: When $(A_1 + A_2) < 0$, $A_2 < 0$ and $(B_1 + B_2) > 0$, $B_2 > 0$, (0, 1) is the stable fixed point. Eventually, the alliance will form the stable cooperation mode of "self-constructing" and "leasing". The key problem for the NEV manufacturers is that it cannot save enough on construction and operating costs when it cooperates with others, which indicates $s_1(C_0 - \alpha C_1) + s_2(1 - \alpha)C_R < \min[(1 - \theta)\pi_0' + \alpha s_2 C_t, (1 - \theta)\pi_0]$. Moreover, the GUEs should meet the conditions $\lambda(\pi_1 - \pi_1') + M_1 < \min[(\pi_0 - \pi_0') - C_t, \theta(\pi_0 - \pi_0') - \beta s_2 C_t]$. Regardless of co-constructing, the GU income increased by purchasing batteries will be less than the strategy of leasing them.

Situation 3: When $(A_1 + A_2) > 0$, $A_2 > 0$ and $(B_1 + B_2) < 0$, $B_2 < 0$, (1, 0) is the stable fixed point. After a period of evolution, the alliance will form the stable cooperation mode of "co-constructing" and "purchasing". At this point, the NEV manufacturers find that the savings in construction and operating costs from co-ownership are sufficiently large to satisfy $s_1(C_0 - \alpha C_1) + s_2(1 - \alpha)C_R > \max[(1 - \theta)\pi_0' + \alpha s_2 C_t, (1 - \theta)\pi_0]$. Moreover, the GUEs think that the incremental benefits during GU when choosing the strategy of purchasing batteries are greater than when choosing the leasing strategy, which indicates $\lambda(\pi_1 - \pi_1') + M_1 > \max[(\pi_0 - \pi_0') - C_t, \theta(\pi_0 - \pi_0') - \beta s_2 C_t]$.

Situation 4: When $(A_1 + A_2) > 0$, $A_2 > 0$ and $(B_1 + B_2) > 0$, $B_2 > 0$, (1, 1) is the stable fixed point. In this situation, both sides of the alliance will eventually choose the positive strategy, forming the stable cooperation mode of "co-constructing" and "leasing". The NEV manufacturers jointly build the recycling sites to save more money, which indicates $s_1(C_0 - \alpha C_1) + s_2(1 - \alpha)C_R > \max[(1 - \theta)\pi_0' + \alpha s_2 C_t, (1 - \theta)\pi_0]$. In terms of the GUEs, the loss of GU revenue from the gradient use of leasing batteries is minimal, and hidden compensation can be obtained in the aspects of battery procurement and secondary battery recycling detection, which indicates $\lambda(\pi_1 - \pi_1') + M_1 < \min[(\pi_0 - \pi_0') - C_t, \theta(\pi_0 - \pi_0') - \beta s_2 C_t]$. This cooperation mode can optimize the layout of battery recycling sites, avoid cross-construction and repeated investment of recycling sites, and realize social resource-saving. In contrast, the leasing mode can force the GUE to actively track and monitor the whereabouts of the batteries, achieve more effective secondary recycling, avoid these batteries flowing into illegal channels, and promote a friendly environment and sustainable development.

Situation 5: When $(A_1 + A_2) < 0$, $A_2 > 0$ and $(B_1 + B_2) < 0$, $B_2 > 0$, i.e., both sides of the system meet the conditions of $s_1(C_0 - \alpha C_1) + s_2(1 - \alpha)C_R \in [(1 - \theta)\pi_0, (1 - \theta)\pi_0' + \alpha s_2 C_t]$ and $\lambda(\pi_1 - \pi_1') + M_1 \in [\theta(\pi_0 - \pi_0') - \beta s_2 C_t, (\pi_0 - \pi_0') - C_t]$, (0, 1) and (1, 0) are both stable fixed points of the evolutionary system. The added profit from renting batteries is more than that from one-time sales of the same amount of batteries, and the cost savings of co-construction from building recycling sites by itself are between the above two. The cost savings of renting batteries of the GUEs in the situation of co-construction is less than that of self-construction by the NEV manufacturers, and the lost revenue of renting batteries should fall between the above two. The final evolutionary steady-state of the system depends on the initial strategy ratio (x_0, y_0) and the relative position of the saddle point (x^*, y^*), as depicted in Figure 3a. When (x_0, y_0) is in the left zone of (x^*, y^*), the area inside the OABD in Figure 3a, (0, 1) is the stable fixed point, which means "self-constructing" and "leasing" is the stable strategy. When (x, y) is in the right zone of (x^*, y^*), the area inside the ODBC in Figure 3a, (1, 0) is the stable fixed point., which means "co-constructing" and "purchasing" is the stable strategy.



(**a**) Situation 5 (**b**) Situation 6

Figure 3. Evolutionary phase diagram of "Situation 5" and "Situation 6".

Situation 6: When $(A_1 + A_2) > 0$, $A_2 < 0$ and $(B_1 + B_2) > 0$, $B_2 < 0$, it means both sides meet the evolutionary conditions of $s_1(C_0 - \alpha C_1) + s_2(1-\alpha)C_R \in [(1-\theta)\pi_0{}' + \alpha s_2 C_t, (1-\theta)\pi_0]$ and $\lambda(\pi_1 - \pi_1{}') + M_1 \in [(\pi_0 - \pi_0{}') - C_t, \theta(\pi_0 - \pi_0{}') - \beta s_2 C_t]$. (0, 0) and (1, 1) are stable fixed points of the system, as depicted in Figure 3b. The final cooperation mode depends on initial strategy ratio (x_0, y_0) and the relative position of the saddle point (x^*, y^*), If (x_0, y_0) is in the left zone of (x^*, y^*), within the OADC region in Figure 3b, (0, 0) indicates the stable fixed point. If (x_0, y_0) is in the right zone of (x^*, y^*), within the ABCD region in Figure 3b, (1, 1) indicates the stable fixed point.

Situation 7: In two cases, all local stability points would be non-stable fixed points, leading to a deadlock of evolution in the alliance, as follows.

7.1 When $(A_1 + A_2) > 0$, $A_2 < 0$ and $(B_1 + B_2) < 0$, $B_2 > 0$, the evolution will fall into deadlock. The NEV manufacturers' earnings meet the conditions of $s_1(C_0 - \alpha C_1) + s_2(1-\alpha)C_R \in [(1-\theta)\pi_0{}' + \alpha s_2 C_t, (1-\theta)\pi_0]$. This state indicates that, compared with the "self-constructing" strategy, the saved costs of the NEV manufacturers of choosing the "co-constructing" strategy are between the added profit value of renting batteries and selling them. Consequently, the NEV manufacturers have the willingness to co-construct recycling sites and rent the recycled batteries. The earnings of the GUEs should meet the conditions of $\lambda(\pi_1 - \pi_1{}') + M_1 \in [\theta(\pi_0 - \pi_0{}') - \beta s_2 C_t, (\pi_0 - \pi_0{}') - C_t]$. This state indicates that the lost revenue from leasing batteries of the GUE is between the costs saved when the NEV manufacturer chooses "co-constructing" and "self-constructing". This would make the GUEs more inclined to purchase batteries under the condition of co-constructing recycling sites. The strategies of the two groups are irreconcilable.

7.2 When $(A_1 + A_2) < 0$, $A_2 > 0$ and $(B_1 + B_2) > 0$, $B_2 < 0$, the earnings of the NEV manufacturers meet conditions of $s_1(C_0 - \alpha C_1) + s_2(1-\alpha)C_R \in [(1-\theta)\pi_0, (1-\theta)\pi_0{}' + \alpha s_2 C_t]$. Compared with the "self-constructing" strategy, the saved costs of the NEV manufacturers of choosing the "co-constructing" strategy are between the added profit value of selling batteries and leasing them, resulting in the NEV manufacturer being willing to jointly build recycling sites and sell the recycled batteries. The earnings of the GUEs should meet the conditions of $\lambda(\pi_1 - \pi_1{}') + M_1 \in [(\pi_0 - \pi_0{}') - C_t, \theta(\pi_0 - \pi_0{}') - \beta s_2 C_t]$.

This state indicates that the lost revenue from leasing batteries of the GUEs is between the saving costs when the NEV manufacturers choose to self-build and co-construct recycling sites. This would make the GUEs more inclined to lease batteries under the condition of co-constructing recycling sites. The strategies of the two groups are irreconcilable.

In Situation 7, the members in the alliance will continuously change their strategies. If the evolutionary conditions remain unchanged, the system will not evolve to a steady-state regardless of how many rounds of the game have been played, and the alliance will enter an evolutionary deadlock. This situation will lead to the internal friction of the alliance, which should be avoided for as long as possible. The influence of parameter changes on breaking the deadlock when an evolutionary deadlock occurs will be discussed later.

5. Simulation and Analysis

5.1. Related Data

In this paper, NEV manufacturers and GUEs are regarded as members of power battery recycling and utilization alliances. The strategic choice and evolution of the members in the alliance determine the cooperation mode of the alliance. For promoting the alliance to form a win-win stable cooperation mode, it is necessary to analyze the key variables that affect the proportion that adopts the positive strategies in the groups. Therefore, MATLAB is used for numerical simulation, and variable parameters are set as reasonably as possible to reflect the influence trend more intuitively among variables.

According to the research report of China Merchants Securities on power battery recycling and GU, there will be 26.69 GWh NEV LIB in China in 2020, among which the lithium iron phosphate batteries which will be suitable for GU represent 20.15 GWh. The market scale of GU is approximately 10 billion Yuan. The recycling price of retired lithium iron phosphate battery is approximately 100 Yuan/kWh, the selling price is approximately 200 Yuan/kWh, and the leasing price is 120 Yuan/kWh. The average income of lithium iron phosphate batteries for GU is 300 Yuan/kWh. At present, there are approximately 10,000 NEV power battery recycling sites in China, with an average allocation of 185 kWh. The annual average battery recycling and GU parameters are set in the same proportion based on these data. Parameters such as recycling site construction cost, secondary testing cost, and co-construction proportion are set according to experts' suggestions. Parameter values are depicted in Table 3.

Table 3. Parameter Values in the initial conditions.

Symbol	π_0	$\pi_0{}'$	π_1	$\pi_1{}'$	C_0	C_1	C_R	C_t	M_1	α	θ
value	5	3	9	7	10	14	2	1	0.5	0.7	0.7

5.2. Impact of Initial Proportion on Evolutionary Results

The setting of initial parameters has a significant influence on the evolution path of alliance cooperation mode. Parameters are set according to the initial conditions in Table 3, and government subsidies and regulatory influences are temporarily excluded (s_1 = 1, s_2 = 1, λ = 1). In this case, the system will eventually evolve to the steady-state of (0, 0), which conforms to "Situation 1". The evolution paths are depicted in Figure 4. Regardless of the initial proportions of the two types of subjects, after a period of evolution, the battery recycling and GU alliance will form the stable cooperation mode of "self-constructing" and "purchasing". The reason is that the savings of the NEV manufacturers choosing to co-construct recycling sites are not sufficient to offset the reduced income, and the cost proportion of the co-construction is too high. The saved costs from the GUE adopting the leasing strategy are not sufficient to offset the surging costs of secondary recovery and testing of batteries after GU.

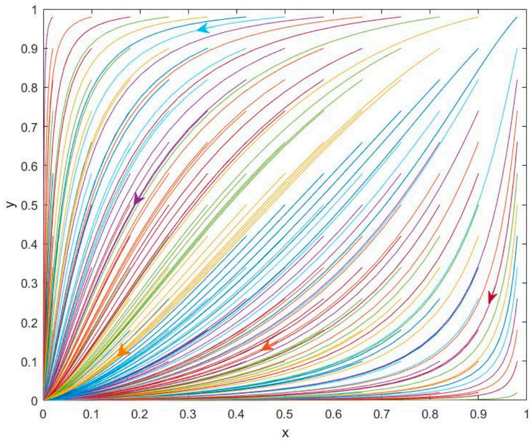


Figure 4. Evolution paths of "Situation 1".

If $\pi_1{}'$ is changed to 7.5 according to the original parameter values, the system will eventually evolve to the steady-state (0, 1), which conforms to "Situation 2". Enhancing the benefits of GU under the leasing mode can promote the GUE to choose the positive strategy. In this case, the profit and loss situation and strategy evolution paths of the NEV manufacturer will not change. However, the GUE will choose the "leasing" strategy because they will not lose too much revenue and can reduce storage, transportation, and testing costs. Therefore, the alliance will form the stable cooperation mode of "self-constructing" and "leasing". The evolution paths are depicted in Figure 5.

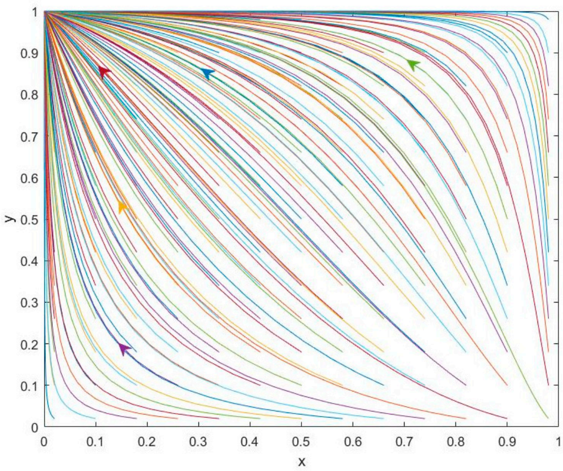


Figure 5. Evolution paths of "Situation 2".

If C_1 is changed to 12 based on the original parameter values, the system will eventually evolve to the steady-state (1, 0), which conforms to "Situation 3". Reducing the cost of co-constructing battery recycling sites can incentivize NEV manufacturers to choose the positive strategy. In this case, the revenue and evolution paths of the GUEs will not change while NEV manufacturers shift their strategies to "co-constructing" due to the reduction in additional costs. The evolution paths of the alliance are depicted in Figure 6.

If α is changed to 0.6 and $\pi_0{}'$ is changed to 2 based on the original parameter values, the system will eventually evolve to the steady-state (1, 1), which conforms to "Situation 4". Reducing the cost-sharing ratio of NEV manufacturers in the case of co-construction and the battery leasing price can promote the system evolve to the ideal steady-state of "co-constructing" and "leasing". Reducing the allocation ratio can motivate NEV manufacturers to take the active strategy, whereas reducing the battery rental price can motivate GUEs to take the active strategy. The evolution paths of the system are depicted in Figure 7.

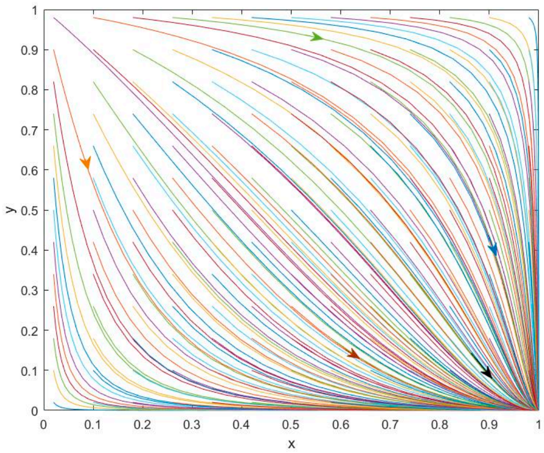


Figure 6. Evolution paths of "Situation 3".

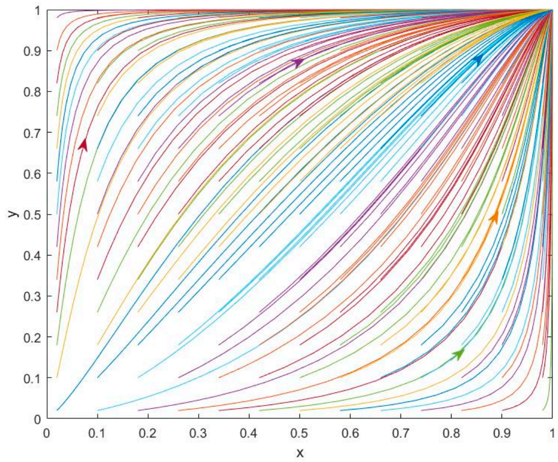


Figure 7. Evolution paths of "Situation 4".

Based on the original parameter values, the cost of co-construction C_1 is reduced to 10, and π_0 is reduced to 3.2. Simultaneously, increasing the revenue of battery-regenerated utilization M_1 to 2 and reducing the battery testing cost C_t to 0.1 produces the alliance evolution paths depicted in Figure 8, which conforms to "Situation 5". In this case, the final steady-state of the alliance will evolve to one of (0, 1) and (1, 0), and the evolution result is closely related to the initial proportion of the subjects that choose the positive strategy. Calculating the saddle point results in (x^*, y^*) = (0.4916, 0.6081). When the initial proportion (x_0, y_0) is in the OABD area, the system will eventually evolve to the state of (1, 0), the mode of "co-constructing" and "purchasing". In contrast, if the initial proportion (x_0, y_0) falls inside the ODBC area, the system will eventually evolve to the state of (1, 0), forming the stable cooperation mode of "self-constructing" and "leasing". The evolution and analysis of "Situation 6" is similar to that of "Situation 5". The system will evolve to the steady-state of (0, 0) or (1, 1) according to the initial proportion (x_0, y_0) and saddle point position. The evolution paths of "Situation 6" are depicted in Figure 9.

According to the evolutionary conditions of "Situation 7.1", set ${\pi_1}' = 9.6$, C_R= 5, $\alpha = 0.7$, C_0= 12.5, C_1= 25, and $\theta = 0.95$. The other parameter values are set to the original values. The evolution paths of the alliance are depicted in Figure 10. Regardless of how many times the game is played, the alliance cannot form a steady-state, which indicates that the system evolves into deadlock.

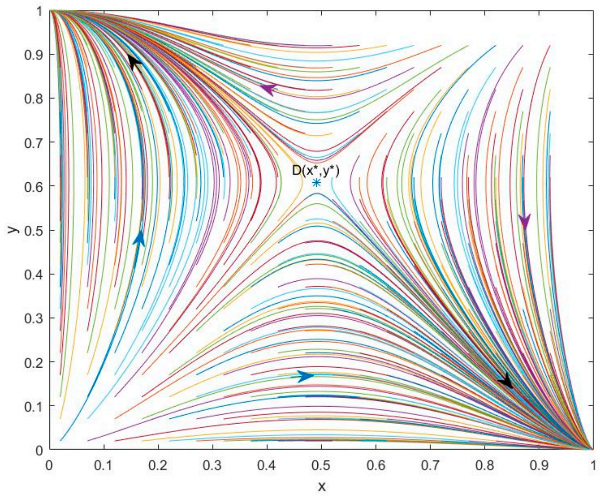


Figure 8. Evolution paths of "Situation 5".

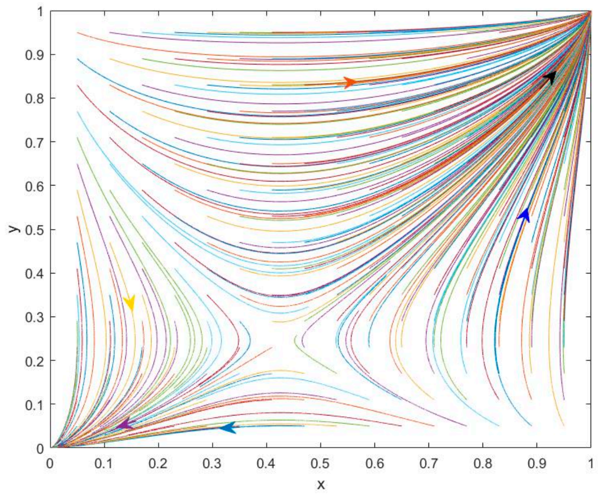


Figure 9. Evolution paths of "Situation 6".

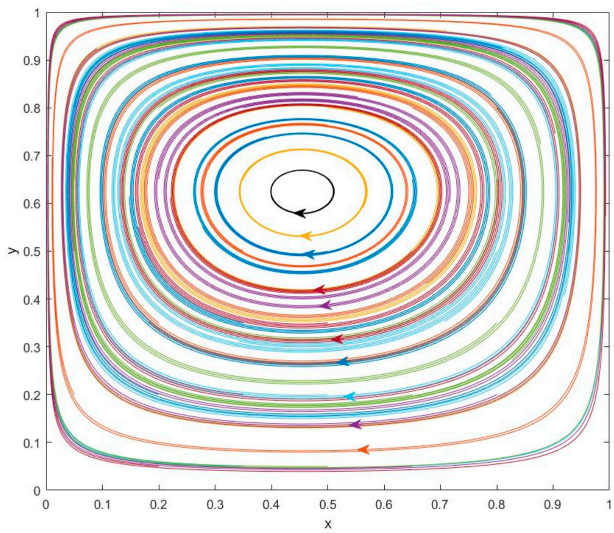


Figure 10. Evolution paths of "Situation 7" (evolutionary deadlock).

China's NEV battery recycling and GU industry is in the early stage of development. Battery recycling, transaction and lease prices, GU product revenue, and the operation costs of recycling sites are all changing with market development. The apportionment scheme of cooperation costs among the members in the alliance is also improving continuously. In the process of alliance development, various evolutionary paths and deadlock situations may appear, so it is necessary to guide and solve them actively in the early stage. The next section discusses the influence and effect of market development parameters and government regulation parameters on changing the evolution paths of the alliance and breaking the evolutionary deadlock.

5.3. Impact of Market Development on Evolutionary Results

The change of market related parameters has an important influence on breaking the deadlock of alliance cooperation. Based on the parameter settings in "Situation 7", setting initial strategy (x, y) as (0.5, 0.5), after a period of evolution, the cooperation mode of alliance will enter an evolutionary deadlock, the evolution paths are depicted in Figure 11(L1). Reducing π_0 and $\pi_0{\prime}$ to 80% of the initial level, the system will eventually evolve to the state of (0, 0). The evolution paths are depicted in Figure 11(L2).

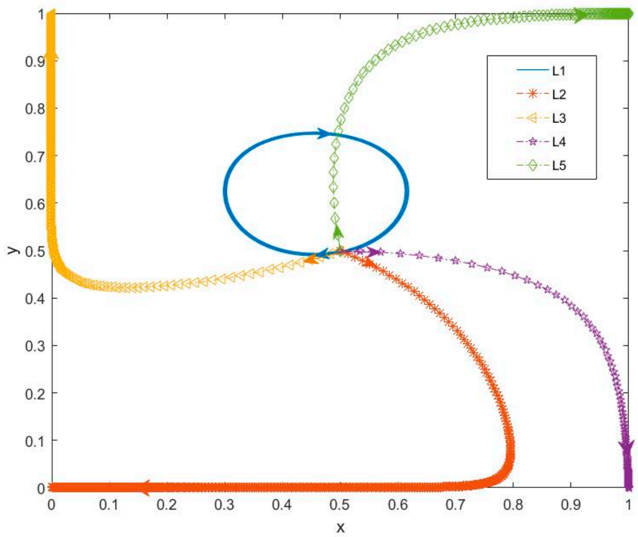


Figure 11. Impacts of market related parameters on alliance evolutionary deadlock.

If C_R is modified to 3 in the deadlock state, the system will evolve to the steady-state of (0, 1). The evolution paths are depicted in Figure 11(L3). If C_1 is modified to 20 in the deadlock state, the system will evolve to the steady-state of (1, 0), as is shown in Figure 11(L4). If $\pi_1{}'$ is modified to 11 in the deadlock state, the system will evolve to the steady-state of (1, 1). The evolution paths are depicted in Figure 11(L5).

Obviously, the deadlock of alliance cooperation mode can be broken through the reduction in market cost parameters, such as costs of purchasing and leasing NEV batteries of GUEs and costs of constructing and operating battery recycling sites. The improvement of GU benefits in the mode of leasing batteries can also break the deadlock and promote the formation of a new cooperation model. However, Figure 11 shows that reducing the costs can only make the evolution system evolve into non-ideal steady-states (0, 0), (0, 1), and (1, 0), while increasing the GU benefits can make the system evolve into the ideal steady-state (1, 1). Therefore, enriching GU scenarios, promoting the maturity of the GU industry, and increasing the GU benefits are the key means of breaking the deadlock of the alliance, form the ideal cooperation mode of "co-construction" to "leasing", and promote the healthy and sustainable development of NEV battery recycling and the GU industry.

The sharing proportion of the co-construction costs of battery recycling sites α and the discount of battery sales and leasing θ reflect the degree of alliance cooperation in the process of market development. The change of these parameters can also break the deadlock of alliance cooperation, but they have different effects on the evolutionary path. Based on parameter settings in "Situation 7", change parameter α step by step, the evolution results of the alliance are depicted in Figure 12. The initial value of α is 0.7, and the evolution path is depicted by the blue curve, which will form an evolutionary deadlock. With the gradual decline in α, the evolutionary path changes. When the cost-sharing ratio of the NEV manufacturer is lower than 60%, the evolutionary deadlock will be broken, and the steady-state of cooperation of "co-constructing" and "purchasing" will be formed. If it is gradually increased in the initial situation, it will not quickly turn the deadlock into cooperation. Only when the share ratio of the NEV manufacturer is higher than 80% and the GUE's share is lower than 20% can the deadlock be broken and the cooperation mode of "self-constructing" and "leasing" be evolved. When the members in the alliance are at an impasse in failing to reach stable cooperation, changing the cost-sharing ratio of the jointly built recycling sites can break the evolutionary deadlock. However, changing this parameter can only promote either part of the two-game members assuming the positive strategy. Achieving the ideal sustainable state requires guidance from other perspectives.

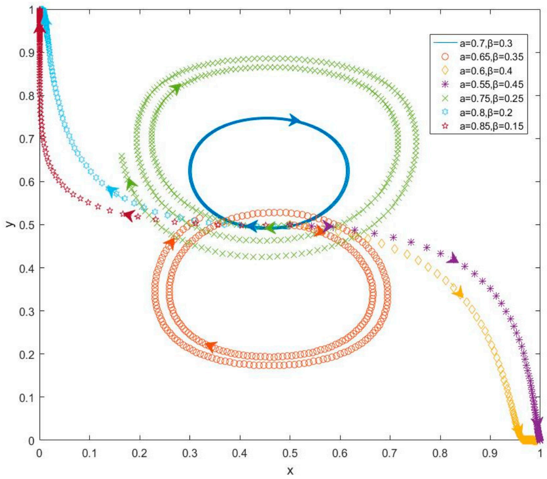


Figure 12. Impacts of the share ratio of co-construction costs α on alliance evolutionary deadlock.

In the co-construction mode, the discount θ given by NEV manufacturers in terms of battery sales or leasing also has a significant impact on the evolution of the alliance. Based on parameter settings of the case of evolution deadlock, θ is gradually reduced. The evolution results of the alliance are depicted in Figure 13. When θ drops from 0.95 to 0.85, although the evolution path changes, the evolution deadlock is not broken. When θ drops to 0.8 (20% discount is given), the evolution deadlock is broken. However, a 20% discount will not effectively promote both sides to choose the leasing mode, and the system will evolve to the stable fixed point of (1, 0), forming the cooperation mode of "co-constructing" and "purchasing". When the preferential margin is further increased to a 25% discount, it will drive GUE to change its strategy and promote the alliance to form the positive cooperation mode of "co-constructing" and "leasing".

In conclusion, when the alliance cooperation mode evolves into deadlock ("Situation 7"), the evolutionary game system does not have strong robustness to slight changes in market-related parameters. Changes in parameters such as costs and benefits and alliance cooperation intensity will break the deadlock to a certain extent. Then, some stable cooperation mode can be formed gradually. By comparison, we can see that the sensitivity of the evolutionary game system to the change of cost and benefit parameters is higher than that of the alliance cooperation intensity. Therefore, regulation measured from the perspective of price can better promote stable cooperation among alliance members.

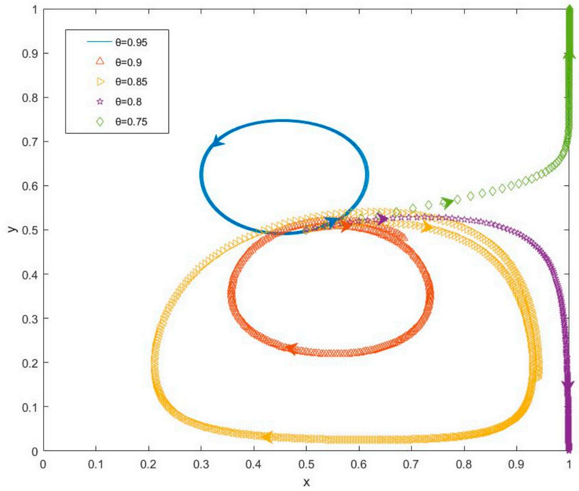


Figure 13. Impacts of discount θ on alliance evolutionary deadlock.

5.4. Impact of Government Regulation on Evolutionary Results

The impacts of recycling site construction subsidies, recycling site operation subsidies, and supervision on the evolution of alliance are discussed under two circumstances. One is that a stable cooperation mode can be formed through evolution, but at least one side of the game members adopts the negative strategy (i.e., "Situation 1", "Situation 2" and "Situation 3"). The other is that a stable cooperation mode cannot be formed, and the alliance enters an evolutionary deadlock state (i.e., "Situation 7").

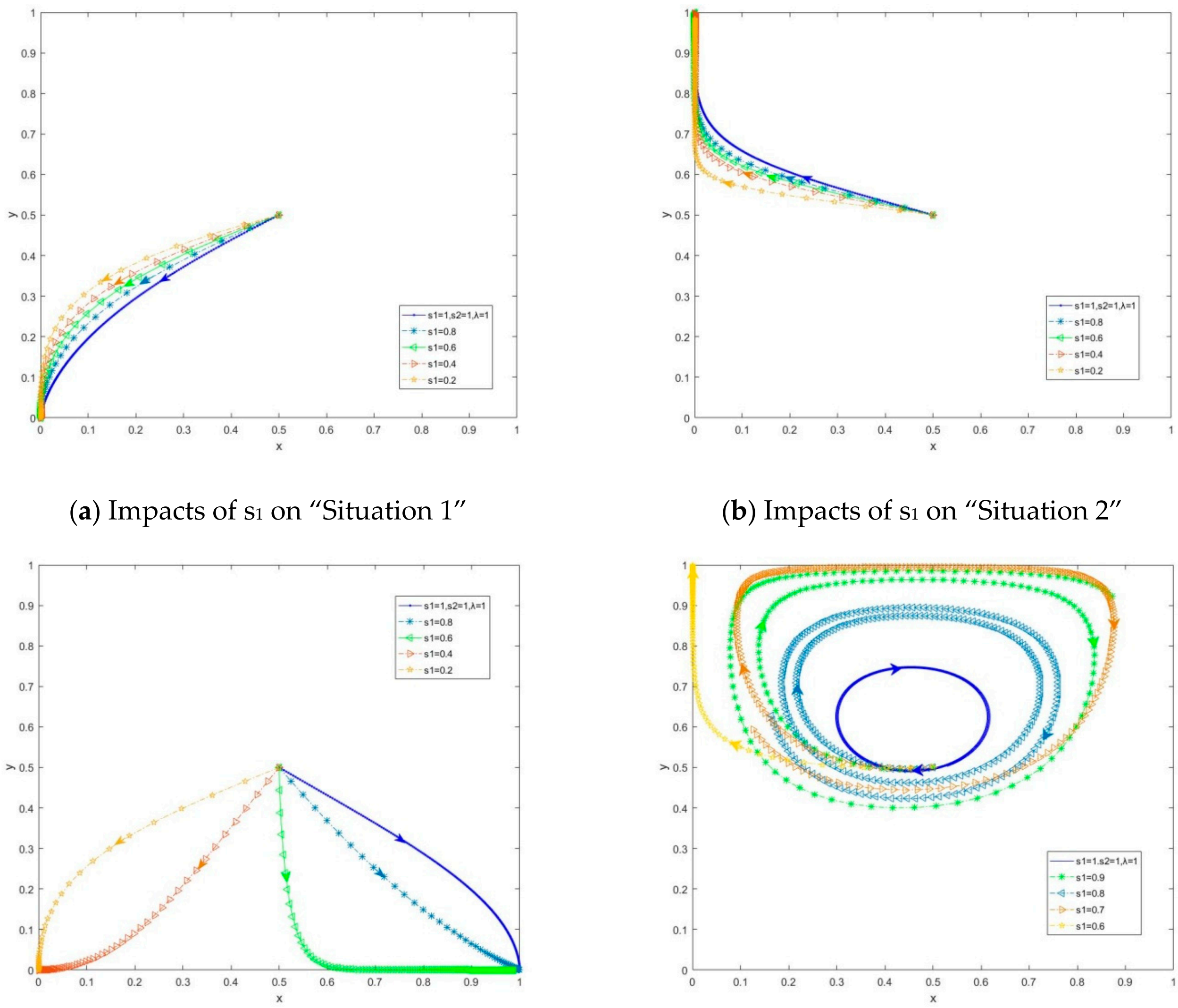
For "Situation 4", without intervention, the alliance will evolve to a cooperative mode of adopting active strategies, and the government will not change the regulatory strategy for intervention, so this situation will not be discussed. "Situation 5" and "Situation 6" differ from "Situations 1", "Situation 2" and "Situation 3" only in their initial proportions and are therefore no longer discussed.

5.4.1. Impacts of Recycling Site Construction Subsidies (s_1) on the Alliance Evolution

In this part, we will discuss whether increasing recycling site construction subsidies can affect the cooperation mode of an alliance. When other parameters are fixed and s_1 is gradually reduced in "Situation 1", "Situation 2", " Situation 3", and "Situation 7", Figure 14a–d shows the respective evolution paths of the cooperation mode. It can be seen that increasing recycling site construction subsidies cannot essentially promote the formation of an ideal cooperation mode in the alliance and promote the sustainable development of the industry.

Specifically, in "Situation 1" and "Situation 2", the evolutionary game system has strong robustness to the disturbance of s_1 and the final cooperation mode of the alliance does not substantially transform with the change of s_1. Therefore, in this case, increasing the recycling site construction subsidies can only have a temporary incentive effect.

In "Situation 3" and "Situation 7", the system is not robust to the disturbance of s_1 and the evolution of the cooperation mode will transform with the change in s_1. However, in "Situation 3", the continuous increase in government subsidies not only did not play a positive role, but it made NEV manufacturers—who originally adopted the strategy of co-construction—choose the negative strategy instead. Therefore, in this situation, recycling site construction subsidies inhibited alliance members' willingness to cooperate and co-construct recycling sites. In "Situation 7", the gradual decrease in s_1 broke the evolution deadlock but it still could not promote the formation of an ideal cooperation mode. Therefore, further market guidance or government regulations should be adopted to intervene.



(**a**) Impacts of s_1 on "Situation 1"

(**b**) Impacts of s_1 on "Situation 2"

(**c**) Impacts of s_1 on "Situation 3"

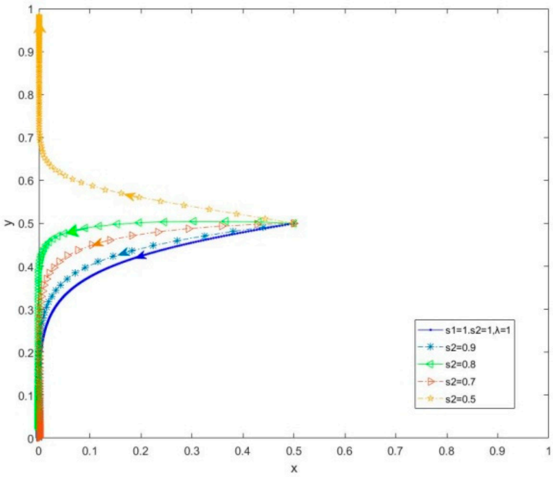
(**d**) Impacts of s_1 on "Situation 7"

Figure 14. Impacts of s_1 on the alliance evolution.

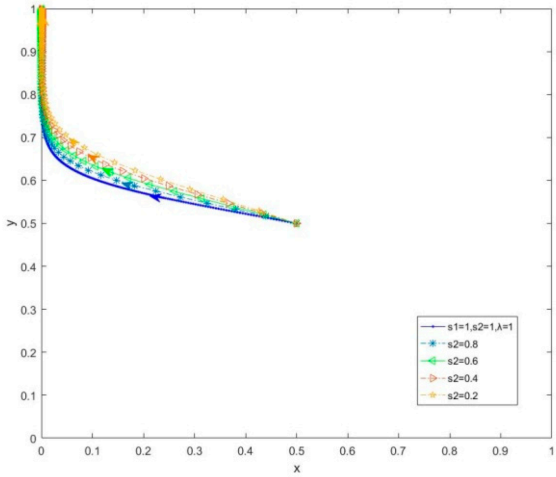
5.4.2. Impacts of Recycling Site Operation Subsidies (s_2) on the Alliance Evolution

In this part, we will discuss the effects of increasing recycling site operation subsidies on the evolution of alliance cooperation mode. When the other parameters are fixed and s_2 is gradually reduced in "Situation 1", "Situation 2", "Situation 3", and "Situation 7", the respective evolution paths of the cooperation mode were as shown in Figure 15a–d. As can be seen, increasing recycling site operation subsidies can promote the formation of an ideal cooperation mode under certain circumstances and promote the sustainable development of battery recycling and the GU industry.

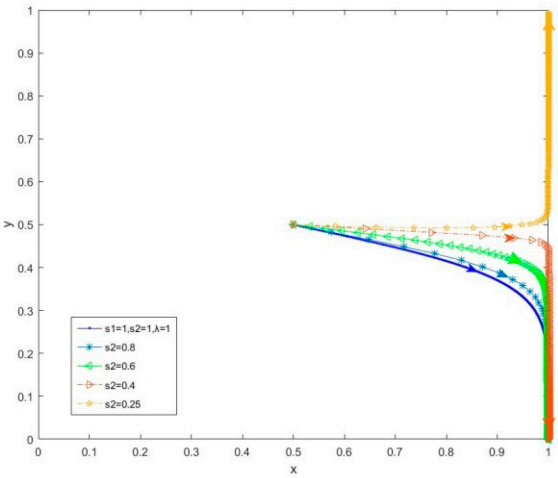
Specifically, in "Situation 2", the disturbance of the evolution system to parameter s_2 is relatively stable and the evolutionary results do not change with the change of s_2 (Figure 15b). Therefore, in this case, increasing recycling site operation subsidies cannot promote sustainable development in the industry.



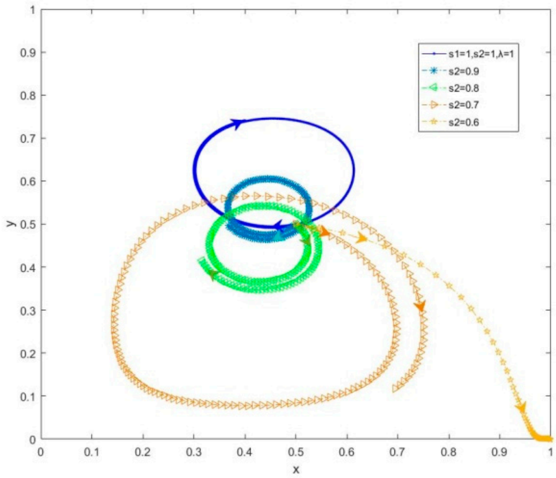
(**a**) Impacts of s_2 on "Situation 1"



(**b**) Impacts of s_2 on "Situation 2"



(**c**) Impacts of s_2 on "Situation 3"



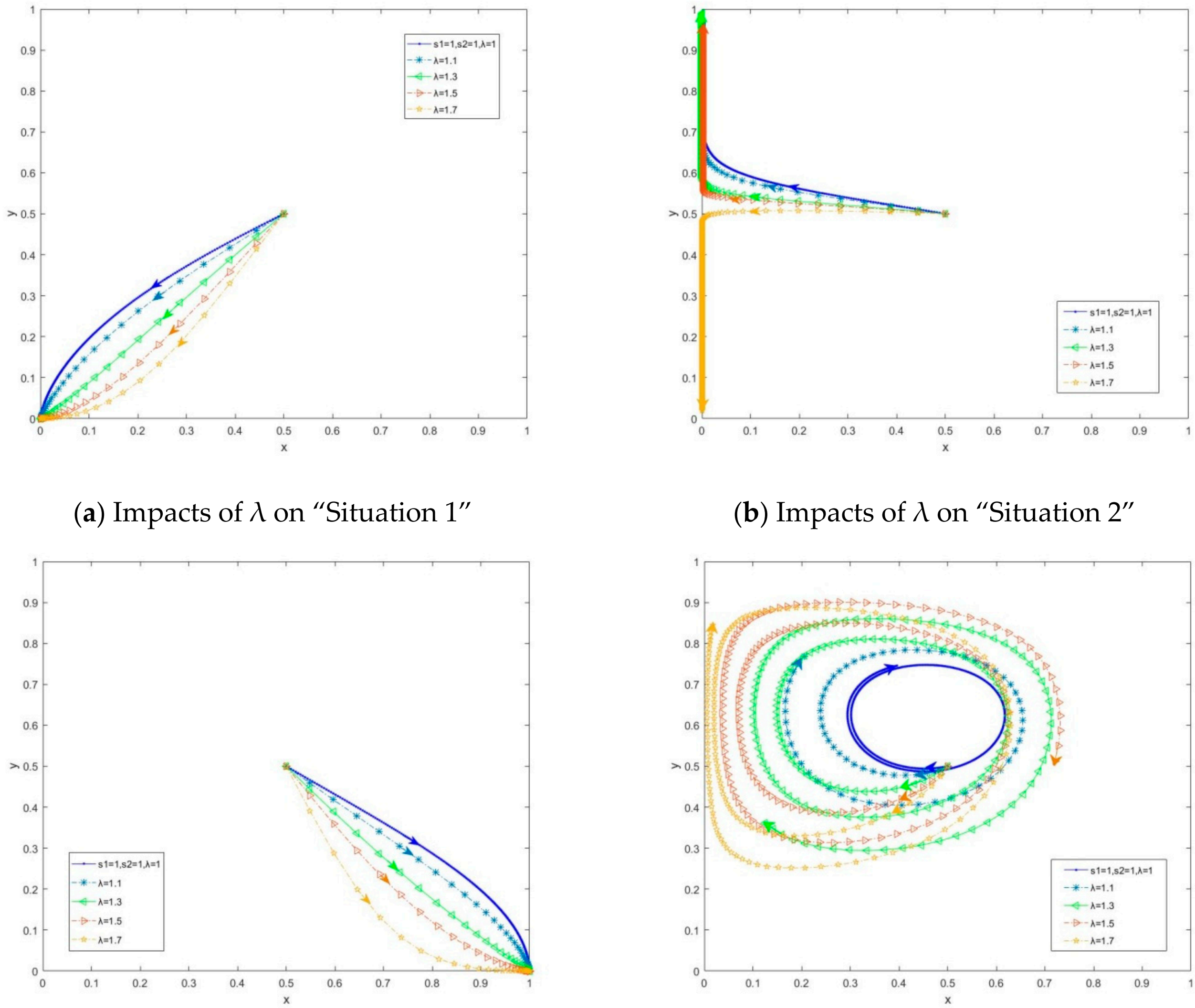
(**d**) Impacts of s_2 on "Situation 7"

Figure 15. Impacts of s_2 on the alliance evolution.

In "Situation 1", "Situation 3", and "Situation 7", the evolution system was highly sensitive to the disturbance of parameter s_2; the evolutionary results will change due to the variation of s_2. When subsidies are sufficient ($1\text{-}s_2 = 0.4$), the evolutionary deadlock of alliance can be broken and the cooperation mode of "co-constructing" and "purchasing" will be established (Figure 15d). Only when the initial conditions meet "Situation 3" can increasing recycling site operation subsidies promote the formation of an ideal cooperation mode in which both NEV manufacturers and GUEs will adopt positive strategies. Therefore, the government can break the deadlock of cooperation first by step-by-step regulation and then by promoting the formation of an ideal cooperation mode.

5.4.3. Impacts of Regulatory Intensity λ on Alliance Evolution

In this part, we will explore the influence of increasing government supervision on battery GU on the evolution of cooperation mode. When other parameters are fixed and λ is gradually reduced in "Situation 1", "Situation 2", "Situation 3", and "Situation 7", Figure 16a–d shows the respective evolution paths of cooperation mode. It can be seen that increasing supervision neither promotes the formation of ideal cooperation mode nor effectively breaks the evolution deadlock. This can only be used as a transitional or combined regulation method.



(**a**) Impacts of λ on "Situation 1" (**b**) Impacts of λ on "Situation 2"

(**c**) Impacts of λ on "Situation 3" (**d**) Impacts of λ on "Situation 7"

Figure 16. Impacts of λ on the alliance evolution.

Specifically, the system is strongly robust to the disturbance of parameter λ under the conditions of "Situation 1", "Situation 3", and "Situation 7". The evolution results of alliance cooperation mode do not change with the variation of λ (Figure 16a,c,d). The deadlock of alliance cooperation cannot be broken by enhancing government supervision.

In "Situation 2", the gradual increase of supervision intensity λ can change the evolutionary paths and results of the alliance cooperation mode (Figure 16b) but it cannot achieve the purpose of promoting the two groups in the alliance to adopt positive strategies. In contrast, it will make more GUEs turn to adopt negative strategies. Therefore, the adjustment of regulatory intensity has no significant effect on promoting the stable cooperation of the alliance and the sustainable development in the industry.

6. Conclusions and Management Implications

6.1. Conclusions

Based on the requirements of China's "New Energy Vehicle Power Battery Escalation Utilization Management Measures" and typical demonstration projects of NEV power battery recycling and GU, a game model between NEV manufacturers and GUEs is established focused on the recycling and GU of NEV power batteries in the context of the decommissioning tide. The evolution trend and stability of the competition and cooperation between the two types of members in the alliance are analyzed comprehensively. The results illustrate that:

(1) When certain conditions are met, the NEV power battery recycling and GU alliance can establish and maintain different types of competition and cooperation relationships. As the main subjects with battery-recycling responsibilities, NEV manufacturers focus on whether co-construction can save enough costs. GUEs are more concerned about whether they can make more profit by purchasing batteries than renting them. Under the condition of "Situations 1–4", if the profit and loss situation is determined, regardless of the initial proportion of both sides in adopting active strategies, the cooperation mode formed by the members of the alliance will not change. Therefore, the guidance and regulation of these situations must only change the profit and loss of the subjects. Under the conditions of "Situation 5 and 6", evolution paths and steady-state of the alliance should be guided according to not only the initial proportion of the subjects but also the profit and loss of the evolution process. Under the conditions of "Situation 7", the alliance may enter an evolutionary deadlock. No matter how much time passes, the members in the alliance cannot form stable cooperation modes, and each subject continues testing and changing strategies, resulting in internal resource consumption.

(2) When the evolution conditions are satisfied and the alliance can evolve to a steady-state, market development and government regulation can change the evolutionary paths and steady-state to some extent. However, the robustness of evolutionary systems to different parameters varies greatly under different conditions, and the sensitivity of subjects' strategies to different types of parameters is also different. Under the market mechanism, raising the threshold of self-constructing of recycling sites (C_0), reducing the co-construction costs of recycling sites (C_1), saving the cost of operation (C_R), and reducing the cost-sharing ratio during co-construction are effective means of encouraging NEV manufacturers to choose the "co-constructing" strategy. Reducing the battery-leasing price and increasing the GU income is necessary to encourage the GUEs to choose positive strategies, which accelerates the alliance to the ideal steady-state of "co-constructing" and "leasing". When the market mechanism does not work, the government's regulation measures, such as increasing the subsidies for the construction and operation of recycling sites and strengthening the supervision of illegal recycling channels, can increase the pace of forming stable cooperation in the alliance. However, the single regulation effect is not adequate. For example, only increasing the subsidies for the construction of recycling sites or increasing the supervision intensity cannot result in the alliance reaching the ideal win-win steady-state. However, it may cause an alliance subject who has a positive intention to eventually choose the negative strategy (as depicted in Figures 14c and 16b). The increase in operation subsidies of recycling sites can only encourage the alliance to form an ideal steady-state of cooperation under the premise of "Situation 3" Therefore, the cooperative steady-state of "Situation 3" can be formed first through the guidance of market mechanism, then government regulation can promote the formation of the ideal stable state of cooperation.

(3) When the alliance evolves into deadlock, measures in market mechanisms can break the deadlock and promote the alliance to evolve to a steady-state, such as reducing the battery purchase costs and leasing costs equidistantly, reducing the recycling site operating costs, reducing the GU yield gap between purchasing and leasing mode, adjusting the cost-sharing ratio, and providing preferential discounts to GUEs when co-constructing recycling sites. It is more effective to reduce the profit difference between purchasing and leasing mode and increase the preferential discount for the GUEs when co-constructing recycling site, which can directly promote the al-

liance evolve to the ideal steady-state of "co-constructing" and "leasing". Concerning government regulations, increasing supervision has little effect on breaking the evolutionary deadlock. Increasing subsidies can only break the evolutionary deadlock if the subsidies are sufficiently large, but it cannot enable the alliance to evolve to the ideal state.

6.2. Management Implications

A reasonable recycling site construction mode cannot only optimize the industry chain, effectively connecting the upstream and downstream, but can also avoid repeated investment and save social resources. NEV manufacturers bear the primary responsibility of power battery recycling and have dominant rights to the construction of recycling sites. They can promote the co-construction and cooperation of battery recycling sites, rationally plan the layout of sites, reduce co-construction and operation costs, provide more preferential measures and subsidies to co-construction partners, and stimulate the vitality of the battery recycling and GU industry from the source.

GU is an effective means to extend the life cycle of power batteries. As the producer and beneficiary of GU battery products, GUEs should also bear the extended responsibility of the producer actively. They should improve the technology, enrich the GU scenarios, and increase the GU profit. In contrast, in cooperation with upstream and downstream enterprises, they should actively adopt leasing methods to acquire batteries and make them gradient used, effectively track and monitor the whereabouts of GU batteries, perform adequately during secondary recycling, and avoid these batteries' flow into illegal channels after GU.

The factors of the market environment are evident in both changing the evolution paths and steady-states of the alliance and breaking the evolution deadlock; however, there is also a large risk of failure without intervention. Therefore, it is necessary for governments to choose an appropriate strategy or a combination of strategies according to the different development situations of industries to promote sustainable development. A single measure such as subsidies or supervision often fails to promote an alliance to develop an ideal mode of cooperation. When an alliance evolves into deadlock, the government should adopt a combination of strategies or phased regulations, break the deadlock of cooperation, and then seek an ideal stable state of cooperation. Increasing subsidies blindly often fails to work. It tends to weaken the market function and cause the members of the alliance to adopt negative strategies.

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Appendix A

According to Table 2 in the main text, the revenue of the NEV manufacturer when choosing the "co-constructing" strategy is:

$$E_{11} = yU_{11} + (1-y)U_{12} \tag{A1}$$

The revenue of the NEV manufacturer when choosing the "self-constructing" strategy is:

$$E_{12} = yU_{21} + (1-y)U_{22} \tag{A2}$$

The expected revenue of the NEV manufacturer is as follows:

$$\overline{E_1} = xE_{11} + (1-x)E_{12} \tag{A3}$$

The revenue of the GUE when choosing the "leasing" strategy is:

$$E_{21} = xV_{11} + (1-x)V_{21} \tag{A4}$$

The revenue of the GUE when choosing the "purchasing" strategy is:

$$E_{22} = xV_{12} + (1-x)V_{22} \tag{A5}$$

The expected revenue of the GUE is as follows:

$$\overline{E_2} = yE_{21} + (1-y)E_{22} \tag{A6}$$

The game process between the NEV manufacturer and the GUE can be represented by the dynamic replication system composed of the following two differential equations:

$$\begin{aligned} &F(x) = \tfrac{dx}{dt} = x(E_{11} - \overline{E_1}) = x(1-x)(E_{11} - E_{12}) \\ &= x(1-x)[y(U_{11} - U_{21}) + (1-y)(U_{12} - U_{22})] \\ &= x(1-x)[y((1-\theta)(\pi_0 - \pi_0{}') - \alpha s_2 C_t) - ((1-\theta)\pi_0 - s_1(C_0 - \alpha C_1) - s_2(1-\alpha)C_R)] \end{aligned} \tag{A7}$$

$$\begin{aligned} &F(y) = \tfrac{dy}{dt} = y(E_{21} - \overline{E_1}) = y(1-y)(E_{21} - E_{22}) \\ &= y(1-y)[x(V_{11} - V_{12}) + (1-x)(V_{21} - V_{22})] \\ &= y(1-y)[x((1-\theta)(\pi_0{}' - \pi_0) + (1-\beta s_2)C_t) + \lambda(\pi_1{}' - \pi_1) - (\pi_0{}' - \pi_0) - C_t - M_1] \end{aligned} \tag{A8}$$

Setting $F(x) = 0$, $F(y) = 0$, we obtain five local equilibrium states of the alliance system (0, 0), (0, 1), (1, 0), (1, 1), (x^*, y^*), in which:

$$(x^*, y^*) = \left(\frac{B_2}{-B_1}, \frac{-A_2}{A_1}\right) \tag{A9}$$

where

$$A_1 = (1-\theta)(\pi_0 - \pi_0{}') - \alpha s_2 C_t \tag{A10}$$

$$A_2 = s_1(C_0 - \alpha C_1) + s_2(1-\alpha)C_R - (1-\theta)\pi_0 \tag{A11}$$

$$B_1 = (1-\theta)(\pi_0{}' - \pi_0) + (1-\beta s_2)C_t \tag{A12}$$

$$B_2 = \lambda(\pi_1{}' - \pi_1) - (\pi_0{}' - \pi_0) - C_t - M_1 \tag{A13}$$

The Jacobi matrix of this system is:

$$Jacobi = \begin{pmatrix} (1-2x)(yA_1 + A_2) & x(1-x)A_1 \\ y(1-y)B_1 & (1-2y)(xB_1 + B_2) \end{pmatrix} \tag{A14}$$

The determinant and trace of the matrix are:

$$DetJ = (1-2x)(1-2y)(yA_1 + A_2)(xB_1 + B_2) - xy(1-x)(1-y)A_1B_1 \tag{A15}$$

$$TrJ = (1-2x)(yA_1 + A_2) + (1-2y)(xB_1 + B_2) \tag{A16}$$

The five local equilibrium points are substituted into the Jacobi matrix to obtain the values of *Det* and *Tr*, which are as depicted in Table 1.

Table A1. *Det* and *Tr* of Local Equilibrium Points.

(x,y)	***Det J***	***Tr J***
(0, 0)	A_2B_2	$A_2 + B_2$
(0, 1)	$-(A_1 + A_2)B_2$	$(A_1 + A_2) - B_2$
(1, 0)	$-A_2(B_1 + B_2)$	$-A_2 + (B_1 + B_2)$
(1, 1)	$(A_1 + A_2)(B_1 + B_2)$	$-(A_1 + A_2) - (B_1 + B_2)$
(x^*,y^*)	$-xy(1-x)(1-y)A_2B_2$	0

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