Tripartite evolutionary game analysis of power battery carbon footprint disclosure under the EU battery regulation

Xia, Xiaoning; Li, Pengwei; Cheng, Yang

Published in:
Energy

DOI (link to publication from Publisher):
10.1016/j.energy.2023.129315

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

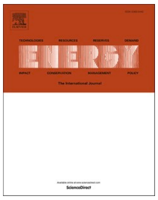
Citation for published version (APA):
Xia, X., Li, P., & Cheng, Y. (2023). Tripartite evolutionary game analysis of power battery carbon footprint disclosure under the EU battery regulation. *Energy*, *284*(129315), [129315]. https://doi.org/10.1016/j.energy.2023.129315

Energy 284 (2023) 129315

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Tripartite evolutionary game analysis of power battery carbon footprint disclosure under the EU battery regulation

Xiaoning Xia [a,b], Pengwei Li [c,*], Yang Cheng [b,**]

[a] School of Economics and Business Administration, Chongqing University, Chongqing, 400030, PR China
[b] Department of Materials and Production, Center for Industrial Production, Aalborg University, Aalborg, 9220, Denmark
[c] Department of Chemistry and Bioscience, Aalborg University, Aalborg, 9220, Denmark

ARTICLE INFO

Handling Editor: X Zhang

Keywords:
EU battery regulation
Carbon footprint
Evolutionary game
Simulation analysis

ABSTRACT

The EU's battery regulation aims to promote low-carbon and sustainable batteries and achieve carbon neutrality goals. However, in the actual implementation, limited government supervision, asymmetric information, and economic interests may induce battery manufacturers and third-party verification agencies to manipulate carbon footprint data. To prevent the occurrence of the above phenomena, this study constructs a tripartite evolutionary game model involving battery manufacturers, third-party verification agencies, and national market authorities. The model examines the strategic decision-making process, influential factors, and evolutionary stability of the three players, followed by simulation analysis. The results showed that the evolutionary system may exhibit two stable states: (0,0,1) and (1,1,0), corresponding to two strategy combinations {disclose false carbon footprints, intend rent-seeking, supervise} and {disclose true carbon footprint, reject rent-seeking, not supervise}, respectively. However, if the benefits of third-party agencies objectively assessing carbon footprints are not substantial enough, there will be only one stable state (0,0,1) in the system. To guide the evolutionary system towards the desired stable state (1,1,0), supportive policies should be implemented along with the EU battery regulation. Therefore, this study puts forward some policy recommendations in terms of institutional improvement, database construction, and the application of emerging technologies.

1. Introduction

As an essential part of the natural environment, climate exerts a profound influence on both the natural ecosystem and the socio-economic system and even restricts all humankind's sustainable development [1]. To combat global climate change and promote a green and low-carbon economy and society, the European Commission has proposed the Banning Gasoline Vehicle Sales Policy (BGVSP) and formulated timetables for doing so [2]. This means that gasoline, diesel, and light commercial vehicles will gradually be replaced by electric vehicles (EVs) [3], which are developing rapidly, and the demand for batteries is accordingly showing a rapid growth trend. However, green development is a complex systematic project [4], it has been demonstrated that batteries, as the core component of EVs, contribute significantly to carbon emissions during their production, use, and recycling stages, which makes the carbon emissions of EVs not to be underestimated [5]. The energy and emission-intensive nature of battery production, especially the preparation of cathode materials, results in significant carbon emissions during the EV production phase [6–8]. Variations in the energy and power mix across different locations also lead to considerable differences in carbon emissions of batteries produced in different regions [9] Additionally, disparities in battery recycling processes lead to significantly divergent carbon emissions during the recycling phase of EVs, with pyrometallurgical recycling resulting in higher carbon emissions compared to hydrometallurgical recycling and direct physical recycling [5].

To deal with the environmental concerns related to batteries and improve the eco-friendly and low-carbon performance of EVs, the European Commission has gradually shifted its focus to the battery industry and launched a series of initiatives. Among these initiatives, the upcoming "EU Batteries and Waste Batteries Regulation" (referred to as the "EU battery regulation") has gained widespread attention. This regulation encompasses all portable batteries, automotive batteries, industrial batteries, and EV batteries marketed or used within EU member

---

[*] Corresponding author.
[**] Corresponding author.
E-mail addresses: pengweili@bio.aau.dk (P. Li), cy@mp.aau.dk (Y. Cheng).

https://doi.org/10.1016/j.energy.2023.129315
Received 27 July 2023; Received in revised form 28 September 2023; Accepted 6 October 2023
Available online 7 October 2023

states, irrespective of whether they are locally manufactured or imported. According to the requirements of EU battery regulation, from July 1, 2024, technical documentation accompanying EV batteries entering the EU must include a carbon footprint statement; otherwise, they will be banned from entering the EU market. Additionally, the EU battery regulation proposes the establishment of a classification system based on the battery's carbon footprint (like the energy efficiency rating system used for household appliances). By January 1, 2026, the carbon footprint classification will be featured on the battery label and technical documentation of EVs. Concurrently, with advancements in battery technology, the EU plans to introduce regulation establishing a maximum allowable level for the carbon footprint of EV batteries, which will take effect from July 1, 2027. At that time, the accompanying technical documentation must demonstrate that the life cycle carbon footprint of the battery falls below the designated maximum value set by the enabling legislation (Fig. 1).

To ensure the credibility of battery carbon footprint labeling under the EU battery regulation, companies are required to disclose their carbon footprints and undergo auditing by third-party verification agencies. Subsequently, national market authorities assess the accuracy of this information. However, government supervision is limited due to constraints on administrative resources, government management, and social costs. For third-party verification agencies, conducting rigorous verifications of the carbon footprint disclosed by battery companies is a labor-intensive, resource-intensive, and time-consuming task. Engaging in rent-seeking behavior not only reduces these costs but also generates rent-seeking benefits. Consequently, there is a potential risk of intentional rent-seeking behavior by third-party agencies. For battery manufacturers, disclosing battery carbon footprints will not only increase compliance costs but may also lead to the leakage of sensitive data throughout the industry chain. Disclosure of falsely lower carbon footprints will help battery manufacturers enter the EU market, gain larger market shares, and derive economic benefits. Consequently, there is a tendency for companies to disclose false carbon footprints and explore rent-seeking opportunities with third-party agencies. In summary, in the context of limited government verification, information asymmetry, and increased corporate compliance costs, battery manufacturers and third-party agencies may conspire to falsify carbon footprint data. To guide companies and third-party agencies to truly disclose and objectively assess battery carbon footprints, this study constructs a three-party evolutionary game model involving battery manufacturers, third-party verification agencies, and national market authorities. By analyzing the strategic choices, influencing factors, and evolutionary paths of each participant in the carbon footprint disclosure process, this study explores ways to achieve an ideal stable state.

The innovation and contribution of this study are: (1) Using evolutionary game to analyze the impact of battery carbon footprint disclosure on stakeholders and the strategic interaction between various players in the context of the EU battery regulation. This is expected to achieve an effective integration of battery carbon footprint research and evolutionary game research, providing valuable supplements to existing research. (2) By exploring the evolutionary game process and the final stable state of each participant, the implementation effect of the EU battery regulation is simulated. (3) According to the research results, specific and feasible policy suggestions are proposed in terms of institutional improvement, database construction, and application of emerging technologies. This is of great practical significance for ensuring the effective implementation of battery regulation and promoting the green and sustainable development of the battery industry.

This study is constructed as follows: Section 2 is the literature review, concentrating on the battery policy of the EU, the carbon footprint of batteries, and the evolutionary game. Section 3 is methodology; Section 4 presents the analysis of the model. Section 5 contains the numerical simulation. Conclusions and policy recommendations are presented in Section 6.

2. Literature review

In recent years, the issue of battery carbon emissions has attracted much attention, and battery-related emission reduction policies have become the focus of political and academic attention. Based on the research topic, the literature highly relevant to this study can be divided into the following three streams.

2.1. Battery policy in the EU

To enhance environmental protection, the EU initiated significant measures related to the battery industry. These measures include the announcement of Directive 2006/66/EC on September 26, 2006 [10], followed by the release of the Strategic Action Plan on Batteries on May 17, 2018 [11]. In subsequent years, the EU successively issued the European Green Agreement [12] and the Circular Economy Action Plan [13], which reiterated the importance of the healthy and sustainable development of the battery industry. To ensure sustainable, high-performance, and safe batteries in the EU market, the European Commission proposed a regulation on batteries and waste batteries on December 10, 2020 [14]. This proposal aimed to replace the existing EU battery directive (2006/66/EC) and shift its implementation from "directive" to "regulation". After further deliberations, on December 9, 2022, the European Parliament, the European Council, and the European Commission reached a provisional agreement on the "EU Batteries and Waste Batteries Regulation" [15]. This regulation was officially adopted by EU member states on January 18, 2023, and later passed with an absolute majority in the European Plenary on June 14, 2023

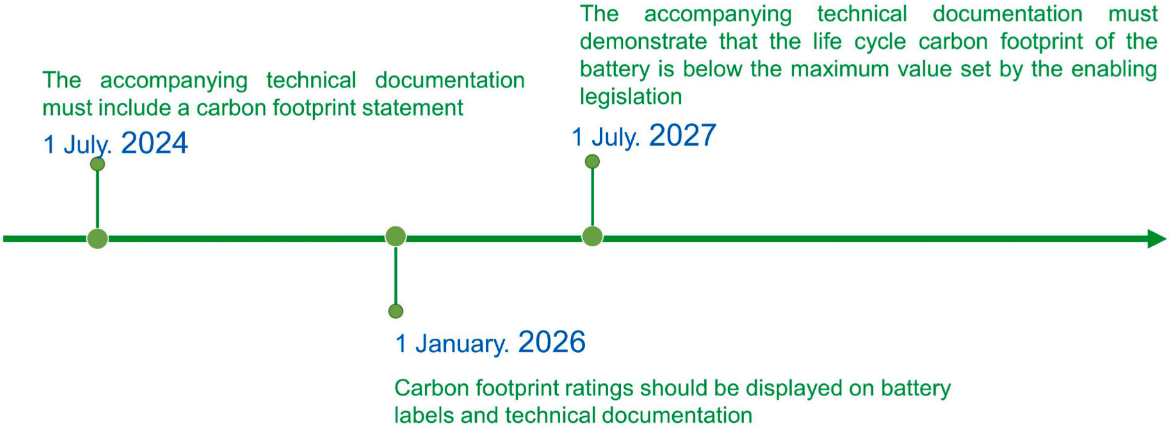


Fig. 1. Timeline of EV battery carbon footprint disclosure.

[16]. On August 17, 2023, this regulation officially came into effect (Fig. 2).

2.2. Battery carbon footprint

The concept of the "footprint family" was simultaneously and independently introduced by Giljum et al. [17] and Stoeglehner and Narodoslawsky [18]. Subsequently, Galli et al. [19,20] integrated ecological footprint, carbon footprint, and water footprint into a unified "footprint family" [21]. In recent years, with the escalating severity of global warming, the carbon footprint has garnered substantial attention from both industry and academia. Carbon footprint is defined as the amount of CO_2 emissions directly or indirectly from an activity [22], or the total CO_2 and other greenhouse gas emissions across the life cycle of a process or product [23,24]. According to the EU battery regulation, we define the carbon footprint of a battery as the total amount of CO_2 emitted directly or indirectly from the battery's raw material acquisition, pretreatment to production, transportation, and recycling.

Existing research has extensively analyzed and explored the carbon footprint of EV batteries using life cycle assessment. Studies have shown that the battery production phase is an important stage of the battery life cycle carbon emissions [25], in which active cathode materials, deformed aluminum, and electrolytes are the main contributors [26–29]. Moreover, the manufacturing location significantly influences the carbon footprint during the battery production stage due to variations in energy and power sources [27,30]. For example, batteries produced in Japan have lower carbon emissions compared to those produced in China and South Korea [31]. In China, where coal-fired electricity is predominant, the production of 24 kWh lithium manganate batteries ($LiMn_2O_4$, LMO) and lithium iron phosphate batteries ($LiFePO_4$, LFP) emit 1866 and 8827 kg CO_{2eq}, respectively. In Europe, the emissions from the production of these two kinds of batteries are 1814 and 7713 kg CO_{2eq}, respectively [9]. During the usage stage, the battery's operational conditions, design parameters, efficiency, weight, and grid carbon intensity indirectly influence their carbon emissions [32–35]. Furthermore, significant variations in carbon emissions arise from different recycling processes. Research indicates that pyrometallurgical recycling processes exhibit higher carbon emissions due to energy consumption and pollution emissions from high-temperature processing, compared to hydrometallurgical recycling and direct physical recycling processes [36,37]. Comparing the carbon footprint of different batteries, Wang et al. [38] demonstrated that the carbon footprints of lithium-air batteries, sodium-ion batteries, and lithium-sulfur batteries are lower than the current mainstream lithium nickel manganese cobalt oxide batteries ($LiNi_xCo_yMn_{1-x-y}O_2$, NCM) and LFP. Among these alternatives, lithium-air batteries exhibit the lowest carbon footprints, followed by sodium-ion batteries.

2.3. Evolutionary games

Evolutionary game theory combines game theory analysis with dynamic evolution process analysis, seeking to explore the dynamic evolution of game participants in repeated game scenarios through evolutionary stability analysis and replicator dynamic analysis. Unlike classic game theory, evolutionary game theory considers bounded rationality and incomplete information symmetry among participants. In the process of evolutionary games, participants are uncertain whether their strategies have reached the optimum, they can only adjust their strategies through imitation to approach an optimal stable state [39]. As a result, evolutionary games have greater applicability to real-life situations compared to traditional game theory and show promising prospects in the field of economics [40–45].

From the perspective of the number of game parties, research on evolutionary games can be roughly divided into two-party evolutionary games [46–50], three-party evolutionary games [51–54], and four-party evolutionary game analysis [55,56]. In terms of three-party evolutionary games, some studies focus on games among enterprises, consumers, and governments [57], while other studies explore the evolutionary games among enterprises, third-party agencies, and governments [58,59], among enterprises, local governments, and central government [2,60], or among governments, enterprises, and other enterprises [52,61]. The evolutionary game on batteries is focused on reutilization and recycling. More specifically, He and Sun [62] explored the extended producer responsibility (EPR) mechanism of power battery recycling from a supply-side perspective based on evolutionary game theory. To address the distinct difficulties in the process of waste battery-to-reutilization, Zhang et al. [63] constructed a tripartite evolutionary game that includes the government, manufacturing, and consumers. To enhance the entire lifecycle value of power battery in the double-closed-loop supply chain that includes cascade utilization, Guan et al. [64] constructed a tripartite evolutionary game model of manufacturers, third-party recyclers, and cascade utilization enterprises in the context of government subsidies and EPR.

The literature review shows that existing studies have conducted comprehensive analyses of carbon emissions of various batteries during the production, usage, and recycling phases, as well as the carbon footprint of the entire life cycle. However, few studies have explored the impact of battery carbon footprint assessment and disclosure on

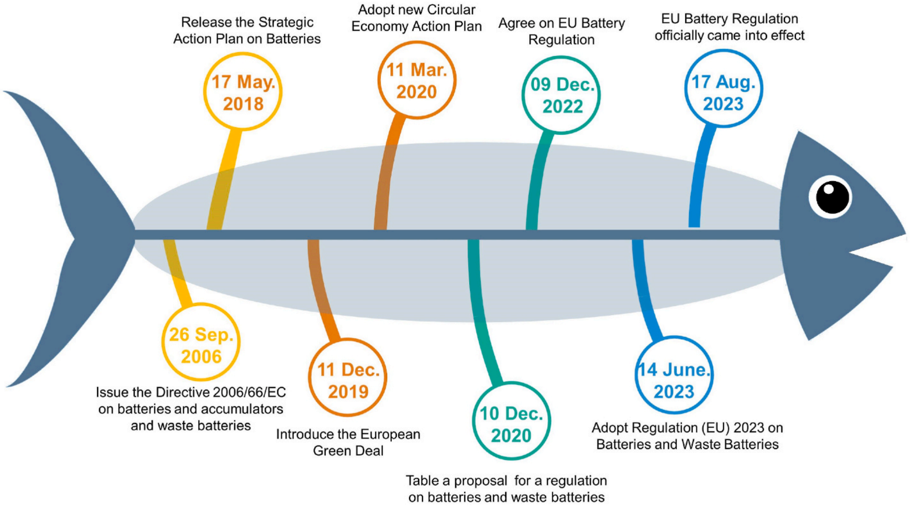


Fig. 2. Timeline of EU battery policy.

stakeholders from an economic perspective. Although evolutionary game theory has been widely used in various aspects, in the field of batteries, research on evolutionary games mainly focuses on the cascade utilization of retired batteries and the recycling of spent batteries. Limited attention has been given to the game among stakeholders concerning carbon emissions, carbon accounting, and carbon disclosure in the EV battery industry. Therefore, based on the existing research foundation and combined with the carbon footprint disclosure and verification requirements of the EU battery regulation, this study constructed a tripartite evolutionary game model including battery manufacturers, third-party verification agencies, and national market authorities, and aims to analyze the stakeholders' strategic choices, influencing factors, and evolutionary stability states.

3. Methodology

According to the objective of the study, this section will investigate the strategic decisions and interactions among battery manufacturers, third-party verification agencies, and national market authorities based on evolutionary game theory, to lay the foundation for the model analysis in the next section. To begin, we will introduce the background of the model, then put forward the basic assumptions, and subsequently formulate the payment matrix for each participant.

3.1. Model background

According to the EU battery regulation, batteries entering the EU market must provide a carbon footprint (CF) statement. This requirement covers the carbon emissions not only generated during the expected lifetime but also from each life cycle stage. This means that battery manufacturers need to measure and disclose the carbon footprint at the stages of raw material acquisition and pre-processing, product production, distribution and transportation, and collection and recycling. Nonetheless, this requirement carries potential risks of supply chain information leakage and core technology exposure, so companies may be unwilling to truthfully disclose the carbon footprint of each link. In addition, before undertaking technology upgrades and low-carbon transformation, companies tend to conservatively estimate and disclose carbon emissions in certain life cycle stages or the entire life cycle to maintain the company's low-carbon image and market competitiveness. If a company fails to truly calculate and disclose the carbon footprint data of a certain life cycle stage or the entire life cycle of the battery, the behavior is regarded as disclosing a false carbon footprint. Therefore, this article does not examine the impact of battery carbon footprint assessment and disclosure on each life cycle stage of the battery in detail. Instead, it divides corporate carbon footprint disclosure behavior into two categories: true disclosure and false disclosure. To ensure the credibility of carbon footprint data, EU regulation requires third-party agencies to verify and certify the carbon footprint data provided by enterprises. As an independent, objective, and professional institution, third-party agencies are a necessary supplement to government functions. However, objective and fair certification means that third-party agencies need to pay high costs in manpower, material resources, and time. On the contrary, casual authentication will save these costs and may even bring additional benefits. As a result, third-party agencies may be driven by profit to assist battery companies in improperly manipulating carbon footprint data. To avoid the above problems, the EU battery regulation indicates that the validity of carbon footprint data will ultimately be verified by government departments. However, due to limited administrative resources, limitations of government management, and considerations of social costs, government supervision is usually subject to certain constraints, and thus there are still opportunities for carbon footprint data manipulation.

To guide battery manufacturers to proactively disclose true carbon footprints and for third-party agencies to objectively verify carbon footprints, thereby saving government and social resources, it is necessary to construct a tripartite evolutionary game model among enterprises, third-party verification agencies, and the national market authorities.

3.2. Assumptions

Based on the relationship between the three game players, the following assumptions are proposed, and relevant parameters are designed.

Assumption 1. Battery manufacturers, third-party verification agencies, and national market authorities represent participant 1, participant 2, and participant 3, respectively. All participants exhibit bounded rationality and possess asymmetric information.

Assumption 2. The strategy space of the battery manufacturer consists of two options: disclose the true carbon footprint or disclose the false carbon footprint. The probability of disclosing true carbon footprint is denoted as x, where $x \in [0, 1]$. The strategy space for third-party verification agencies includes two choices: reject rent-seeking or intend rent-seeking. The probability of rejecting rent-seeking is denoted as y, where $y \in [0, 1]$. The strategy space of national market authorities is comprised of two options: supervise or not supervise. The probability of supervising is denoted as z, where $z \in [0, 1]$.

Assumption 3. The battery manufacturer earns I_{m1} for disclosing a true carbon footprint, and I_{m2} for disclosing a false carbon footprint and successfully entering the EU market. As disclosing a false (lower than actual) carbon footprint will improve the company's green image and market share, thus $I_{m1} < I_{m2}$. When battery manufacturers disclose false carbon footprints, they incur false costs denoted as C_m. To make the products pass the verification and enter the market, companies that disclose false carbon footprints will seek rent from third-party verification agencies, with the cost of rent-seeking represented as K.

Assumption 4. The benefits for the third-party verification agencies in rejecting or intending rent-seeking are denoted as I_{a1} and I_{a2}, respectively. Intending rent-seeking allows lenient evaluations, saving manpower, resources, and time, hence, $I_{a1} < I_{a2}$. Counterfeiting costs arise when third-party verification agencies intend to seek rent, denoted as C_a. When battery manufacturers disclose a false carbon footprint, the product cannot enter the EU market if the third-party verification agencies refuse to rent-seek; if the third-party verification agencies intend to rent-seeking, rent-seeking is successful, the battery is allowed to entry, and the third-party verification agencies will receive the rent-seeking revenue K.

Assumption 5. The social benefits of battery manufacturers disclosing true and false carbon footprint are denoted as I_{g1} and I_{g2}, respectively. Disclosing the true carbon footprint contributes to the promotion of regulation and the green and low-carbon development of the battery industry. Conversely, disclosing false carbon footprints may be imitated by peer companies, thereby affecting the battery industry's development, and hindering the achievement of carbon neutrality goals. Hence, $I_{g1} > I_{g2}$. The cost of government supervision is denoted as C_g. Fines (F_m and F_a) are imposed on manufacturers or verification agencies if they are found to be falsified during the disclosure and verification process.

Fig. 3 illustrates the logical relationship of the tripartite evolutionary game model for carbon footprint disclosure in vehicle batteries. Table 1 presents the parameters involved in the game process.

3.3. Payoff matrix construction

According to the above assumptions, there are eight strategic combinations in the evolutionary game among battery manufacturers, third-party verification agencies, and national market authorities.

Fig. 3. Logic relation diagram of the three-party evolutionary game.

Table 1
Parameters of the three-party evolutionary game.

Parameter	Description	Remark
I_{m1}	Benefits for battery manufacturers disclosing true CF	$I_{m1} > 0$
I_{m2}	Benefits for battery manufacturers disclosing false CF	$I_{m2} > I_{m1} > 0$
C_m	Counterfeiting cost for battery manufacturers disclosing false CF	$C_m > 0$
K	Rent-seeking costs (benefits)	$K > 0$
I_{a1}	Revenue of the third-party verification agency rejecting rent-seeking	$I_{a1} > 0$
I_{a2}	Revenue of the third-party verification agency intent on rent-seeking	$I_{a2} > I_{a1} > 0$
C_a	Fraudulent costs of the third-party verification agency	$C_a > 0$
I_{g1}	Societal benefits of battery manufacturers disclosing true CF	$I_{g1} > 0$
I_{g2}	Societal benefits of battery manufacturers disclosing false CF	$I_{g1} > I_{g2} > 0$
C_g	Supervising costs of the national market authority	$C_g > 0$
F_m	Fines imposed on battery manufacturers for disclosing false CF	$F_m > 0$
F_a	Fines imposed on the third-party verification agency for rent-seeking	$F_a > 0$

(1) When the strategy combination is {disclose true carbon footprint, reject rent-seeking, supervise}, companies and third-party agencies receive regular benefits, and the government pays the cost of supervision. The utilities of the three participants are I_{m1}, I_{a1}, and $I_{g1} - C_g$, respectively.

(2) When the strategy combination is {disclose true carbon footprint, intend rent-seeking, supervise}, companies gain regular profits, third-party agencies pay counterfeiting costs and fines, and the government spends the cost of supervision and obtains fine income. As a result, the utilities of the three participants are I_{m1}, $I_{a2} - C_a - F_a$, and $I_{g1} - C_g + F_a$, respectively.

(3) When the strategy combination is {disclose false carbon footprint, reject rent-seeking, supervise}, companies pay counterfeiting costs and fines, third-party agencies gain regular revenue, and the government spends the cost of regulation and obtains fine income. As a result, the utilities of the three participants are $-C_m - F_m$, I_{a1}, and $I_{g2} - C_g + F_m$, respectively.

(4) When the strategy combination is {disclose false carbon footprint, intend rent-seeking, supervise}, companies and the third-party agencies reach an agreement on falsifying carbon footprint data. Enterprises pay counterfeiting costs and rent-seeking costs, and third-party agencies pay counterfeiting costs but gain rent-seeking benefits. However, due to government supervision, companies and agencies face fines. As a result, the utilities of the three participants are $I_{m2} - C_m - K - F_m$, $I_{a2} - C_a + K - F_a$, and $I_{g2} - C_g + F_m + F_a$, respectively.

(5) When the strategy combination is {disclose true carbon footprint, reject rent-seeking, don't supervise}, companies and third-party agencies gain regular benefits, and the government also saves supervision costs. This is an ideal state, and the utilities of the three participants are I_{m1}, I_{a1}, and I_{g1}, respectively.

(6) When the strategy combination is {disclose true carbon footprint, intend rent-seeking, don't supervise}, companies gain regular benefits, and third-party agencies pay counterfeiting costs. The utilities of the three participants are I_{m1}, $I_{a2} - C_a$, and I_{g1}, respectively.

(7) When the strategy combination is {disclose false carbon footprint, reject rent-seeking, don't supervise}, due to objective verification by third-party agencies, manufacturers fail to enter the EU market and gain any benefits while paying the cost of counterfeiting. Third-party agencies and the government gain regular benefits. Therefore, the utilities of the three participants are $-C_m$, I_{a1}, and I_{g2}, respectively.

(8) When the strategy combination is {disclose false carbon footprint, intend rent-seeking, don't supervise}, companies and third-party agencies reach an agreement on falsifying carbon footprint data. Enterprises pay counterfeiting costs and rent-seeking costs, third-party agencies pay counterfeiting costs but gain rent-seeking benefits. As a result. the utilities of the three participants are $I_{m2} - C_m - K$, $I_{a2} - C_a + K$, and I_{g2}, respectively.

Based on the above strategic combinations, the payoff matrix of the evolutionary game is constructed, as shown in Table 2.

4. Model analysis

According to the payoff matrix shown in Table 2, the replicated dynamic equations for battery manufacturers, third-party verification agencies, and national market authorities can be calculated, and then the stability analysis of the evolutionary game system can be performed.

4.1. Replicated dynamic system

4.1.1. Replication dynamic equation for battery manufacturer

The expected return of the battery manufacturer for disclosing true carbon footprint, disclosing false carbon footprint, and the average expected return are denoted as E_{11}, E_{12} and $\overline{E_1}$:

Table 2
The payoff matrix of battery manufacturers, third-party verification agencies, and the national market authorities.

Manufacturers	Third-party agencies	National market authorities	
		Supervise z	Don't supervise $1 - z$
Disclose true CF x	Reject rent-seeking y	$I_{m1}, I_{a1}, I_{g1} - C_g$	I_{m1}, I_{a1}, I_{g1}
	Intend rent-seeking $1 - y$	$I_{m1}, I_{a2} - C_a - F_a, I_{g1} - C_g + F_a$	$I_{m1}, I_{a2} - C_a, I_{g1}$
Disclose false CF $1 - x$	Reject rent-seeking y	$-C_m - F_m, I_{a1}, I_{g2} - C_g + F_m$	$-C_m, I_{a1}, I_{g2}$
	Intend rent-seeking $1 - y$	$I_{m2} - C_m - K - F_m, I_{a2} - C_a + K - F_a, I_{g2} - C_g + F_m + F_a$	$I_{m2} - C_m - K, I_{a2} - C_a + K, I_{g2}$

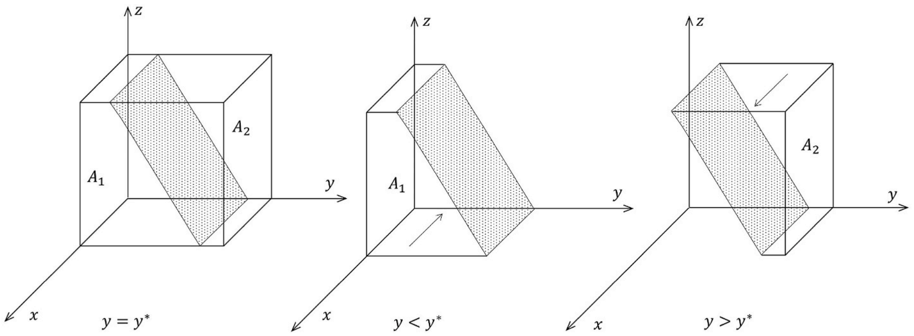


Fig. 4. Strategy evolution phase diagram of battery manufacturers.

$$E_{11} = I_{m1}[yz + (1-y)z + y(1-z) + (1-y)(1-z)] = I_{m1} \tag{1}$$

$$\begin{aligned} E_{12} &= yz(-C_m - F_m) + (1-y)z(I_{m2} - C_m - K - F_m) + y(1-z)(-C_m) \\ &+ (1-y)(1-z)(I_{m2} - C_m - K) = I_{m2} - C_m - K - zF_m + y(K - I_{m2}) \end{aligned} \tag{2}$$

$$\begin{aligned} \overline{E_1} &= xE_{11} + (1-x)E_{12} \\ &= xI_{m1} + (1-x)[I_{m2} - C_m - K - zF_m + y(K - I_{m2})] \end{aligned} \tag{3}$$

The replication dynamic equation for the battery manufacturer's strategy selection is:

$$F_1(x) = \frac{dx}{dt} = x(E_{11} - \overline{E_1}) = x(1-x)[C_m + I_{m1} - I_{m2} + K + zF_m + y(I_{m2} - K)] \tag{4}$$

Denote $U(y) = C_m + I_{m1} - I_{m2} + K + zF_m + y(I_{m2} - K)$, since rent-seeking costs are lower than the benefits of disclosing false carbon footprints, $\frac{\partial U(y)}{\partial y} > 0$.

$$f(x) = \frac{dF_1(x)}{dx} = (1-2x)[C_m + I_{m1} - I_{m2} + K + zF_m + y(I_{m2} - K)] \tag{5}$$

According to the stability theorem of the differential equation, the probability that a battery manufacturer disclosing true carbon footprint is in a steady state must satisfy the conditions: $F(x) = 0$ and $f(x) < 0$. When $y = \frac{C_m + I_{m1} - I_{m2} + K + zF_m}{K - I_{m2}} = y^*$, $U(y) \equiv 0$, then $f(x) \equiv 0$, stabilization strategies for battery makers are uncertain. When $y < y^*$, since $U(y)$ is an increasing is function of y, $U(y) < 0$. Therefore, $f(x)|_{x=0} < 0$, $x = 0$ is the evolutionary stable strategy (ESS) of the battery manufacturer. When $y > y^*$, since $U(y)$ is an increasing function of y, $U(y) > 0$. Therefore, $f(x)|_{x=1} < 0$, $x = 1$ is the ESS of the battery manufacturer.

The strategy evolution phase diagram of battery manufacturers is shown in Fig. 4. The probability of battery manufacturers disclosing false carbon footprint and true carbon footprint is the volume of A_1 and A_2, denoted as V_{A1} and V_{A2}, respectively. $V_{A2} = 1 - V_{A1}$, and $V_{A1}, V_{A2} \in [0, 1]$.

$$V_{A2} = 1 - V_{A1} = 1 - \int_0^1 \int_0^1 \frac{C_m + I_{m1} - I_{m2} + K + zF_m}{K - I_{m2}} dzdx = \frac{C_m + I_{m1} + \frac{1}{2}F_m}{K - I_{m2}} \tag{6}$$

According to $\frac{\partial V_{A2}}{\partial K} > 0$, $\frac{\partial V_{A2}}{\partial C_m} > 0$, $\frac{\partial V_{A2}}{\partial F_m} > 0$, $\frac{\partial V_{A2}}{\partial I_{m1}} > 0$, and $\frac{\partial V_{A2}}{\partial I_{m2}} < 0$, we know that the probability of battery manufacturers disclosing true carbon footprints is positively correlated with rent-seeking costs, fraudulent costs, fines, and the benefits of disclosing true carbon footprints, and negatively correlated with the benefits of disclosing false carbon footprints.

4.1.2. Replication dynamic equation for third-party verification agencies

The expected return of the third-party verification agencies for rejecting rent-seeking (rigorous evaluation), intending rent-seeking (lenient evaluation), and the average expected return are denoted as E_{21}, E_{22} and $\overline{E_2}$:

$$E_{21} = I_{a1}[xz + (1-x)z + x(1-z) + (1-x)(1-z)] = I_{a1} \tag{7}$$

$$\begin{aligned} E_{22} &= xz(I_{a2} - C_a - F_a) + (1-x)z(I_{a2} - C_a + K - F_a) + x(1-z)(I_{a2} - C_a) + \\ &(1-x)(1-z)(I_{a2} - C_a + K) = I_{a2} - C_a + K - zF_a - xK \end{aligned} \tag{8}$$

$$\overline{E_2} = yE_{21} + (1-y)E_{22} = yI_{a1} + (1-y)(I_{a2} - C_a + K - zF_a - xK) \tag{9}$$

The replication dynamic equation for the strategy selection of the third-party verification agencies is:

$$F_2(y) = \frac{dy}{dt} = y \cdot (E_{21} - \overline{E_2}) = y(1-y)(C_a + I_{a1} - I_{a2} - K + zF_a + xK) \tag{10}$$

Denote $V(z) = C_a + I_{a1} - I_{a2} - K + zF_a + xK$, $\frac{\partial V(z)}{\partial z} = F_a > 0$.

$$f(y) = \frac{dF_2(y)}{dy} = (1-2y)[C_a + I_{a1} - I_{a2} - K + zF_a + xK] \tag{11}$$

According to the stability theorem of differential equations, the probability that third-party verification agencies rejecting rent-seeking (rigorous evaluation) is in a stable state must satisfy conditions: $F(y) = 0$ and $f(y) < 0$. When $z = -\frac{C_a + I_{a1} - I_{a2} - K + xK}{F_a} = z^*$, $V(z) \equiv 0$, then $f(y) \equiv 0$, stabilization strategies for the third-party verification agencies are uncertain. When $z < z^*$, since $V(z)$ is an increasing function of z, $V(z) < 0$. Therefore, $f(y)|_{y=0} < 0$, $y = 0$ is the ESS for the third-party verification agencies. When $z > z^*$, since $V(z)$ is an increasing function of z, $V(z) > 0$. Therefore, $f(y)|_{y=1} < 0$, $y = 1$ is the ESS for the third-party verification agencies.

The phase diagram of the strategy evolution of the third-party verification agencies is shown in Fig. 5. The probability that the third-party verification agencies intend to seek rent and reject rent-seeking is the volume of B_1 and B_2, denoted as V_{B1} and V_{B2}, respectively. $V_{B2} = 1 - V_{B1}$, and $V_{B1}, V_{B2} \in [0,1]$.

$$V_{B2} = 1 - V_{B1} = 1 - \int_0^1 \int_0^1 -\frac{C_a + I_{a1} - I_{a2} - K + xK}{F_a} dxdy = \frac{F_a + C_a + I_{a1} - I_{a2} - \frac{1}{2}K}{F_a} \tag{12}$$

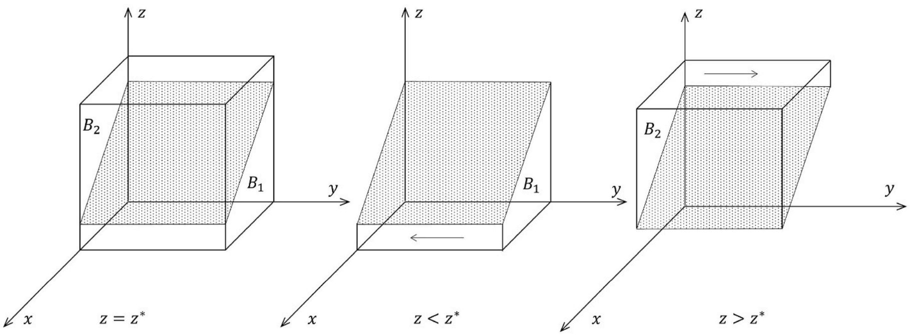


Fig. 5. Phase diagram of third-party verification agencies strategy evolution.

According to $\frac{\partial V_{B2}}{\partial C_a} > 0$, $\frac{\partial V_{B2}}{\partial F_a} > 0$, $\frac{\partial V_{B2}}{\partial I_{a1}} > 0$, $\frac{\partial V_{B2}}{\partial K} < 0$, and $\frac{\partial V_{B2}}{\partial I_{a2}} < 0$, the probability of rejecting rent-seeking by the third-party agencies is positively correlated with fraud costs, fines, and carefully assessed returns, and negatively correlated with rent-seeking returns and casually assessed returns.

4.1.3. Replication dynamic equation for the national market authorities

The expected return of the national market authorities' supervision, without supervision, and the average expected return are E_{31}, E_{32} and $\overline{E_3}$:

$$\mathrm{E_{31}} = \mathrm{xy}\left(\mathrm{I_{g1}} - \mathrm{C_g}\right) + \mathrm{x}(1-\mathrm{y})\left(\mathrm{I_{g1}} - \mathrm{C_g} + \mathrm{F_a}\right) + (1-\mathrm{x})\mathrm{y}\left(\mathrm{I_{g1}} - \mathrm{C_g} + \mathrm{F_m}\right) + (1-\mathrm{x})(1-\mathrm{y})\left(\mathrm{I_{g2}} - \mathrm{C_g} + \mathrm{F_m} + \mathrm{F_a}\right) = \mathrm{F_a} - \mathrm{C_g} + \mathrm{F_m} + \mathrm{I_{g2}} - \mathrm{x}\left(\mathrm{F_m} + \mathrm{I_{g2}} - \mathrm{I_{g1}}\right) - \mathrm{yF_a} \tag{13}$$

$$\mathrm{E_{32}} = \mathrm{xyI_{g1}} + \mathrm{x}(1-\mathrm{y})\mathrm{I_{g1}} + (1-\mathrm{x})\mathrm{yI_{g2}} + (1-\mathrm{x})(1-\mathrm{y})\mathrm{I_{g2}} = \mathrm{I_{g2}} + \mathrm{x}\left(\mathrm{I_{g1}} - \mathrm{I_{g2}}\right) \tag{14}$$

$$\begin{aligned}\overline{\mathrm{E_3}} &= \mathrm{zE_{31}} + (1-\mathrm{z})\mathrm{E_{32}} \\ &= \mathrm{I_{g2}} + \mathrm{z}\left(\mathrm{F_a} + \mathrm{F_m} - \mathrm{C_g}\right) + \mathrm{x}\left(\mathrm{I_{g1}} - \mathrm{I_{g2}}\right) - \mathrm{xzF_m} - \mathrm{yzF_a}\end{aligned} \tag{15}$$

The replication dynamic equation for the strategy choice of the national market authorities is:

$$\mathrm{F_3(z)} = \frac{\mathrm{dz}}{\mathrm{dt}} = \mathrm{z}\left(\mathrm{E_{31}} - \overline{\mathrm{E_3}}\right) = \mathrm{z}(\mathrm{z}-1)\left(\mathrm{C_g} - \mathrm{F_a} - \mathrm{F_m} + \mathrm{xF_m} + \mathrm{yF_a}\right) \tag{16}$$

Denote $W(x) = C_g - F_a - F_m + xF_m + yF_a$, $\frac{\partial W(x)}{\partial x} = F_m > 0$.

$$\mathrm{f(z)} = \frac{\mathrm{dF_3(z)}}{\mathrm{dz}} = (2\mathrm{z}-1)\left[\mathrm{C_g} - \mathrm{F_a} - \mathrm{F_m} + \mathrm{xF_m} + \mathrm{yF_a}\right] \tag{17}$$

According to the stability theorem for differential equations, the probability that the national market authorities choose further supervision is in a stable state must satisfy the conditions of $F(z) = 0$ and $f(z) < 0$. When $x = -\frac{C_g - F_a - F_m + yF_a}{F_m} = x^*$, $W(x) \equiv 0$, then $f(z) \equiv 0$, stabilization strategies for the national market authorities are uncertain. When $x < x^*$, since $W(x)$ is an increasing function of x, $W(x) < 0$. Therefore, $f(z)|_{z=1} < 0$, $z = 1$ is the ESS of the national market authorities. When $x > x^*$, since $W(x)$ is an increasing function of x, $W(x) > 0$. Therefore, $f(z)|_{z=0} < 0$, $z = 0$ is the ESS of the national market authorities.

The phase diagram of the strategy evolution of the national market authorities is shown in Fig. 6. The probability of national market authorities supervising and not supervising is the volume of C_1 and C_2, denoted as V_{C1} and V_{C2}, respectively. $V_{C2} = 1 - V_{C1}$, and V_{C1}, $V_{C2} \in [0, 1]$.

$$\mathrm{V_{C2}} = 1 - \mathrm{V_{C1}} = 1 - \int_0^1\int_0^1 -\frac{\mathrm{C_g} - \mathrm{F_a} - \mathrm{F_m} + \mathrm{yF_a}}{\mathrm{F_m}}\mathrm{dydz} = \frac{\mathrm{C_g} - \frac{1}{2}\mathrm{F_a}}{\mathrm{F_m}} \tag{18}$$

According to $\frac{\partial V_{C2}}{\partial C_g} > 0$, $\frac{\partial V_{C2}}{\partial F_m} < 0$, and $\frac{\partial V_{C2}}{\partial F_a} < 0$, the probability of non-supervision by national market authorities is positively related to the cost of supervision, and negatively related to the benefit of penalties.

4.2. Stability analysis of the evolutionary system

Further solving the replicated dynamic equations (5), (10) and (15) shows that, there are 15 equilibrium points in the game process among battery companies, the third-party verification agencies and national market authorities, including 8 pure strategy equilibrium points $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, $E_8(1,1,1)$ and 7 mixed strategy equilibrium points $E_9((C_mF_a - C_aF_m - C_gI_{m2} + C_g\mathrm{K} + F_aI_{m1} - F_mI_{a1} + F_mI_{a2} + F_mI_{m2})/(F_mI_{m2}), -(C_mF_a - C_aF_m + C_g\mathrm{K} + F_aI_{m1} - F_mI_{a1} - F_aI_{m2} + F_mI_{a2})/(F_aI_{m2}), -(C_gK^2 + C_aF_mI_{m2} - C_aF_mK + C_mF_aK - C_gI_{m2}K + F_mI_{a1}I_{m2} - F_mI_{a2}I_{m2} + F_aI_{m1}K - F_mI_{a1}K + F_mI_{a2}K)/(F_aF_mI_{m2}))$, $\mathrm{E_{10}}(-$

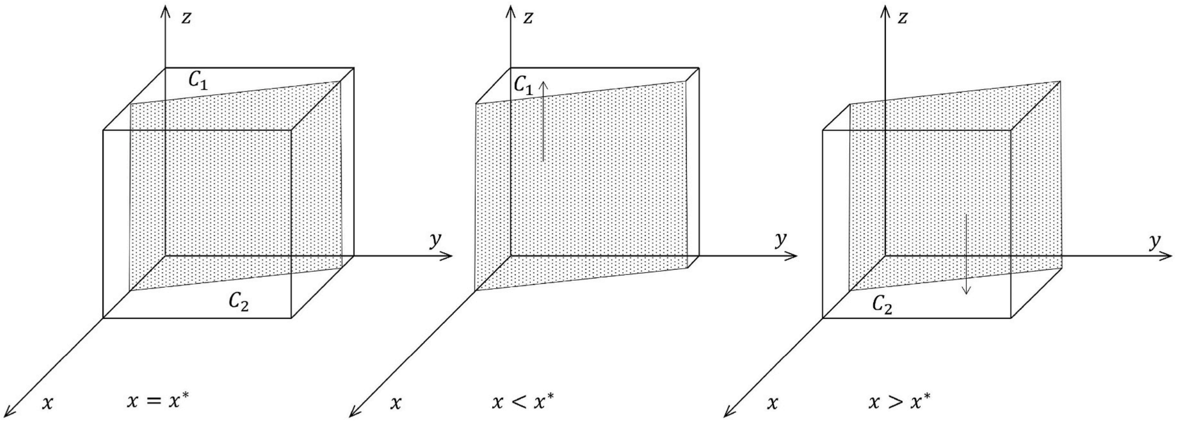


Fig. 6. Phase diagram of the strategy evolution of the national market authorities.

$(C_a + I_{a1} - I_{a2} - K)/K, -(C_m + I_{m1} - I_{m2} + K)/(I_{m2} - K), 0)$, $E_{11}(-(C_g - F_m)/F_m, 1, -(C_m + I_{m1})/F_m)$, $E_{12}((F_a - C_g + F_m)/F_m, 0, -(C_m + I_{m1} - I_{m2} + K)/F_m)$, $E_{13}(-(C_a + F_a + I_{a1} - I_{a2} - K)/K, -(C_m + F_m + I_{m1} - I_{m2} + K)/(I_{m2} - K), 1)$, $E_{14}(0, (F_a - C_g + F_m)/F_a, -(C_a + I_{a1} - I_{a2} - K)/F_a)$, $E_{15}(1, -(C_g - F_a)/F_a, -(C_a + I_{a1} - I_{a2})/F_a)$. E_{11} is meaningless for $-(C_m + I_{m1})/F_m < 0$. For $x, y, z \in [0,1]$, $E_9, E_{10}, E_{12} \sim E_{15}$ are meaningful under certain conditions. If the equilibrium of the three-party evolutionary game is an asymptotically stable state, the equilibrium must be a strict Nash equilibrium, which is a pure strategy equilibrium. Therefore, the asymptotic stability of the three-party evolutionary game only needs to discuss the asymptotic stability of the pure strategy equilibrium point in the replication dynamic equation, that is, discuss the asymptotic stability of $E_1 \sim E_8$ [59,65].

According to the Lyapunov system stability discriminant method, the equilibrium point is asymptotically stable when all the eigenvalues of the Jacobian matrix are negative [66]; The equilibrium point is unstable when at least one of the eigenvalues of the Jacobian matrix is positive. The Jacobian matrix of the game system of battery manufacturers, third-party verification agencies, and national market authorities is denoted as J:

$$J = \begin{bmatrix} \dfrac{\partial F_1(x)}{\partial x} & \dfrac{\partial F_1(x)}{\partial y} & \dfrac{\partial F_1(x)}{\partial z} \\ \dfrac{\partial F_2(y)}{\partial x} & \dfrac{\partial F_2(y)}{\partial y} & \dfrac{\partial F_2(y)}{\partial z} \\ \dfrac{\partial F_3(z)}{\partial x} & \dfrac{\partial F_3(z)}{\partial y} & \dfrac{\partial F_3(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} \tag{19}$$

$$\begin{cases} J_{11} = (1-2x)[C_m + I_{m1} - I_{m2} + K + zF_m + y(I_{m2} - K)] \\ J_{12} = x(1-x)(I_{m2} - K) \\ J_{13} = x(1-x)F_m \\ J_{21} = y(1-y)K \\ J_{22} = (1-2y)[C_a + I_{a1} - I_{a2} - K + zF_a + xK] \\ J_{23} = x(1-x)F_a \\ J_{31} = z(z-1)F_m \\ J_{32} = z(z-1)F_a \\ J_{33} = (2z-1)[C_g - F_a - F_m + xF_m + yF_a] \end{cases} \tag{20}$$

Taking the equilibrium point $E_1(0,0,0)$ as an example, its Jacobian matrix can be abbreviated as:

$$J_1 = \begin{bmatrix} C_m + I_{m1} - I_{m2} + K & 0 & 0 \\ 0 & C_a + I_{a1} - I_{a2} - K & 0 \\ 0 & 0 & F_a + F_m - C_g \end{bmatrix} \tag{21}$$

The corresponding eigenvalues of the Jacobian matrix are: $\lambda_1 = F_a + F_m - C_g, \lambda_2 = C_a + I_{a1} - I_{a2} - K, \lambda_3 = C_m + I_{m1} - I_{m2} + K$, respectively. Similarly, the eigenvalues of the Jacobian matrix corresponding to the other seven pure strategy equilibrium points can be calculated, as shown in Table 3.

Table 3
Equilibrium points and eigenvalues of the system.

Equilibrium points		Eigenvalues		Asymptotic stability
	λ_1	λ_2	λ_3	
$E_1(0,0,0)$	$F_a + F_m - C_g$	$C_a + I_{a1} - I_{a2} - K$	$C_m + I_{m1} - I_{m2} + K$	Unstable
$E_2(1,0,0)$	$F_a - C_g$	$C_a + I_{a1} - I_{a2}$	$-C_m - I_{m1} + I_{m2} - K$	Unstable
$E_3(0,1,0)$	$F_m - C_g$	$C_m + I_{m1}$	$-C_a - I_{a1} + I_{a2} + K$	Unstable
$E_4(0,0,1)$	$-F_a - F_m + C_g$	$C_m + I_{m1} - I_{m2} + K + F_m$	$C_a + I_{a1} - I_{a2} - K + F_a$	Condition
$E_5(1,1,0)$	$-C_g$	$-C_m - I_{m1}$	$-C_a - I_{a1} + I_{a2}$	Condition
$E_6(1,0,1)$	$-F_a + C_g$	$C_a + I_{a1} - I_{a2} + F_a$	$-C_m - I_{m1} + I_{m2} - K - F_m$	Unstable
$E_7(0,1,1)$	$-F_m + C_g$	$C_m + I_{m1} + F_m$	$-C_a - I_{a1} + I_{a2} + K - F_a$	Unstable
$E_8(1,1,1)$	C_g	$-C_m - I_{m1} - F_m$	$-C_a - I_{a1} + I_{a2} - F_a$	Unstable

Based on the conditions of $0 < C_g - \frac{1}{2}F_a < F_m$ and $F_a + F_m - C_g > 0$, E_1 is an unstable point. Considering $C_m + I_{m1} + \frac{1}{2}F_m < I_{m2} - K$ and $-C_m - I_{m1} + I_{m2} - K > 0$, E_2 is also an unstable point. Additionally, under the condition: $-F_a < C_a + I_{a1} - I_{a2} - \frac{1}{2}K < 0$, $C_a + I_{a1} - I_{a2} + F_a > 0$, E_6 is identified as an unstable point. Meanwhile, E_3, E_7, E_8 are also classified as unstable points due to $C_m + I_{m1} > 0$, $C_m + I_{m1} + F_m > 0$, $C_g > 0$. E_4 and E_5 have asymptotic evolutionary stability when certain conditions are satisfied as analyzed in the following scenarios:

Scenario 1. When $I_{a2} - I_{a1} < C_a$, the evolutionary system exhibits at least one evolutionary stable strategy (ESS), $E_5(1,1,0)$. This means that when the fraudulent cost of third-party verification agencies exceeds the additional benefits obtained by casually verifying the carbon footprint, third-party agencies choose to reject rent-seeking and objectively assess the disclosed carbon footprints. In response, battery manufacturers opt to disclose the true carbon footprint, while national market authorities choose not to supervise, aiming to save social resources. As a result, the strategy evolution of the game participants stabilizes at {disclose true carbon footprint, reject rent-seeking, not supervise}.

Scenario 2. When $I_{a1} < I_{a2} - C_a + K - F_a$ and $I_{m1} < I_{m2} - C_m - K - F_m$, the evolutionary system demonstrates at least one ESS, $E_4(0,0,1)$. In this scenario, the combined cost of falsification, rent-seeking, and fines for battery manufacturers is lower than the additional benefits of disclosing false carbon footprints; the total cost of falsification and penalties for third-party verification agencies is lower than the additional benefits from rent-seeking. Consequently, manufacturers and third-party agencies succeed in rent-seeking, and national market authorities choose to supervise. The strategy evolution of the game participants stabilizes at {disclose false carbon footprint, intend rent-seeking, supervise}.

Scenario 3. When $I_{a2} - C_a < I_{a1} < I_{a2} - C_a + K - F_a$ and $I_{m1} < I_{m2} - C_m - K - F_m$, the evolutionary system exhibits two ESSs: $E_4(0,0,1)$ and $E_5(1,1,0)$. In this case, when the total cost of counterfeiting, rent-seeking, and fines for battery manufacturers is lower than the additional benefits of disclosing false carbon footprints, and the benefits for third-party verification agencies from rejecting rent-seeking are higher than intentional rent-seeking but lower than being fined for rent-seeking, the agencies may choose to reject or intend rent-seeking. Similarly, national market authorities may choose to supervise or not supervise. Depending on the initial strategy selection, the strategy portfolio evolution stabilizes at either {disclose false carbon footprint, intend rent-seeking, supervise} or {disclose true carbon footprint, reject rent-seeking, not supervise}.

Scenario 4. When $C_a + I_{a1} - I_{a2} - K + F_a < F_a - K < 0$ or $C_a + I_{a1} - I_{a2} - K + F_a < 0 < F_a - K$, and $I_{m1} < I_{m2} - C_m - K - F_m$, there is only one ESS, $E_4(0,0,1)$. In this scenario, the total cost of falsification, rent-seeking, and fines for battery manufacturers is lower than the additional income from disclosing false carbon footprints, and the benefits of third-party verification agencies rejecting rent-seeking is lower than that of being punished for successful rent-seeking, thence third-party agencies will inevitably choose intentional rent-seeking. Consequently, battery manufacturers opt to disclose false carbon footprints, and national market authorities choose to conduct supervision. As a result, the strategy portfolio evolution stabilizes at {disclose false carbon footprint,

Table 4
Stable equilibrium points and conditions.

Scenarios	Conditions		$E_4(0,0,1)$	$E_5(1,1,0)$
Scenario 1	$-C_a - I_{a1} + I_{a2} < 0$		/	Stable
Scenario 2	$C_a + I_{a1} - I_{a2} - K + F_a < 0$	$C_m + I_{m1} - I_{m2} + K + F_m < 0$	Stable	/
Scenario 3	$-K + F_a < C_a + I_{a1} - I_{a2} - K + F_a < 0$	$C_m + I_{m1} - I_{m2} + K + F_m < 0$	Stable	Stable
Scenario 4	$C_a + I_{a1} - I_{a2} - K + F_a < F_a - K < 0$ or $C_a + I_{a1} - I_{a2} - K + F_a < 0 < F_a - K$	$C_m + I_{m1} - I_{m2} + K + F_m < 0$	Stable	Unstable

Note：/indicates uncertainty.

intend rent-seeking, supervise}.

The above scenarios are summarized in Table 4.

5. Numerical simulation

The key to constructing a simulation model is whether it can describe the internal regularity of changes in things [50]. However, due to the lack of actual data or the complexity of the real world, it is difficult to extract relevant information. Hence, many similar studies use idealized parameters to simulate theoretical models. Considering that the newly introduced EU battery regulation has not yet been implemented and it is difficult to obtain actual data for simulation, this study refers to the literature [2,67] for parameter settings. When setting the parameters, we also strive to make them more logically consistent. Finally, according to the set parameters, Matlab2023a is used to conduct numerical simulations to verify the effectiveness of the evolutionary stability analysis.

5.1. Impact of different initial parameters on system stability

Since Scenario 3 includes the situations of Scenario 1 and Scenario 2, we mainly simulate the situations of Scenario 3 and Scenario 4 in this section. Specifically, we set two sets of values separately. Array 1 that satisfies the conditions of Scenario 3: $I_{m1} = 100, I_{m2} = 180, C_m = 14, K = 36, F_m = 16, C_g = 15, F_a = 12, I_{a2} = 80, C_a = 18, I_{a1} = 74$; Array 2 that satisfies the conditions of Scenario 4: $I_{m1} = 100, I_{m2} = 180, C_m = 14, K = 36, F_m = 16, C_g = 15, F_a = 12, I_{a2} = 80, C_a = 18, I_{a1} = 55$. The above two sets of values evolved 50 times over time starting from different initial strategy combinations, and the results are shown in Fig. 7.

Fig. 7a demonstrates that in Scenario 3, the evolutionary game system exhibits two ESSs: $E_4(0,0,1)$ and $E_5(1,1,0)$. The ultimate stable strategy combination is determined by the initial position of the three-party strategy. To achieve the ideal state of {disclose true carbon footprint, reject rent-seeking, not supervise}, the government can enhance penalties for battery manufacturers and third-party agencies, and utilize the media to criticize or praise relevant participants, thereby increasing the probability of truthful disclosing and objective assessment of carbon footprints.

Fig. 7b reveals that in Scenario 4, the evolutionary game system has only one ESS, $E_4(0,0,1)$. Compared with “Array 1”, the benefit of third-party verification agencies rejecting rent-seeking (objective evaluation) in “Array 2” is significantly lower, resulting in an increased probability of intentional rent-seeking. Consequently, the probability of battery companies disclosing false carbon footprints increases, and the possibility of supervision by national market authorities will increase, which ultimately leads the three-party game towards a stable state of {disclose false carbon footprints, intend rent-seeking, supervise}.

5.2. Impact of battery manufacturer counterfeiting cost and fines on system stability

To analyze the impact of C_m and F_m on the evolutionary game process and results, we set $C_m = 9, 14, 19$, and $F_m = 13, 16, 19$, respectively, and let the replicated dynamic equations evolve 50 times, as shown in Fig. 8.

Fig. 8 demonstrates that an increase in C_m and F_m leads to a higher probability of manufacturers disclosing the true carbon footprint. However, as the system evolves towards a stable point, the probability of rent-seeking intentions of third-party agencies increases and the probability of supervision by national market authorities decreases. This resulted in battery manufacturers still having incentives to disclose false carbon footprints, despite the high costs of counterfeiting and fines. Consequently, x gradually decreases, z gradually increases, and the three parties of the game move to a steady state of {disclose false carbon footprint, intend rent-seeking, supervise}.

5.3. Impact of rent-seeking cost (income) on system stability

To analyze the impact of rent-seeking cost (income) K on the process and results of the evolutionary game, we set $K = 31, 36, 41$, and let the replicated dynamic equations evolve 50 times. The results are shown in Fig. 9.

According to Fig. 9, an increase in the rent-seeking revenue (cost) K leads to a higher probability of intentional rent-seeking by third-party agencies. However, as the evolutionary system evolves to a stable point, the reduced probability of government supervision incentivizes companies to bear higher rent-seeking costs to enter the EU market and occupy market share by disclosing false carbon footprints. In this regard, the government must increase supervision. Consequently, x gradually

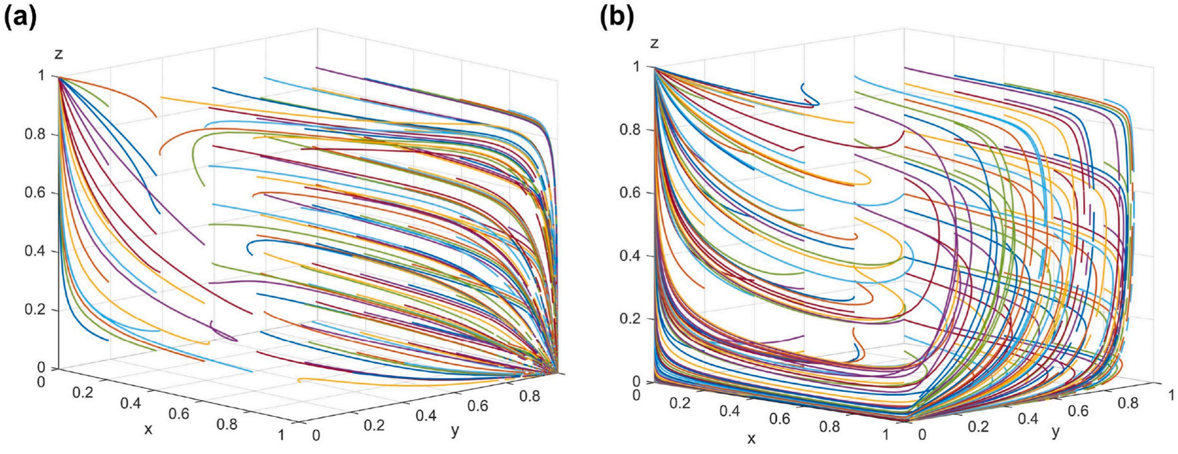


Fig. 7. (a) The result of evolutions of array 1; (b) The result of evolutions of array 2.

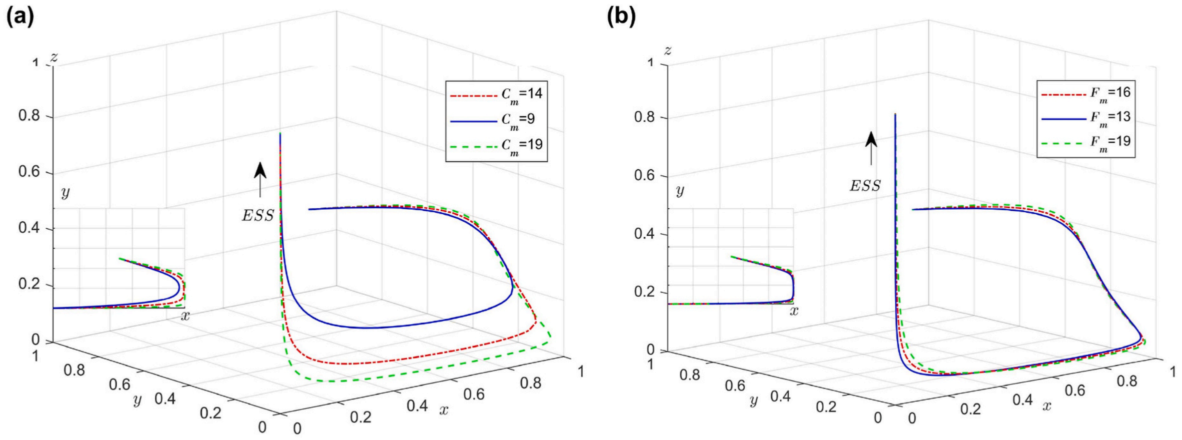


Fig. 8. (a) The influence of C_m on evolutionary processes; (b) The influence of F_m on evolutionary processes.

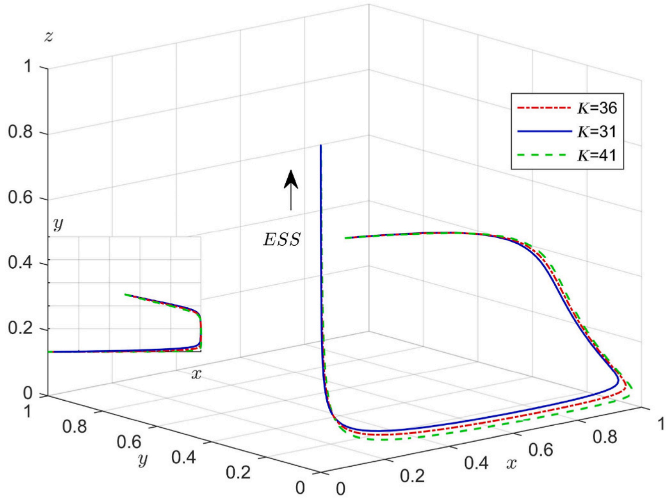


Fig. 9. The influence of K on evolutionary processes.

decreases, z gradually increases, and eventually the three parties of the game towards a steady state of {disclose false carbon footprint, intend rent-seeking, supervise}.

5.4. Impact of third-party agencies counterfeiting cost and fines on system stability

To analyze the impact of C_a and F_a on the evolutionary game process and results, we set $C_a = 13, 18, 23$ and $F_a = 9, 12, 15$, respectively, and let the replicated dynamic equations evolve 50 times, as shown in Fig. 10.

Fig. 10 illustrates that elevating the costs of falsification and penalties for third-party agencies can temporarily increase the likelihood of these agencies rejecting rent-seeking. However, as the system approaches a stable point, the decreased probability of government supervision and the increased likelihood of companies disclosing false carbon footprints create an incentive for third-party agencies to engage in rent-seeking behavior to generate additional revenue. In response, the government must intensify supervision. Consequently, y gradually decreases, z gradually increases, leading the three parties in the game to eventually settle in a stable state of {disclose false carbon footprints, intend rent-seeking, supervise}.

6. Conclusions and policy recommendations

6.1. Conclusions

EU battery regulation requires that from July 2024, power batteries sold in the European market must be accompanied by a carbon footprint declaration and labeling. This process involves battery manufacturers calculating and disclosing the battery's carbon footprint, which is

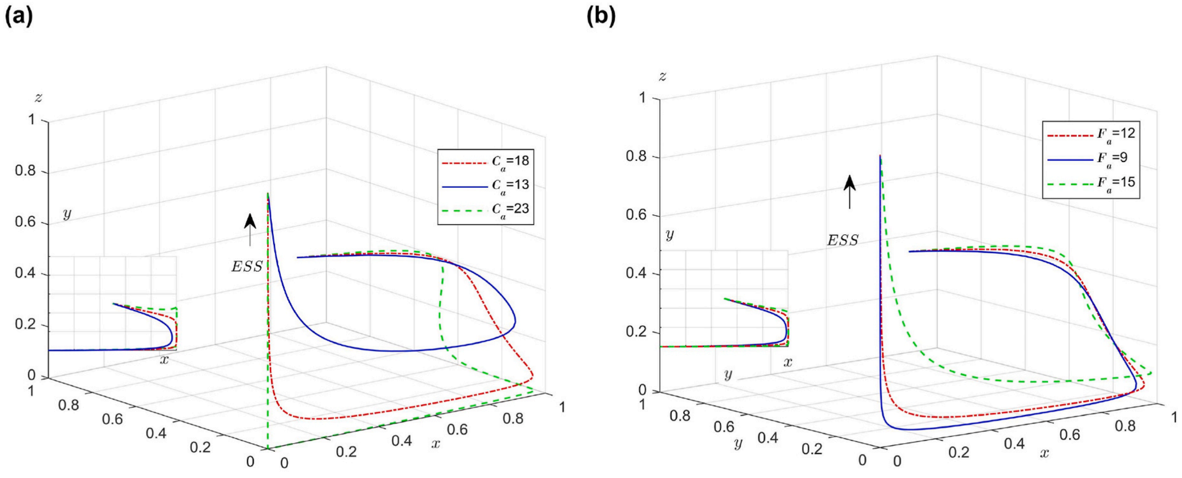


Fig. 10. (a) The influence of C_a on evolutionary processes; (b) The influence of F_a on evolutionary processes.

certified by an independent third-party agency, and then verified by the government. However, due to limited administrative resources, information asymmetry, and profit motivation, battery manufacturers and third-party agencies may engage in rent-seeking behavior and falsify carbon data. To prevent the occurrence of this phenomenon and ensure the effective implementation of battery regulation, this study constructs a three-party evolutionary game model including battery manufacturers, third-party verification agencies, and national market authorities, analyzes and simulates the strategy choices of each participant, the stability of the strategy and the factors affecting the strategy choices, and derives the conditions that need to be met to achieve a stable strategy. The main conclusions are as follows:

(1) The evolutionary game system may exhibit two stable states: (0,0,1) and (1,1,0), corresponding to two strategy combinations {disclose false carbon footprints, intend rent-seeking, supervise} and {disclose true carbon footprint, reject rent-seeking, not supervise}, respectively. However, if the benefits of third-party agencies objectively assessing carbon footprints are not substantial enough, there will be only one stable state (0,0,1) in the system.

(2) For battery manufacturers: the cost of counterfeiting, rent-seeking costs, and fines can increase the motivation of battery manufacturers to disclose their true carbon footprint to a certain extent, while the economic benefits brought by disclosing false carbon footprints will induce manufacturers to disclose false data. In addition, disclosing true carbon footprints may involve the leakage of supply chain information and core technology, while disclosing false carbon footprints can enhance a company's green and low-carbon image and market share. Establishing and improving the reward and punishment mechanism can restrain corporate behavior from both economic and reputational aspects. In addition, maintaining the objectivity, impartiality, and independence of third-party verification agencies and providing necessary government supervision will guide manufacturers to calculate and disclose true carbon footprint.

(3) For third-party verification agencies: higher fraud costs, fines, and benefits from careful evaluation help agencies maintain their due objectivity and fairness while rent-seeking behavior brings cost savings and additional benefits that may induce them to seek rent. To maintain the credibility of third-party agencies, it is necessary to establish a credit assessment and rating mechanism. Agencies with higher credit ratings will receive government incentives or subsidies, more opportunities for cooperation, and wider market recognition, while those with lower credit ratings may face the risk of having their accreditation withdrawn.

(4) For the government: comprehensive supervision will inevitably lead to an increase in supervision costs. To ensure the effectiveness of the implementation of battery regulations and reduce social costs as much as possible, some supplementary measures can be considered, such as green finance, tax incentives, and improving carbon verification industry standards.

6.2. Policy recommendations

Accurate and dependable carbon emission data is the basis for the orderly promotion of battery regulation. To guarantee the authenticity, accuracy, and completeness of battery carbon footprint data, thus achieving low-carbon and sustainable development of batteries and related industries, this research proposes the following policy recommendations:

(1) Improvement of institutional: (a) Establish a sound long-term capacity-building mechanism. Clarify the obligations and legal responsibilities of battery manufacturers as the subject of carbon footprint disclosure. Conduct access reviews for third-party agencies, focusing on the professional qualifications of practitioners to ensure that they have sufficient professional capabilities. Standardize the operating procedures of third-party agencies and advocate industry self-discipline. (b) Establish and improve the information disclosure system. Improve the information disclosure and credit system construction, strengthen the supervision of industry and society, establish a "blacklist" mechanism for enterprises and a "clearance" mechanism for third-party verification agencies, and increase penalties for carbon data falsification.

(2) Construction of database: (a) Establish a common or mutually recognized basic database. Ensure the consistency of data on carbon emission factors in different regions and provide a reliable database for the entire industry chain and the whole life cycle carbon footprint accounting. (b) Continuously update the carbon emission factor database. Ensure that the database is continuously updated to reflect the latest scientific and technological advances and reduce problems that may be caused by data obsolescence.

(3) Application of emerging technologies: (a) Application of Internet of Things and remote sensing technology. The adoption of these collection technologies helps to solve the authenticity problem in the generation and verification of carbon emission data, that is, retaining carbon emission data among enterprises, third-party agencies, and governments through a distributed ledger system to ensure that the data cannot be tampered with and to reduce the risk of complicity. (b) Data management and cross-validation. The authenticity of data can be enhanced through the management and cross-verification of on-chain and off-chain data. (c) Gradually introduce online monitoring tools. When technically feasible, the introduction of online monitoring means more real-time data collection and verification, which is also one of the directions for future development.

7. Limitation and future work

While this study enriches the research on battery carbon footprint and evolutionary game at the theoretical level and provides feasible policy suggestions for the effective implementation of the EU battery regulation in practice, it also has several limitations. Given that the battery regulation has not yet been supported by empirical data, we can only rely on numerical simulations to simulate the policy effects. In the future, if actual cases and available data can be obtained, we will strive to combine quantitative and qualitative analysis to make the research more theoretical and practical. To facilitate the establishment and solution of the model and understand the evolutionary path of the company in the game process, this article does not examine in detail the impact of battery carbon footprint disclosure on various life cycle stages of batteries. In the future, we will provide a comprehensive examination and analysis of the impacts of carbon footprint disclosure and assessment throughout various stages of battery production, utilization, and recycling.

CRediT authorship contribution statement

Xiaoning Xia: Conceptualization, Methodology, Software, Writing – original draft. **Pengwei Li:** Investigation, Writing-Reviewing and Editing, Visualization, Formal analysis. **Yang Cheng:** Supervision, Methodology, Writing – review & editing, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

This work was financially supported by China Scholarship Council (Nos. 202206050119, 202206080061) and Double Thousand Plan of Jiangxi Province.

References

[1] Lu S, Zhao Y, Chen Z, Dou M, Zhang Q, Yang W. Association between atrial fibrillation incidence and temperatures, wind scale and air quality: an exploratory study for Shanghai and Kunming. Sustainability 2021;13. https://doi.org/10.3390/su13095247.

[2] Li K, Dong F. Government strategy for banning gasoline vehicles: evidence from tripartite evolutionary game. Energy 2022;254. https://doi.org/10.1016/j.energy.2022.124158.

[3] Yang W, Pan L, Ding Q. Dynamic analysis of natural gas substitution for crude oil: scenario simulation and quantitative evaluation. Energy 2023;282:128764. https://doi.org/10.1016/j.energy.2023.128764.

[4] Yang W, Hu Y, Ding Q, Gao H, Li L. Comprehensive evaluation and comparative analysis of the green development level of provinces in eastern and western China. Sustainability 2023;15. https://doi.org/10.3390/su15053965.

[5] Li P, Xia X, Guo J. A review of the life cycle carbon footprint of electric vehicle batteries. Sep Purif Technol 2022;296:121389. https://doi.org/10.1016/j.seppur.2022.121389.

[6] Girardi P, Gargiulo A, Brambilla PC. A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study. Int J Life Cycle Assess 2015;20:1127–42. https://doi.org/10.1007/s11367-015-0903-x.

[7] Qiao Q, Zhao F, Liu Z, Jiang S, Hao H. Comparative study on life cycle CO_2 emissions from the production of electric and conventional vehicles in China. Energy Proc 2017;105:3584–95. https://doi.org/10.1016/j.egypro.2017.03.827.

[8] Temporelli A, Carvalho ML, Girardi P. Life cycle assessment of electric vehicle batteries: an overview of recent literature. Energies 2020;13:2864. https://doi.org/10.3390/en13112864.

[9] Marques P, Garcia R, Kulay L, Freire F. Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. J Clean Prod 2019;229:787–94. https://doi.org/10.1016/j.jclepro.2019.05.026.

[10] EU. Directive 2006/66/EC, https://eur-lex.europa.eu/eli/dir/2006/66/oj; 2006.

[11] EU. Strategic action plan on batteries. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj. 2018. eur-lex.europa.eu/resource.html?uri=cellar:0e8b694e-59b5-11e8-ab41-01aa75ed71a1.0003.02/DOC_3&format=PDF.

[12] Eu A. European green deal. 2019. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

[13] EU. Circular economy action plan. 2020. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en.

[14] EU. Proposal for a regulation of the European parliament and of the council concerning batteries and waste batteries. 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020PC0798.

[15] EU. Green Deal. EU agrees new law on more sustainable and circular batteries to support EU's energy transition and competitive industry. 2022. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7588.

[16] EU. The proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries. 2023. https://www.europarl.europa.eu/doceo/document/TA-9-2023-0237_EN.html.

[17] Giljum S, Hinterberger Sl F. Measuring natural resource use context, indicators and EU policy processes. 2008.

[18] Stoeglehner G, Narodoslawsky M. Implementing ecological footprinting in decision-making processes. Land Use Pol 2008;25:421–31. https://doi.org/10.1016/j.landusepol.2007.10.002.

[19] Galli A, Wiedmann T, Ercin E, Knoblauch D, Ewing B, Giljum S. Integrating ecological, carbon and water footprint into a "Footprint Family" of indicators: definition and role in tracking human pressure on the planet. Ecol Indicat 2012;16:100–12. https://doi.org/10.1016/j.ecolind.2011.06.017.

[20] Galli A, Weinzettel J, Cranston G, Ercin E. A footprint family extended MRIO model to support Europe's transition to a One Planet Economy. Sci Total Environ 2013;461–462:813–8. https://doi.org/10.1016/j.scitotenv.2012.11.071.

[21] Fang K, Heijungs R, de Snoo GR. Theoretical exploration for the combination of the ecological, energy, carbon, and water footprints: overview of a footprint family. Ecol Indicat 2014;36:508–18. https://doi.org/10.1016/j.ecolind.2013.08.017.

[22] Wiedmann T, Minx J. A definition of 'carbon footprint'. Ecological Economics Research Trends 2008;1:1–11.

[23] Baldo GL, Marino M, Montani M, Ryding S-O. The carbon footprint measurement toolkit for the EU Ecolabel. Int J Life Cycle Assess 2009;14:591–6. https://doi.org/10.1007/s11367-009-0115-3.

[24] Hertwich EG, Peters GP. Carbon footprint of nations: a global, trade-linked analysis. Environ Sci Technol 2009;43:6414–20. https://doi.org/10.1021/es803496a.

[25] Kim HC, Wallington TJ, Arsenault R, Bae C, Ahn S, Lee J. Cradle-to-gate emissions from a commercial electric vehicle Li-ion battery: a comparative analysis. Environ Sci Technol 2016;50:7715–22. https://doi.org/10.1021/acs.est.6b00830.

[26] Accardo A, Dotelli G, Musa ML, Spessa E. Life cycle assessment of an NMC battery for application to electric light-duty commercial vehicles and comparison with a sodium-nickel-chloride battery. Appl Sci 2021;11:1160. https://doi.org/10.3390/app11031160.

[27] Dai Q, Kelly JC, Gaines L, Wang M. Life cycle analysis of lithium-ion batteries for automotive applications. Batteries 2019;5:48. https://doi.org/10.3390/batteries5020048.

[28] Hao H, Mu Z, Jiang S, Liu Z, Zhao F. GHG Emissions from the production of lithium-ion batteries for electric vehicles in China. Sustainability 2017;9:504. https://doi.org/10.3390/su9040504.

[29] Sun X, Luo X, Zhang Z, Meng F, Yang J. Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. J Clean Prod 2020;273:123006. https://doi.org/10.1016/j.jclepro.2020.123006.

[30] Philippot M, Alvarez G, Ayerbe E, Van Mierlo J, Messagie M. Eco-efficiency of a lithium-ion battery for electric vehicles: influence of manufacturing country and commodity prices on GHG emissions and costs. Batteries 2019;5:23. https://doi.org/10.3390/batteries5010023.

[31] Mahmud M, Huda N, Farjana S, Lang C. Comparative life cycle environmental impact analysis of lithium-ion (LiIo) and nickel-metal hydride (NiMH) batteries. Batteries 2019;5:22. https://doi.org/10.3390/batteries5010022.

[32] Cusenza MA, Bobba S, Ardente F, Cellura M, Di Persio F. Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. J Clean Prod 2019;215:634–49. https://doi.org/10.1016/j.jclepro.2019.01.056.

[33] Ellingsen LA-W, Hung CR, Strømman AH. Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. Transport Res Transport Environ 2017;55:82–90. https://doi.org/10.1016/j.trd.2017.06.028.

[34] Wang Y, Yu Y, Huang K, Chen B, Deng W, Yao Y. Quantifying the environmental impact of a Li-rich high-capacity cathode material in electric vehicles via life cycle assessment. Environ Sci Pollut Res 2017;24:1251–60. https://doi.org/10.1007/s11356-016-7849-9.

[35] Zackrisson M, Fransson K, Hildenbrand J, Lampic G, O'Dwyer C. Life cycle assessment of lithium-air battery cells. J Clean Prod 2016;135:299–311. https://doi.org/10.1016/j.jclepro.2016.06.104.

[36] Mohr M, Peters JF, Baumann M, Weil M. Toward a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes. J Ind Ecol 2020;24:1310–22. https://doi.org/10.1111/jiec.13021.

[37] Tao Y, You F. Comparative life cycle assessment of three recycling approaches for electric vehicle lithium-ion battery after cascaded use. Chem Eng Trans 2020;81:1123–8. https://doi.org/10.3303/CET2081188.

[38] Wang L, Hu J, Yu Y, Huang K, Hu Y. Lithium-air, lithium-sulfur, and sodium-ion, which secondary battery category is more environmentally friendly and promising based on footprint family indicators? J Clean Prod 2020;276:124244. https://doi.org/10.1016/j.jclepro.2020.124244.

[39] Hodgson GM, Huang K. Evolutionary game theory and evolutionary economics: are they different species? J Evol Econ 2012;22. https://doi.org/10.1007/s00191-010-0203-3.

[40] Friedman D. Evolutionary games in economics. Econometrica 1991;59:637–66. https://doi.org/10.2307/2938222.

[41] Bester H, Güth W. Is altruism evolutionarily stable? J Econ Behav Organ 1998;34:193–209. https://doi.org/10.1016/S0167-2681(97)00060-7.

[42] Haruvy E, Prasad A. Optimal freeware quality in the presence of network externalities: an evolutionary game theoretical approach. J Evol Econ 2001;11:231–48. https://doi.org/10.1007/PL00003860.

[43] Kosfeld M. Why shops close again: an evolutionary perspective on the deregulation of shopping hours. Eur Econ Rev 2002;46:51–72. https://doi.org/10.1016/S0014-2921(01)00092-7.

[44] Nyborg K, Rege M. On social norms: the evolution of considerate smoking behavior. J Econ Behav Organ 2003;52:323–40. https://doi.org/10.1016/S0167-2681(03)00031-3.

[45] Arce MDG, Counterterrorism Sandler T. A game-theoretic analysis. J Conflict Resolut 2005;49:183–200. https://www.jstor.org/stable/30045107.

[46] Awaga AL, Xu W, Liu L, Zhang Y. Evolutionary game of green manufacturing mode of enterprises under the influence of government reward and punishment. Adv Prod Eng Manag 2020;15:416–30. https://doi.org/10.14743/apem2020.4.375.

[47] Chen H, Wang J, Miao Y. Evolutionary game analysis on the selection of green and low carbon innovation between manufacturing enterprises. Alex Eng J 2021;60:2139–47. https://doi.org/10.1016/j.aej.2020.12.015.

[48] Ji P, Ma X, Li G. Developing green purchasing relationships for the manufacturing industry: an evolutionary game theory perspective. Int J Prod Econ 2015;166:155–62. https://doi.org/10.1016/j.ijpe.2014.10.009.

[49] Nie Q, Zhang L, Tong Z, Hubacek K. Strategies for applying carbon trading to the new energy vehicle market in China: an improved evolutionary game analysis for the bus industry. Energy 2022;259:124904. https://doi.org/10.1016/j.energy.2022.124904.

[50] Sun Y, Liu B, Sun Z, Yang R. Inter-regional cooperation in the transfers of energy-intensive industry: an evolutionary game approach. Energy 2023;282:128313. https://doi.org/10.1016/j.energy.2023.128313.

[51] Hu Q, Xiong F, Shen GQ, Liu R, Wu H, Xue J. Promoting green buildings in China's multi-level governance system: a tripartite evolutionary game analysis. Build Environ 2023;242:110548. https://doi.org/10.1016/j.buildenv.2023.110548.

[52] Li B, Wang Q, Chen B, Sun T, Wang Z, Cheng Y. Tripartite evolutionary game analysis of governance mechanism in Chinese WEEE recycling industry. Comput Ind Eng 2022;167. https://doi.org/10.1016/j.cie.2022.108045.

[53] Xue J, He Y, Gao P, Tang Y, Xu H. Multi-agent evolutionary game model: corporate low-carbon manufacturing, Chinese government supervision, and public media investigation. Sustainability 2022;14:5587. https://doi.org/10.3390/su14095587.

[54] Yang Y, Yang W, Chen H, Li Y. China's energy whistleblowing and energy supervision policy: an evolutionary game perspective. Energy 2020;213:118774. https://doi.org/10.1016/j.energy.2020.118774.

[55] Ma C, Chen Y, Nie S. Four-way evolutionary game analysis of government project bidding collusion in a state of limited rationality based on prospect theory. Comput Intell Neurosci 2022;2022:1–19. https://doi.org/10.1155/2022/6092802.

[56] Yang W, Yang Y, Chen H. How to stimulate Chinese energy companies to comply with emission regulations? Evidence from four-party evolutionary game analysis. Energy 2022;258:124867. https://doi.org/10.1016/j.energy.2022.124867.

[57] Zheng S, Yu L. The government's subsidy strategy of carbon-sink fishery based on evolutionary game. Energy 2022;254. https://doi.org/10.1016/j.energy.2022.124282.

[58] Mcallister L. Regulation by third-party verification. BCL Rev 2012;53:1.

[59] Haoyang W, Lei G, Ying J. The predicament of clean energy technology promotion in China in the carbon neutrality context: lessons from China's environmental regulation policies from the perspective of the evolutionary game theory. Energy Rep 2022;8:4706–23. https://doi.org/10.1016/j.egyr.2022.03.142.

[60] Wang Y, Wang D, Shi X. Exploring the dilemma of overcapacity governance in China's coal industry: a tripartite evolutionary game model. Res Pol 2021:71. https://doi.org/10.1016/j.resourpol.2021.102000.

[61] Wei'an L, Yin M. A tripartite evolutionary game study on green governance in China's coating industry. Environ Sci Pollut Res 2022;29:61161–77. https://doi.org/10.1007/s11356-022-20220-2.

[62] He L, Sun B. Exploring the EPR system for power battery recycling from a supply-side perspective: an evolutionary game analysis. Waste Manag 2022;140:204–12. https://doi.org/10.1016/j.wasman.2021.11.026.

[63] Zhang H, Zhu K, Hang Z, Zhou D, Zhou Y, Xu Z. Waste battery-to-reutilization decisions under government subsidies: an evolutionary game approach. Energy 2022;259:124835. https://doi.org/10.1016/j.energy.2022.124835.

[64] Guan Y, He T-H, Hou Q. Tripartite evolutionary game analysis of power battery cascade utilization under government subsidies. IEEE Access 2023;11:66382–99. https://doi.org/10.1109/access.2023.3290171.

[65] Zhang T, Qin H, Xu W. Environmental regulation, greenwashing behaviour, and green governance of high-pollution enterprises in China. Int J Environ Res Publ Health 2022;19:12539. https://doi.org/10.3390/ijerph191912539.

[66] Ritzberger K, Weibull JW. Evolutionary selection in normal-form games. Econometrica 1995;63:1371. https://doi.org/10.2307/2171774.

[67] Liu Y, Cui M, Gao X. Building up scrap steel bases for perfecting scrap steel industry chain in China: an evolutionary game perspective. Energy 2023;278:127742. https://doi.org/10.1016/j.energy.2023.127742.