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# The industrial prospect of electric vehicles—time delay stochastic evolutionary game evidence from the U.S., China, the EU, and Japan

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The global transition to electric vehicles (EVs) represents a critical decarbonization strategy for the transportation sector, yet development pathways diverge substantially across major economies despite common climate objectives. This study addresses the knowledge gap in understanding why heterogeneous EV industrialization strategies emerge under similar technological and environmental pressures. Using a delayed stochastic evolutionary game–theoretic model capturing policy–market–technology interactions, this paper analyses EV development trajectories in the U.S., China, the EU, and Japan. The results demonstrate convergent evolution in the U.S., China, and the EU, driven by coordinated policy–market dynamics, which contrasts with Japan's unstable oscillation between government- and enterprise-led approaches because historical hydrogen vehicle prioritization dampens consumer adoption. The key mechanisms governing these pathways are as follows: information timeliness directly governs policy agility, with prolonged lags weakening regulatory efficacy. Carbon pricing nonlinearly accelerates EV adoption, quadrupling carbon prices yields no incremental time advantage over doubling them, and subsidies exhibit bounded influence, temporarily boosting consumer demand and R&D incentives but failing to shift equilibrium outcomes, underscoring the dominance of profit and market-share imperatives over subsidy-driven innovation. This work advances a unified framework explaining heterogeneous EV development pathways, offering policymakers actionable insights for aligning decarbonization goals with industrial realities through calibrated interventions.

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## Introduction

According to the International Energy Agency's 2024 report, global electric vehicle (EV) sales have achieved remarkable growth over the past three years: China has maintained its leading position (35% market share), the EU has steadily expanded (28%), and the United States has accelerated its catch-up trajectory (18%) (IEA, 2024). However, this rapid development conceals fundamental industrial paradoxes: Europe and North America face a "demand cliff" triggered by subsidy phase-outs, China grapples with inventory crises stemming from production overcapacity, and Japan's hesitation regarding hydrogen strategies reveals collective anxiety over technological pathway selection. These global industrial oscillations essentially reflect spatiotemporal mismatches in the tripartite game among governments, enterprises, and consumers. The "triple barriers" formed by policy lags, technology iteration cycles, and consumer cognition delays have fundamentally reshaped the evolutionary trajectories of national EV industries. Under complex conditions of policy tool iteration, technological route fragmentation, and increasing market barriers, establishing sustainable EV industry development pathways has become a critical prerequisite for scientifically formulating national response strategies (Naumanen et al., 2019; Qadir et al., 2024).

The development of emerging industries is shaped by multiple determinants. Given that the U.S., the EU, China, and Japan constitute the world's leading automotive manufacturing nations and collectively account for the predominant share of global EV sales, this study specifically focuses on analyzing the evolutionary pathways of EV industry development within these four critical markets. The development of the EV industry in the United States is driven primarily by the market, with government support serving as a secondary factor. The United States enhances the production efficiency and brand effect of EVs through collaborative development within the industry chain. Additionally, it reduces consumer costs for purchasing and using vehicles through tax incentives and infrastructure construction (Yang et al., 2024). The development of the EV industry in China relies primarily on policy-driven initiatives. China has set development goals and technological pathways for EVs through policy guidance, achieving technological advancements and demand growth in EVs from both the technological innovation and market cultivation perspectives (Ou et al., 2020). By reducing the production and usage costs of EVs through financial subsidies, China has developed new industrial competitive advantages by promoting industrial chain upgrades (Xiong et al., 2022; Tian et al., 2024; Ehsan et al., 2024). The development of the EV industry in the EU emphasizes both policy guidance and technological innovation. The development of EVs in the EU, represented by Germany, features clear strategic planning and the promotion of international cooperation. While promoting the popularization of EVs through measures such as vehicle purchase subsidies and charging pile subsidies, international cooperation is leveraged to reduce the cost of EV research and development and enhance vehicle performance (Chang, 2023; Liu, 2023; Reibsch et al., 2024; Gracia et al., 2024). The development of the EV industry in Japan is relatively conservative. Its EV industry features diverse technological routes, ranging from pure electric and hybrids to plug-in hybrids and fuel cells. Japan's EV development aims to meet market changes and the needs of different consumers through diversified development strategies (Ozawa et al., 2023; Zhang et al., 2024). Although the manufacturing of EVs has developed strongly in the pursuit of various countries, it is undeniable that high investments in research and development and technological innovation have brought about technological bottlenecks and financial pressures, which are significant obstacles to the further development of EVs. Intense market competition and intensifying price wars have also forced countries to reassess the market positioning and competitive strategies of EVs, manifested as escalating disputes in the EV industry and recent adjustments to EV development policies in various countries (Masiero et al., 2017).

While existing studies have identified singular drivers such as subsidy policies and infrastructure investment, they have yet to unravel the transmission mechanisms underlying the tripartite dynamic game among governments, enterprises, and consumers, particularly overlooking the strategy space compression effect induced by evolving international carbon pricing regimes (Liu et al., 2024; Zhan et al., 2024; Zhu et al., 2024). This study builds a tripartite stochastic game-theoretic framework that integrates carbon price transmission and information time lag effects to decode the formative mechanisms behind the heterogeneous development trajectories of EV industries in the U.S., China, the EU, and Japan, thereby providing an analytical coordinate system for addressing the "subsidy dependency syndrome" and "technological lock-in dilemmas". Specifically, we develop an empirically grounded modeling architecture comprising governments, EV manufacturers, and consumers, employing stochastic delayed differential games to disentangle how information asymmetry, carbon pricing, subsidy phase-out dynamics, and R&D commitment collectively shape strategic evolutionary patterns across national EV ecosystems.

The marginal contributions of this paper are reflected in the following aspects. First, we transcend the conventional policy-market duality framework (Sathiyan et al. 2022; Fan et al. 2025) by addressing two overlooked dimensions: (1) the distortionary effects of information lags on multi-agent decision-making and (2) the moderating role of cross-national carbon price disparities. Integrating these variables, we develop a four-dimensional analytical framework (policy–market–information–carbon pricing) that enhances the explanatory power of traditional models in scenario simulations. Second, we pioneer a tripartite methodological paradigm shift. Building on classical three-party evolutionary game theory, we (1) incorporate stochastic differential terms via geometric Brownian motion to quantify market uncertainty, (2) embed time-delay feedback mechanisms via delay differential equations to model policy transmission lags, and (3) construct a cross-national comparative system with U.S., China, EU, and Japanese parameters to decode path dependency. This approach overcomes the limitations of single-country case studies and purely theoretical conjectures. Third, the empirical findings are used to reconstruct industrial cognition. Unlike theoretical simulations in conventional evolutionary game studies (e.g., Encarnação et al., 2018), our panel data from four countries/regions reveal (1) an inverse relationship between the information lag coefficient ($\tau$) and policy inefficacy and (2) pronounced threshold effects of carbon pricing. Higher carbon prices accelerate evolutionary equilibrium timing, creating a policy window for EV technology upgrading and supply-chain restructuring while compelling legacy automakers to internalize costs for the low-carbon transition. These marginal contributions provide actionable critical-value parameters for policymakers, addressing prior quantitative gaps.

The structure of this paper is as follows: Section "Literature review" reviews existing research findings to provide theoretical support for this study. Section "Game model setting" constructs a stochastic game model with a time delay. Section "Data sources and descriptions" collects and preprocesses the relevant data. Section "Results and discussion" presents the development paths of the EV industry in different countries (regions) and the impact of major influencing factors on the basis of the model and data. Section "Conclusion and policy recommendations" summarizes the results of this paper and proposes corresponding strategic adjustment suggestions.

## Literature review

To study the development models of EVs in different countries (regions), it is necessary to grasp the current development status of the global EV industry for the first step. On this basis, the impact of different influencing factors on the EV industry should be analyzed to propose the development direction of the EV industry in different countries (regions) on the basis of multiparty game theory.

**Evolutionary pathways and current trajectories of EV industries in major economies**. The existing research has primarily employed industry life cycle theory and the diffusion of innovations theory to analyze the stage-specific characteristics and technological penetration pathways of EV industries across different regions.

The U.S. EV industry follows a typical "technology-driven" development trajectory. Its industry life cycle has evolved from initial exploration (late 19th century to early 20th century) to policy-driven growth (1970s–1980s), technological breakthroughs (1990s), and commercial expansion (early 21st century to present) (Cutcliffe and Kirsch, 2001; Diouf, 2024). In recent years, the U.S. EV market has experienced rapid growth. Although EVs still account for a relatively small share of total U.S. vehicle sales (e.g., approximately 10% in 2023), the growth momentum is robust. The U.S. government supports EV industry development and supply-chain enhancement through legislation and fiscal subsidies (Archsmith et al., 2022; Afzal and Hawkins, 2024). Concurrently, U.S. EV manufacturers are actively exploring innovative business and service models to meet diverse consumer demands (Wang & Zhao, 2021). Against this backdrop, the U.S. case exemplifies the dual role of the policy impetus and technology diffusion, aligning with the "S-curve diffusion" pattern—slow initial growth followed by exponential expansion due to technological maturation and cost reductions.

The development trajectory of the EU exhibits a policy-driven pattern characterized by prolonged interplay between regulatory constraints and industrial transformation. The EU's EV industry, following the U.S. pathway, has evolved through three distinct phases: early-stage exploration (1970s–1990s), policy-driven innovation (2000s–2010s), and market expansion with scale economies (2010s–present) (Serralles, 2006; Szabo and Newell, 2024). The EU and its member states have promoted EV adoption through fiscal incentives, tax benefits, and infrastructure investments (Gryparis et al., 2020), achieving notable technological advancements. However, challenges persist, including demand contraction postsubsidy phase-outs, inadequate charging infrastructure, and consumer range anxiety, resulting in market volatility (Serralles, 2006). Illustratively, pure EV sales plummeted 43.9% annually by August 2024, with EVs maintaining a lower market share and insufficient growth momentum than combustion engine vehicles do (Möring-Martínez et al., 2024). This policy–market dynamic aligns with institutional theory, where coercive regulatory forces dominate industrial transitions, whereas corporate strategic inertia creates periodic disequilibrium.

The Chinese pathway exemplifies a "state-led model," marked by rapid industrial development with pronounced outcomes, operating within a dynamic equilibrium between policy subsidies and market consolidation. China's EV evolution comprises four phases: exploration (2000–2012), unrestrained growth (2013–2017), market shakeout (2018–2020), and rationalized competition (2021–present) (Wang and Kimble, 2021; Zhao et al., 2019; Wang and Yu, 2021; Xiong et al., 2022). Extensive studies have highlighted that national and local fiscal subsidies fueled speculative market behavior and unregulated expansion in China's EV sector (Chen and Midler, 2016; Pelegov and Eremenko, 2021). Subsidy reductions and market stagnation triggered industry-wide restructuring (Lin et al., 2024). This trajectory aligns with the resource-based view, where scale-driven production and supply-chain integration (e.g., CATL's battery innovations) create inimitable competitive advantages.

Japan's EV industry is entrenched in a "technology-locked model," characterized by technological conservatism and path dependency dilemmas. Its development spans three phases: early-stage exploration (1960s–1990s), hybrid vehicle breakthroughs (late 1990s–early 2010s), and EV R&D adoption (2010s–present) (Kempton and Kubo, 2000; Ahman, 2006; Yamashita, 2009). In recent years, Japan has prioritized hydrogen fuel cell vehicles (FCVs), achieving notable advancements in technological innovation and policy frameworks (Takahashi, 2021). Despite progress, Japan's EV market remains cautious, with subdued consumer adoption rates and low EV sales penetration relative to those of the EU, the U.S., and China (Palmer et al., 2018). This trajectory exemplifies path dependency theory, where early-mover advantages in hybrid technologies engendered innovation rigidity, hindering adaptation to global electrification trends.

**Main factors influencing the development of the EV industry**. There are numerous factors influencing the development of the EV industry, but from a subjective perspective, the primary driving forces behind its advancement can be categorized into government, enterprises, and individuals (Kumar Alok 2020).

*Policy-driven mechanisms*. Drawing on North's institutional theory, governments shape institutional environments for EV development through coercive policy instruments (e.g., the EU's 2035 internal combustion engine vehicle ban) and incentive-based policy tools (Sheldon and Tamara, 2022; Zhang et al., 2023; Jia et al., 2023). On the one hand, the government's support and encouragement policies for EVs, including financial subsidies, tax incentives, and preferential electricity prices, have directly facilitated the research, development, production, and sales of EVs (Liu et al., 2021). On the other hand, the government has standardized the development of the EV industry by formulating relevant regulations and standards, providing legal support for the popularization of EVs (Yuan et al., 2015). Furthermore, the development of EVs requires corresponding infrastructure support, including charging stations and battery swapping stations (Fan et al., 2023). The government plays a pivotal role in advancing the construction of related infrastructure.

*Competitive dynamics of firms*. On the basis of the theory of resources and capabilities, supply-chain actors and automakers jointly shape the competitive landscape and evolutionary trajectory of the EV industry (Shang et al., 2025). In terms of enterprises, various supply-chain enterprisers and automobile enterprisers have jointly shaped the competitive landscape and development trends of the EV industry. First, capital serves as the foundation for enterprise development. Enterprises with strong capital resources are capable of rapidly carrying out research and development, production, and market promotion of EVs (Pei et al., 2023). Second, technological innovation capability is the core of competitiveness for EV enterprises. Enterprises possessing independent intellectual property rights and core technologies can occupy a favorable position in market competition (Grosjean et al., 2012). Third, enterprises should respond to the rapid changes in the EV industry on the basis of clear strategic planning and strong execution capabilities (Shi and Wang, 2024). Fourth, enterprises need to possess strong supply-chain management capabilities to ensure a stable supply of raw materials and components and reduce production costs (Benjamin et al., 2022; Ghorbani et al., 2024). Finally, enterprises need to have strong marketing capabilities, utilizing precise market positioning, effective marketing channels, and innovative marketing methods to enhance brand awareness and market share (Kumar and Revankar, 2017).

*Market acceptance*. On the basis of the technology acceptance model and diffusion of innovations theory, the adoption of EVs reflects dual influences from perceived usefulness (e.g., driving range) and perceived ease of use (e.g., charging convenience) in consumer decision-making (Kim and Cho, 2024). Discrete choice experiments by Fatah et al. (2024) revealed significantly higher price elasticity coefficients for EVs than for conventional vehicles, aligning with early adopter characteristics in the Bass diffusion model. Government procurement of EVs has positive spillover effects on private consumption through observational learning (Lin and Shi, 2024).

Growing environmental awareness and technological advancements are accelerating EV demand (Fatah et al., 2024; Lin and Shi, 2024). However, Bigerna et al. (2017a, 2017b) emphasized that green technology diffusion depends not only on performance but also on credible messaging and user-friendly payment schemes to lower behavioral barriers. Converting abstract environmental benefits into tangible economic value is critical for broader adoption. Thus, EV market demand is shaped by consumer perceptions, pricing, and key performance attributes (e.g., range).

**Game theory in the EV industry**. Evolutionary game theory (Hilbe et al., 2018; Zhao and Du, 2021) provides an integrated framework to analyze multiagent interactions—from microlevel technological adoption to macrolevel institutional design. In the EV sector, strategic equilibria emerge from dynamic interactions between technology pathways and policy incentives.

Supply-chain analyses demonstrate the critical role of policy interventions in market equilibrium. Under Stackelberg game frameworks, Ma et al. (2020) and Liu et al. (2024) revealed how subsidies interact with strategic consumer behavior to shape pricing strategies and market shares between EVs and conventional vehicles, highlighting the tension between policy optimization and corporate competition. Cao et al. (2021) extended this via dynamic game theory, showing that sustainable EV markets require not only short-term subsidies but also long-term incentives (e.g., R&D competition, infrastructure investment, and ecosystem coevolution). Trencher et al. (2021)'s cross-national comparison further underscored that successful EV adoption relies on industrial ecosystem development, technical standardization, and market cultivation—not just fiscal incentives. Collectively, these studies emphasize dynamic equilibria among policymakers, firms, and consumers as the linchpin of industry evolution.

Above all, the development of the EV industry has garnered significant attention. Extensive and in-depth research has been conducted on its development path, influencing factors, and future strategies, yielding fruitful results. However, the existing literature has focused primarily on the current state of the development of the EV industry during the modeling process, predominantly using assignment methods in simulations. Compared with traditional industries, the development of the EV industry involves not only a complex feedback loop involving government promotion, automotive company profits, and market selection but also a synergistic effect of technological breakthroughs and industrial chain development. Furthermore, it is an important manifestation of emission reduction goals and the green economy. Therefore, this industry faces higher levels of uncertainty. To better depict the complex game dynamics of this industry, this paper selects a stochastic evolutionary game model with time delays, further considering the impact of time delays and carbon prices on the equilibrium state. Real data is used to describe and predict the behaviors and strategic choices of game participants in the development of the EV industry within a complex dynamic environment.

## Game model setting

**Research hypotheses and parameter settings**. The EV industry is currently in its growth phase, having already passed the initial research and development and production stages. Competition among vehicle enterprisers is intensifying, with each company competing to launch EVs of superior quality. Accordingly, the strategic choice for vehicle enterprisers is no longer whether to produce traditional fuel vehicles or develop new energy vehicles, but whether to produce new energy vehicles under current technology or increase capital investment to achieve the upgrading and replacement of new energy vehicles. Consumers can choose to purchase traditional fuel vehicles or new energy vehicles currently available in the market.

To summarize the main methods, market-based measurement methods neglect dynamic policy–market feedback loops (Peng et al., 2025). However, path-dependence effects are quantified via replicator dynamics, which agent-based models struggle to parameterize empirically (Mahmoudi et al., 2024). Through their rigorous mathematical frameworks, game-theoretic models can transform the vague "development pathways" in industries into computable and predictable chains of strategic interactions, capturing key contradictions in industrial evolution (Li et al., 2024). Therefore, this paper employs such models to analyze the evolutionary trajectories of the EV industry across nations. The development of the EV industry involves three main entities: the government, EV enterprises, and consumers. All three entities are characterized by bounded rationality. Ideally, enterprisers can choose the type of new energy vehicle to produce, consumers are willing to purchase new energy vehicles, and the government promotes and supervises the research, development, and production of new energy vehicles through policy measures while also encouraging consumers to purchase such vehicles. Throughout this process, enterprisers adjust their high-quality new energy vehicle research and development strategies on the basis of short- and long-term benefits and costs, consumers adjust their new energy vehicle purchase strategies on the basis of price and utility, and the government adjusts its subsidy strategies on the basis of market conditions, costs, and policy objectives. The government, enterprises, and consumers engage in repeated games on the basis of their respective benefits and costs.

To analyze EV industry dynamics, this study develops a four-dimensional framework comprising economic, technological, behavioral, and institutional factors:

*Economic dimension*. Grounded in evolutionary economics, firm R&D decisions follow path-dependent cost–benefit mechanisms. The key variables include subsidy-adjusted R&D costs and production cost differentials, capturing the "Red Queen effect" (Barnett and Hansen, 1996; Kamikawa and Brummer, 2024).

*Technological dimension*. Adopting dynamic technology diffusion theory, we measure premium pricing capability as the intensity of technological disruption.

**Table 1 Relevant parameters of the tripartite evolutionary game model.**

| Parameters | Definition | Dimension |
|---|---|---|
| $P_1$ | Long-term sales revenue from the development of high-quality EVs by enterprises | Economic dimension |
| $P_2$ | Sales revenue of EVs under the current technological level of the enterprise | Economic dimension |
| $P_3$ | Sales revenue from the production of traditional fuel vehicles by enterprises | Economic dimension |
| $C_1$ | The cost of research and development for high-quality EVs produced by enterprises | Economic dimension |
| $C_2$ | The production cost of EVs at the current technological level of the enterprise | Economic dimension |
| $C_3$ | The cost of producing traditional fuel vehicles for enterprises | Economic dimension |
| $C_4$ | Carbon emission costs of traditional fuel vehicles | Economic dimension |
| $C_5$ | The impact of technological advancements in EVs on the cost of traditional fuel-powered vehicles | Technical dimension |
| $S_1$ | The social benefits of producing high-quality EVs | Institutional dimension |
| $S_2$ | The social benefits of EVs at the current technological level | Institutional dimension |
| $S_3$ | Social benefits of traditional fuel vehicles | Institutional dimension |
| $U_1$ | Consumer utility of high-quality EVs | Behavioral dimension |
| $U_2$ | Consumer utility of EVs at the current technological level | Behavioral dimension |
| $U_3$ | Consumer utility of traditional fuel vehicles | Behavioral dimension |
| $U_4$ | The impact of technological advancements in EVs on the utility of fuel-powered vehicle consumers | Technical dimension |
| $E_1$ | Subsidies for EV production | Institutional dimension |
| $E_2$ | Consumer subsidies for EVs | Institutional dimension |
| $E_3$ | Benefits from government subsidies (including reputation, social benefits, and market order) | Institutional dimension |
| $T_1$ | Consumption tax on EVs | Institutional dimension |
| $T_2$ | Consumption tax on traditional fuel vehicles | Institutional dimension |

*Behavioral dimension*. Per Hicksian compensated demand (Hicks, 1939), consumers minimize costs while maintaining utility, operationalized via price elasticity differentials.

*Institutional dimension*. Employing externality internalization theory, policy incentives (subsidies, tax credits) serve as the experimental lever.

In modeling the tripartite evolutionary game of EV industry development, incorporating time delays and stochastic elements is crucial for capturing real-world complexities. First, policy adjustments such as subsidy phase-outs and carbon emission allowance system revisions typically require 6-12 months for legislative review and corporate response before market impacts materialize. Technological conversion lags exist between R&D investments and product enhancement. Consumer adoption follows S-shaped diffusion curves influenced by social network effects. Second, significant uncertainties emerge from market fluctuations, technological breakthroughs, and implementation variances in subsidy policies. This study enhances conventional tripartite game models by integrating time-delay differential equations and stochastic processes to better characterize the industry's intricate dynamics.

On the basis of the above observations, basic assumptions are made before a three-party evolutionary game model is constructed.

**Assumption 1:** On the basis of the findings of Lim et al. (2022) and Li et al. (2023), the government benefits derived from the development of the EV industry can be systematically articulated as follows. Assuming that $E_S$ represents the expected revenue generated by the government's strategy of subsidizing and supporting the EV industry, $E_{nS}$ represents the expected revenue generated by the strategy of not supporting the EV industry. The government provides subsidies at a ratio of $x$, whereas the nonsubsidy ratio is $1 - x$. The government needs to bear the EV production subsidy $E_1$ and EV consumption subsidy $E_2$ and obtain government subsidies, including reputation, social benefits, and market order, with a total revenue of $E_3$, as well as the current social benefits of EV $S_1$ and the social benefits of high-quality EV $S_2$.

**Assumption 2:** On the basis of the research findings of Massiani (2015), enterprises can obtain profits in the EV industry as follows. Assume that $E_m$ represents the expected revenue for enterprises choosing to develop and produce high-quality EVs, and that $E_{nm}$ represents the revenue for those choosing not to develop and produce high-quality EVs (maintaining the current production of EVs). The proportion of enterprises choosing to develop and produce high-quality EVs is $y$, whereas the proportion not choosing to develop is $1 - y$. Enterprises are responsible for bearing the research and development cost $C_1$ of high-quality EVs, the production cost $C_2$ of EVs under the current technological level, the production cost $C_3$ of traditional fuel vehicles, and the consumption taxes $T_1$ and $T_2$ on EVs and traditional fuel vehicles, respectively; they also obtain long-term sales revenue $P_1$ from high-quality EVs, revenue $P_2$ from EVs under the current technological level, sales revenue $P_3$ from traditional fuel vehicles, and government production subsidies $E_1$.

**Assumption 3:** On the basis of the research findings of Plötz et al. (2014) and Stekelberg and Vance (2024), the consumer benefits derived from the purchase of an EV can be systematically articulated as follows. Assume that $E_o$ represents the benefit of consumers choosing to purchase EVs and that $E_{no}$ represents the benefit of consumers choosing to purchase traditional fuel vehicles. The proportion of consumers choosing to purchase EVs is $z$, whereas the proportion of those choosing not to purchase EVs but to purchase traditional fuel vehicles is $1 - z$. Consumers bear the selling prices of different types of vehicles, namely, $P_1$, $P_2$, and $P_3$, and obtain utilities $U_1$, $U_2$, and $U_3$ for purchasing fuel vehicles, EVs, and high-quality EVs, respectively.

**Assumption 4:** On the basis of the research findings of Fei et al. (2025), given that various countries (regions) have begun to incorporate carbon emissions into their respective markets, the carbon emission cost of traditional fuel vehicles is set to $C_4$. The specific settings of the main parameters in this paper are shown in Table 1.

where $S_1 > S_2 > S_3$, $P_1 - C_1 > P_2 - C_2$, $P_1 - C_1 > P_3 - C_3$, $C_5 < 0$, $U_4 < 0$, $C_2 < C_1$, $C_3 < C_1$, $P_1 > C_1$, $P_2 > C_2$, $P_3 > C_3$, and all other parameters are nonnegative.

**Stochastic evolutionary game model with time delay**. On the basis of the parameter selection in section "Research hypotheses and parameter settings", the government, enterprises and consumers obtain corresponding utilities by choosing any one of the strategies. By integrating the utility performance of

**Table 2 Payoff matrix for the government, enterprises and consumers.**

| Government | Enterprise | EV purchase (z) | Fuel vehicles purchase (1-z) |
|---|---|---|---|
| Subsidy ($x$) | R&D ($y$) | $S_1+S_2+T_1-E_1-E_2+E_3$<br>$P_1+P_2-C_1-C_2+E_1$<br>$U_1+U_2-T_1+E_2$ | $S_3+T_2+E_3$<br>$C_5+P_3-C_3$<br>$U_3+U_4-T_2-C_4$ |
| | Non-R&D ($1-y$) | $S_2+T_1-E_1-E_2+E_3$<br>$P_2-C_2+E_1$<br>$U_2-T_1+E_2$ | $S_3+T_2+E_3$<br>$P_3-C_3$<br>$U_3-T_2-C_4$ |
| Nonsubsidy ($1-x$) | R&D ($y$) | $S_1+S_2+T_1$<br>$P_1+P_2-C_1-C_2$<br>$U_1+U_2-T_1$ | $S_3+T_2$<br>$C_5+P_3-C_3$<br>$U_3+U_4-T_2-C_4$ |
| | Non-R&D ($1-y$) | $S_2+T_1$<br>$P_2-C_2$<br>$U_2-T_1$ | $S_3+T_2$<br>$P_3-C_3$<br>$U_3-T_2-C_4$ |

different strategies, we obtain the utility function presented in Table 2.

On the basis of the utility function presented in Table 2, the replication dynamic equation for tripartite decision-making can be analyzed.

First, we analyze the replication dynamic equation of government decision-making.

Let $E_g$ represent the average return of all strategies adopted by the government $E_g = xE_S + (1-x)E_{nS}$. After the calculation, the following equation is obtained:

$$\begin{aligned}E_S = {} & yz(S_1+S_2+T_1-E_1-E_2+E_3) + y(1-z)(S_3+T_2+E_3)\\ & +(1-y)z(S_2+T_1-E_1-E_2+E_3)\\ & +(1-y)(1-z)(S_3+T_2+E_3),\end{aligned}$$

$$\begin{aligned}E_{nS} = {} & yz(S_1+S_2+T_1) + y(1-z)(S_3+T_2)\\ & +(1-y)z(S_2+T_1) + (1-y)(1-z)(S_3+T_2),\end{aligned}$$

and the dynamic equation for government decision replication is as follows:

$$\begin{aligned}F(x) = \frac{dx}{dt} = x\left(E_S - E_g\right) = x(1-x)\left(E_S - E_{nS}\right)\\ = x(1-x)\left[z(-E_1-E_2)+E_3\right]\end{aligned} \quad (1)$$

Second, we analyze the replication dynamic equation of enterprise decision-making.

Let $E_b$ represent the average revenue of the enterprise adopting all strategies $E_b = yE_m + (1-y)E_{nm}$. After the calculation, the following equation is obtained:

$$\begin{aligned}E_m = {} & xz(P_1+P_2-C_1-C_2+E_1) + x(1-z)(C_5+P_3-C_3)\\ & +(1-x)z(P_1+P_2-C_1-C_2) + (1-x)(1-z)(C_5+P_3-C_3)\end{aligned}$$

$$\begin{aligned}E_{nm} = {} & xz(P_2-C_2+E_1) + x(1-z)(P_3-C_3)\\ & +(1-x)z(P_2-C_2) + (1-x)(1-z)(P_3-C_3)\end{aligned}$$

and the dynamic equation for enterprise decision replication is as follows:

$$\begin{aligned}F(y) = \frac{dy}{dt} = y(E_m - E_b) = y(1-y)(E_m - E_{nm})\\ = y(1-y)\left[z(P_1-C_1)+(1-z)C_5\right]\end{aligned} \quad (2)$$

Third, we analyze the replication dynamic equation of consumer decision-making.

Let $E_c$ represent the average return of all strategies adopted by the consumer $E_c = zE_o + (1-z)E_{no}$. After the calculation, the following equation is obtained:

$$\begin{aligned}E_o = {} & xy(U_1+U_2-T_1+E_2) + x(1-y)(U_2-T_1+E_2)\\ & +(1-x)y(U_1+U_2-T_1) + (1-x)(1-y)(U_2-T_1)\end{aligned}$$

$$\begin{aligned}E_{no} = {} & xy(U_3+U_4-T_2-C_4) + x(1-y)(U_3-T_2-C_4)\\ & +(1-x)y(U_3+U_4-T_2-C_4) + (1-x)(1-y)(U_3-T_2-C_4)\end{aligned}$$

and the dynamic equation for consumer decision replication is as follows:

$$\begin{aligned}F(z) = \tfrac{dz}{dt} = z(E_o - E_c) = z(1-z)(E_o - E_{no})\\ = z(1-z)[y(U_1-U_4) + xE_2 + U_2 - U_3 + T_2 - T_1 + C_4]\end{aligned} \quad (3)$$

On the basis of the general form of stochastic differential equations, this paper introduces Gaussian white noise into the replication dynamic equation of a three-party Itô stochastic evolutionary game, which represents the random perturbations in the game system as follows:

$$dx(t) = \left[z(-E_1-E_2)+E_3\right]x(t)[1-x(t)]dt + \sigma x(t)[1-x(t)]d\omega(t) \quad (4)$$

$$dy(t) = \left[z(P_1-C_1)+(1-z)C_5\right]y(t)\left[1-y(t)\right]dt + \sigma y(t)\left[1-y(t)\right]d\omega(t) \quad (5)$$

$$\begin{aligned}dz(t) = {} & [y(U_1-U_4)+xE_2+U_2-U_3+T_2-T_1+C_4]z(t)[1-z(t)]dt\\ & +\sigma z(t)[1-z(t)]d\omega(t)\end{aligned} \quad (6)$$

Since $x$, $y$, and $z$ are all within the range of $[0, 1]$, $1-x$, $1-y$, and $1-z$ are all nonnegative real numbers, which will not affect the evolutionary outcome of the final strategy.

This paper follows the approach of Xu et al. (2015) and modifies the traditional three-party game model in Eqs. (4) to (6) as follows:

$$\begin{aligned}dx(t) &= \left[z(-E_1-E_2)+E_3\right]x(t)dt + \sigma x(t)d\omega(t)\\ dy(t) &= \left[z(P_1-C_1)+(1-z)C_5\right]y(t)dt + \sigma y(t)d\omega(t)\\ dz(t) &= [y(U_1-U_4)+xE_2+U_2-U_3+T_2-T_1+C_4]z(t)dt\\ &\quad +\sigma z(t)d\omega(t)\end{aligned} \quad (7)$$

Among them, $x(t)$, $y(t)$, and $z(t)$ are all one-dimensional Itô stochastic differential equations. Here, $\omega(t)$ denotes a one-dimensional standard Brownian motion, $\omega(t) \sim N(0, t)$. $d\omega(t)$ represents Gaussian white noise. When $t > 0$ and its step size is $h > 0$, its increment $\Delta\omega(t) = \omega(t+h) - \omega(t)$ also follows a

**Table 3 Eigenvalues and stability corresponding to the equilibrium points.**

| Equilibrium | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | Stability | Explanation |
|---|---|---|---|---|---|
| (0,0,0) | $E_3$ | $C_5$ | $U_2 - U_3 + T_2 - T_1 + C_4$ | Instable | $\lambda_1 (+)$ |
| (1,0,0) | $-E_3$ | $C_5$ | $E_2 + U_2 - U_3 + T_2 - T_1 + C_4$ | Instable | $\lambda_3 (+)$ |
| (0,1,0) | $E_3$ | $-C_5$ | $U_1 - U_4 + U_2 - U_3 + T_2 - T_1 + C_4$ | Instable | $\lambda (+)$ |
| (0,0,1) | $E_3 - E_1 - E_2$ | $P_1 - C_1$ | $U_3 - U_2 - T_2 + T_1 - C_4$ | Instable | $\lambda_1 (+)$ |
| (1,1,0) | $-E_3$ | $-C_5$ | $U_1 - U_4 + E_2 + U_2 - U_3 + T_2 - T_1 + C_4$ | Instable | $\lambda_2 (+)$ |
| (1,0,1) | $E_1 + E_2 - E_3$ | $P_1 - C_1$ | $U_3 - U_2 - E_2 - T_2 + T_1 - C_4$ | Instable | $\lambda_2 (+)$ |
| (0,1,1) | $E_3 - E_1 - E_2$ | $C_1 - P_1$ | $U_4 - U_1 - U_2 + U_3 - T_2 + T_1 - C_4$ | Instable | $\lambda_1 (+)$ |
| (1,1,1) | $E_1 + E_2 - E_3$ | $C_1 - P_1$ | $U_4 - U_1 - E_2 - U_2 + U_3 - T_2 + T_1 - C_4$ | Stable | $\lambda (-)$ |

normal distribution $N(0, h)$. $\sigma$ denotes the intensity of a random disturbance, which is taken as a positive constant.

In Eq. (7), the decision-making of the game participants in the next step is solely dependent on the current situation. However, in reality, both parties in the game will make predictions on the basis of the cumulative experience of the game process; that is, the game participants will make predictions on the basis of the dynamic information of the opponent's previous decisions. This process can be understood as the game participants having a lag effect on the opponent's information. Assuming that among the three parties in the game, the government's information lag to consumers is $\tau_1$, the enterprise's information lag to consumers is $\tau_2$, the consumer's information lag to the government is $\tau_3$, and the consumer's information lag to the enterprise is $\tau_4$. Then, the stochastic evolutionary game model in this paper becomes a stochastic evolutionary game model with time delays, that is,

$$\begin{aligned}
\frac{dx(t)}{dt} &= x\left[z\left(t-\tau_1\right)\left(-E_1-E_2\right)+E_3\right]+\sigma x d\omega(t)\\
\frac{dy(t)}{dt} &= y\left[z\left(t-\tau_2\right)\left(P_1-C_1\right)+\left(1-z\left(t-\tau_2\right)\right)C_5\right]+\sigma y d\omega(t)\\
\frac{dz(t)}{dt} &= z[y\left(t-\tau_4\right)(U_1-U_4)+x\left(t-\tau_3\right)E_2+U_2-U_3\\
&\quad +T_2-T_1+C_4]+\sigma z d\omega(t)
\end{aligned} \tag{8}$$

This model is also a time-delay system.

**Model stability analysis**. Let $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$. This yields 8 equilibrium points for the evolutionary game system involving the government, car companies, and consumers to be analyzed: (0,0,0), (1,0,0), (0,1,0), (0,0,1), (1,1,0), (1,0,1), (0,1,1), and (1,1,1). The Jacobian matrix of the system can be obtained on the basis of the replication dynamic equations of the government, enterprises, and consumers.

$$\begin{pmatrix}
(1-2x)[z(-E_1-E_2)+E_3] & 0 & x(1-x)(-E_1-E_2)\\
0 & (1-2y)[z(P_1-C_1)+(1-z)C_5] & y(1-y)(P_1-C_1-C_5)\\
z(1-z)E_2 & z(1-z)(U_1-U_4) & (1-2z)[y(U_1-U_4)+xE_2+U_2-U_3+T_2-T_1+C_4]
\end{pmatrix} \tag{9}$$

According to Lyapunov's stability criterion, the condition for determining the equilibrium point as a stable strategy is that the real part of the characteristic roots of the Jacobian matrix is less than zero. The eigenvalues corresponding to the equilibrium point and the stability determination are shown in Table 3.

As shown in Table 3, the evolutionary game in this paper has only one evolutionary equilibrium solution (1,1,1) that was ultimately established.

Compared with the deterministic evolutionary game model, the stochastic evolutionary game model can more accurately and realistically reflect the dynamic evolution process of strategic behaviors among the three groups. To this end, based on Eq. (8), random perturbation factors are added to obtain a stochastic evolutionary game model for the government–enterprise–consumer tripartite relationship in the development process of new energy vehicles. The stochastic replication dynamic equation of Eq. (8) can be seen that its form is a nonlinear Ito-type stochastic differential equation with Gaussian perturbations, requiring numerical solutions to approximate its analytical solutions. Let the general form of the Itô-type stochastic differential equation be

$$dx(t) = f(t, x(t))dt + g(t, x(t))d\omega(t) \tag{10}$$

where $t \in \left[t_0, T\right]$, $x\left(t_0\right) = x_0$, and $x_0 \in R$; $\omega(t)$ is a standard one-dimensional Brownian motion following a normal distribution. Let the sampling frequency be $s$, the initial time be $t_0$, and the nth sampling time be $t_n (n \in \{0, 1, \ldots, s\})$. The step size for discretizing this stochastic differential equation is $h = \left(T - t_0\right)/s$, where $t_n = t_0 + nh$.

Using the stochastic Taylor series expansion of the above expression and applying the Euler method from the literature Kai and Gu (2022) for numerical simulation, we can truncate certain terms in the Taylor series expansion for numerical solution, thus obtaining the following:

$$x\left(t_{n+1}\right) = x\left(t_n\right) + hf\left(x\left(t_n\right)\right) + \Delta\omega_n g\left(x\left(t_n\right)\right) \tag{11}$$

According to the method described above, expanding the three equations in Eq. (8) yields the following:

$$\begin{aligned}
x(t_{n+1}) &= x(t_n) + hx(t_n)\left[z\left(-E_1-E_2\right)+E_3\right]+\Delta\omega_n \sigma x(t_n)\\
y(t_{n+1}) &= y(t_n) + hy(t_n)\left[z\left(P_1-C_1\right)+(1-z)C_5\right]+\Delta\omega_n \sigma y(t_n)\\
z(t_{n+1}) &= z(t_n) + hz(t_n)\left[y(U_1-U_4)+xE_2+U_2-U_3+T_2-T_1+C_4\right]\\
&\quad +\Delta\omega_n \sigma z(t_n)
\end{aligned} \tag{12}$$

The evolutionary equilibrium solution in Eq. (8) can be solved iteratively through Equation (12).

For the evolutionary equilibrium solution existing in Eq. (8), the stability of the solution needs to be analyzed on the basis of the stability criterion theorem of stochastic differential equations. Assuming that there exists a function $V(t, x)$ and positive constants $c_1$, $c_2$, such that $c_1|x|^p \le V(t,x) \le c_2|x|^p$, $t \ge 0$. If there exists a positive constant $\mu$ such that $LV(t,x) \le -\mu V(t,x)$ for $t \ge 0$, then the zero-solution expectation matrix of the formula exhibits exponential stability, and the inequality $E\left|x\left(t, x_0\right)\right|^p \le \left(c_2/c_1\right)\left|x_0\right|^{p_e} -\mu t (t \ge 0)$ holds.

**Table 4 Market performance of EV SUVs.**

| Country | Price premium coefficient (SUV MSRP/Sedan SMRP) | Battery integration index (Sedan average: 7.1) | Premium EV SUV market share (MSRP ≥ \$50,000) |
|---|---|---|---|
| U.S. | 1.35 | 9.2 (Tesla Model X) | 75% |
| China | 1.30 | 8.7 (NIO ES8) | 67% |
| EU | 1.29 | 8.9 (BMW iX) | 66% |
| Japan | 1.27 | -- | 58% |

Let $V(t,x)=x, V(t,y)=y, V(t,z)=z, c_1=c_2=1, p=1$, and

$$\begin{cases} LV(t,x)=f(t,x)=x\left[z\left(-E_1-E_2\right)+E_3\right] \\ LV(t,y)=f(t,y)=y[z(P_1-C_1)+(1-z)C_5] \\ LV(t,z)=f(t,z)=z[y(U_1-U_4)+xE_2+U_2-U_3+T_2-T_1+C_4] \end{cases} \tag{13}$$

If the zero-solution moment index of Eq. (13) is stable, it needs to satisfy the following:

$$\begin{cases} x\left[z\left(-E_1-E_2\right)+E_3\right]\le -x \\ y\left[z\left(P_1-C_1\right)+(1-z)C_5\right]\le -y \\ z[y(U_1-U_4)+xE_2+U_2-U_3+T_2-T_1+C_4]\le -z \end{cases} \tag{14}$$

If the zero-solution moment index of Eq. (13) is unstable, it needs to satisfy the following:

$$\begin{cases} x\left[z\left(-E_1-E_2\right)+E_3\right]\ge x \\ y\left[z\left(P_1-C_1\right)+(1-z)C_5\right]\ge y \\ z[y(U_1-U_4)+xE_2+U_2-U_3+T_2-T_1+C_4]\ge z \end{cases} \tag{15}$$

In this work, if Eq. (14) is satisfied during the three-party game process, it implies that as time progresses, the game participants tend to opt for affirmative strategies. Conversely, when Eq. (15) is satisfied, the game participants will ultimately choose negative strategies.

In section "Results and discussion", the robustness of the time-delay stochastic evolutionary game model constructed in this paper can be tested via specific data.

## Data sources and descriptions

According to Table 1, the data in this paper consists of three aspects: vehicle data at the enterprise level, utility data at the social level, and tax subsidy data at the government level. Since this paper aims to compare the development status of new energy vehicles in different countries (regions), there are issues of inconsistent statistical dimensions and significant differences in statistical content among various macro data indicators, making it difficult to conduct horizontal comparisons. Therefore, this paper takes similar vehicle models sold in different countries (regions) as examples, with the goal of measuring the full life cycle enterprise value and social value of one vehicle. Enterprise-government-consumer game theory analysis is conducted for different types of vehicles in various countries (regions), and the results are compared and analyzed.

At the level of basic vehicle data, the data in this paper are sourced from reports by Lutsey and Nicholas (2019), Lutsey et al. (2021), Rapson and Muehlegger (2021), Schwartz et al. (2021), Morrison and Wappelhorst (2023), etc. This study encompasses the EV markets of the U.S., China, the EU (represented by Germany), and Japan, where significant divergences exist in technical roadmaps and product classification standards. For example, China prioritizes the driving range for vehicle grading, the EU emphasizes carbon emission metrics, and the U.S. employs EPA energy efficiency tiers, creating challenges in cross-market technical benchmarking. To address this, we adopt three normalized dimensions: price premium coefficients (JATO Dynamics 2023 Global Automotive Pricing Database), the technology integration index (calculated via representative SUV models, 2023), and premium market share (MarkLines Global Sales Monitor 2023). These dimensions address cross-market comparability challenges arising from divergent EV classification systems.

On the basis of Table 4 and considering the constrained EV charging capacity in most countries/regions, this study adopts the mean BEV300 from the EV SUV category as the representative metric for premium EVs. As the research object for new energy vehicles, this paper uses gasoline vehicles at the same level as the comparison object. In terms of vehicle costs, the profit of car companies is 10% of the vehicle manufacturing cost, and the profit of dealers is 10% of the sum of the vehicle manufacturing cost and the car company's profit. This paper calculates the costs of different vehicle models on the basis of the above-average values.

At the level of social utility data, each production of an EV not only has direct economic value in terms of technological advancement and cost reduction but also profoundly influences and values the entire country and industry through market penetration and brand influence enhancement. Therefore, this paper calculates the social benefits $S_1$, $S_2$, and $S_3$ of high-quality EVs, EVs at the current technological level, and traditional fuel vehicles using three, two, and one profit, respectively. Moreover, the utility of traditional fuel vehicles is based mainly on price advantages. This paper takes the price difference between traditional fuel vehicles and similar EVs as the utility $U_3$ of traditional fuel vehicles. The utility of new EVs includes the savings in maintenance and fuel costs compared with traditional fuel vehicles. By calculating the total life cycle cost savings, we obtain the corresponding utility values $U_1$ and $U_2$.

## Results and discussion

Using the method in the section "Data sources and descriptions" and empirical market data, we identify EV industry development trajectories across countries/regions, quantify the impact of key determinants on these trajectories, and test the robustness of the proposed stochastic delay evolutionary game model.

**EV industry development trajectories**. The evolutionary game model requires solving equilibrium points through differential equation iterative algorithms. To mitigate matrix condition number deterioration and iterative divergence caused by extreme values, all raw data were normalized (converted to USD units and scaled down by a factor of 1000). Supplementary Table S1 details the processed dataset. Using Eq. (8) and these calibrated inputs, we derive country/region-specific EV industry development trajectories.

As shown in Fig. 1, in the development process of the EV industry, the U.S., China and the EU have the same trend during their stochastic evolutionary games. Specifically, the R&D strategy of enterprises first stabilizes, followed by consumer purchases,

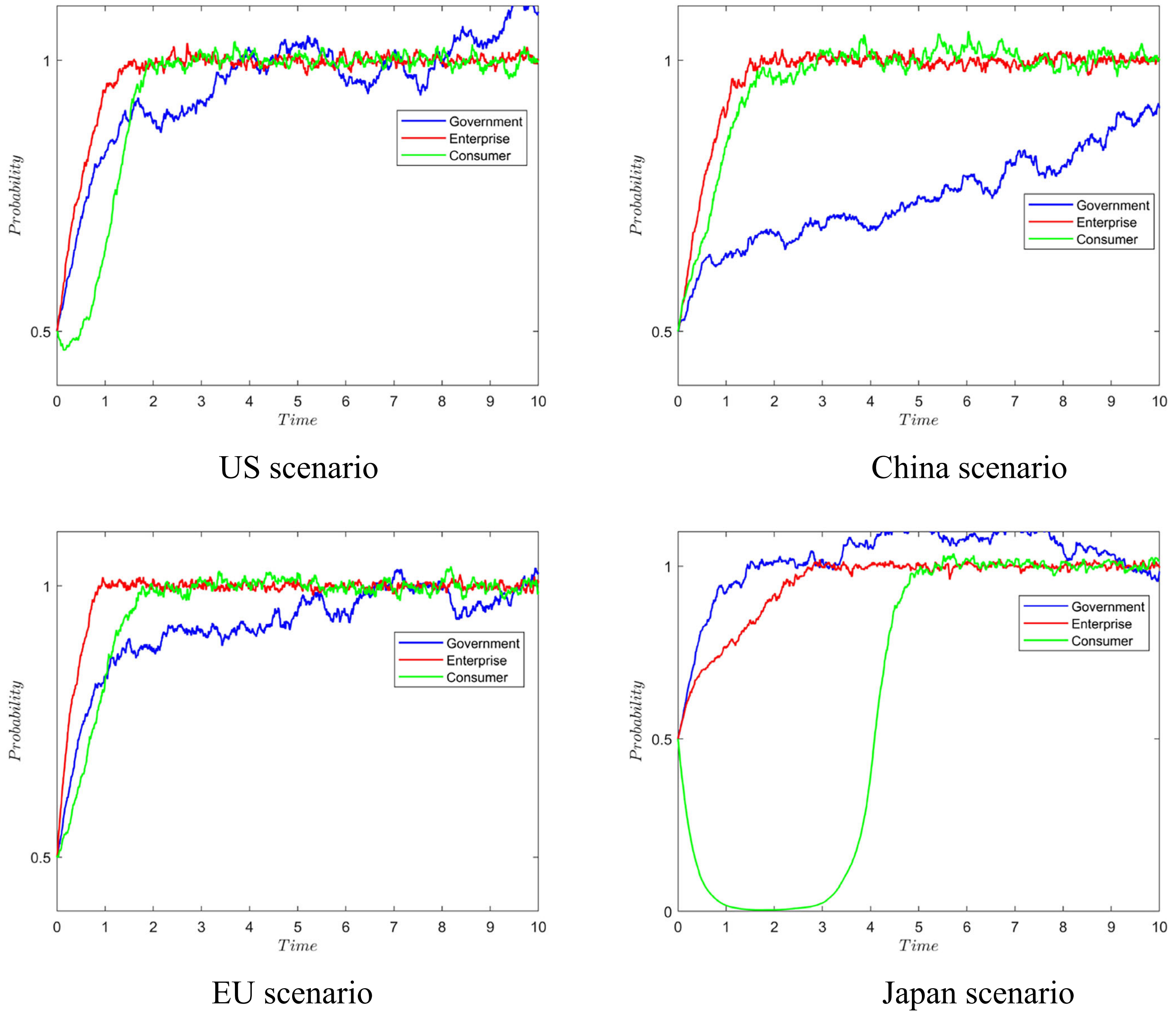


**Fig. 1 Game process of the EV industry in different countries (regions) (the time delay is set to 0.5 times).** The blue, red, and green lines represent the usage rates of the corresponding strategies for the government, businesses, and consumers, respectively. Lines tending to stabilize indicate the achievement of an evolutionarily stable strategy (ESS).

and then, government subsidies reach stability. This trend aligns with analytical solutions, ultimately stabilizing at the state of $x(t) = 1$, $y(t) = 1$, and $z(t) = 1$. Although the evolutionary strategies and equilibrium points of the three countries (regions) tend to be consistent, the form and rate of evolution to the equilibrium point differ. First, in terms of government subsidies, although all countries (regions) choose to subsidize new energy vehicles, the time for their nonsubsidy strategy to evolve to an equilibrium strategy varies. The United States has the fastest rate of increase in new energy vehicle subsidies, taking approximately 5 times to evolve to an equilibrium state. Similarly, although the EU's subsidy policy evolves 2 times later than that of the U.S., its initial evolution rate is similar to that of the U.S. China's new energy vehicle subsidy strategy probability has increased at the slowest rate, with the longest evolution cycle. This result is directly related to China's current highly competitive new energy vehicle market, the highest level of marketization, and the weaker influence of government subsidies. Second, in terms of consumers purchasing new energy vehicles, the evolutionary game strategies of China, the U.S., and the EU are similar. Although the advantages of fuel cost and oil vehicle price make American consumers less likely to purchase new energy vehicles in the short term, other advantages of new energy vehicles quickly compensate for the cost deficiency. Chinese consumers spend an average of 1.5 times in game time choosing to purchase new energy vehicles, whereas American and European consumers spend only 2 times making the same choice. Finally, in terms of whether enterprises develop high-quality new energy vehicles, the willingness to develop among enterprises in China, the U.S., and the EU is strong.

Japan's EV development trajectory diverges markedly from those of China, the U.S., and the EU. While its government demonstrates the strongest subsidy commitment—achieving strategic equilibrium fastest—Japanese automakers exhibit weaker R&D commitment than their counterparts in those markets do, resulting in a longer time taken to reach a stable strategy. Moreover, the strategy for consumers to choose to purchase new energy vehicles requires a lengthy evolution period in Japan, and

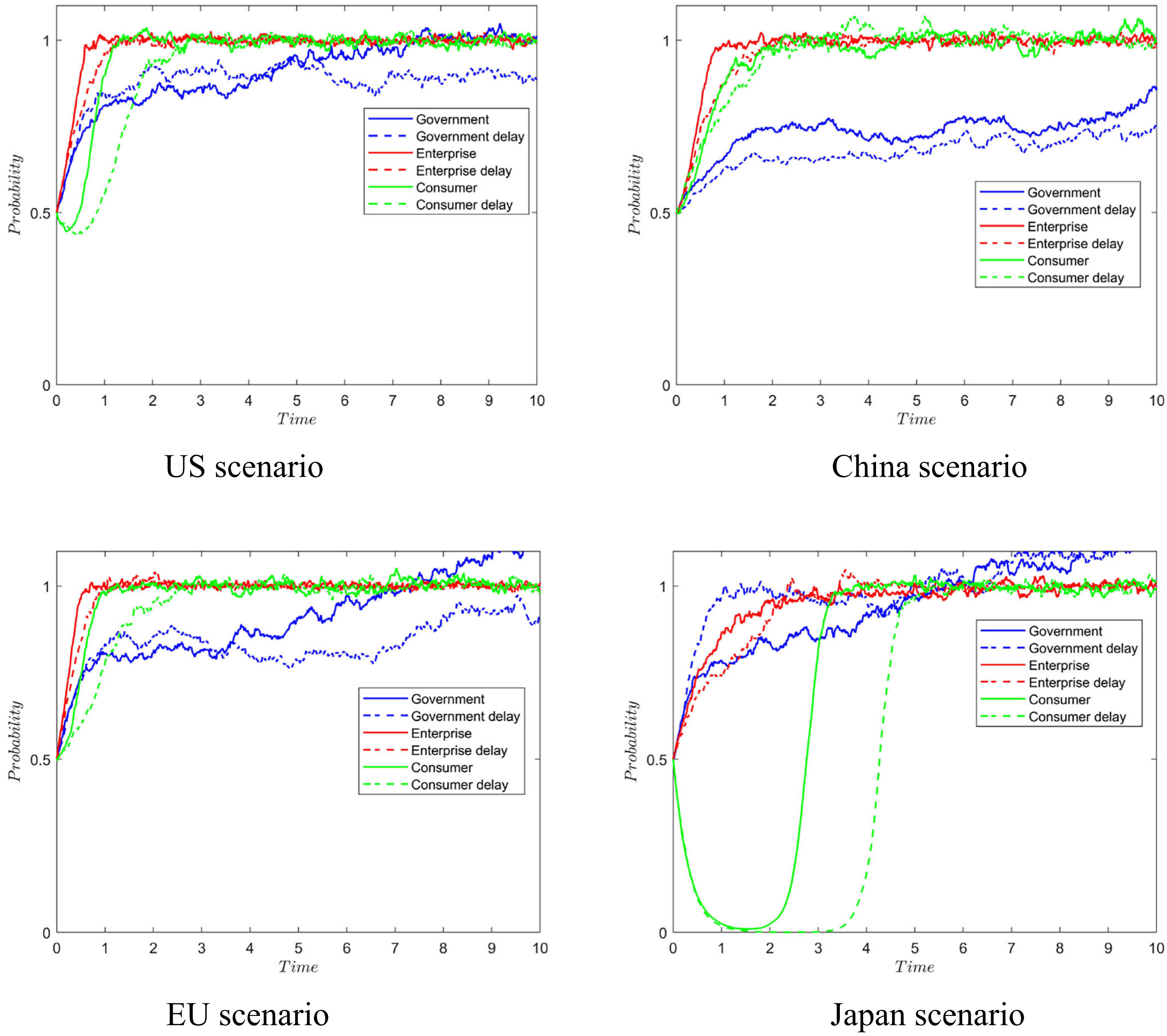


**Fig. 2 Impact of a 2-times delay on the evolution process of strategies adopted by EV industry players in various countries (regions).** The solid line represents no time delay, whereas the dashed line represents a 2-times delay.

in the short term, Japanese consumers' willingness to purchase new energy vehicles is very low. In summary, from the perspective of the consumer side, the evolutionary game paths of new energy vehicles in China, the U.S., and the EU are similar. This similar development path is a key reason for the excellent development of the new energy vehicle industry in China, the U.S., and the EU.

### Analysis of the mechanisms influencing EV industry development pathways

*Impact of information delays*. Information lags distort game-theoretic outcomes by impairing firms' R&D commitments, market positioning, consumer demand fulfillment, and supply-chain coordination efficiency while reducing policy adaptability. This subsection parameterizes these delays to explain cross-regional variations in EV industry trajectories.

Figure 2 demonstrates that information delays disproportionately prolong government subsidy equilibrium convergence. The solid trajectories (without delays) reach equilibrium faster than their dashed counterparts do ($\tau = 2$). Across 100 evolutionary dynamics simulations, the U.S., China, and EU subsidy strategies exhibit 127% longer convergence versus the baseline under $\tau = 2$, versus 68% and 54% delays for firms and consumers, respectively. Notably, Japan exhibits inverse dynamics: government subsidy convergence accelerates (blue dashed trajectory) despite firm (+39%) and consumer (+61%) response delays. This anomaly likely stems from Japan's industry-centric policymaking, where incomplete information triggers oversubsidization traps—governments prioritize sustained EV competitiveness through irrational subsidies, diverging from consumer/firm responses.

*Impact of carbon pricing*. As carbon pricing mechanisms mature, their price signals reshape industrial ecosystems through production cost restructuring effects and shifts in market demand elasticity. While rising carbon costs amplify marginal costs for internal combustion vehicles, explicit environmental cost

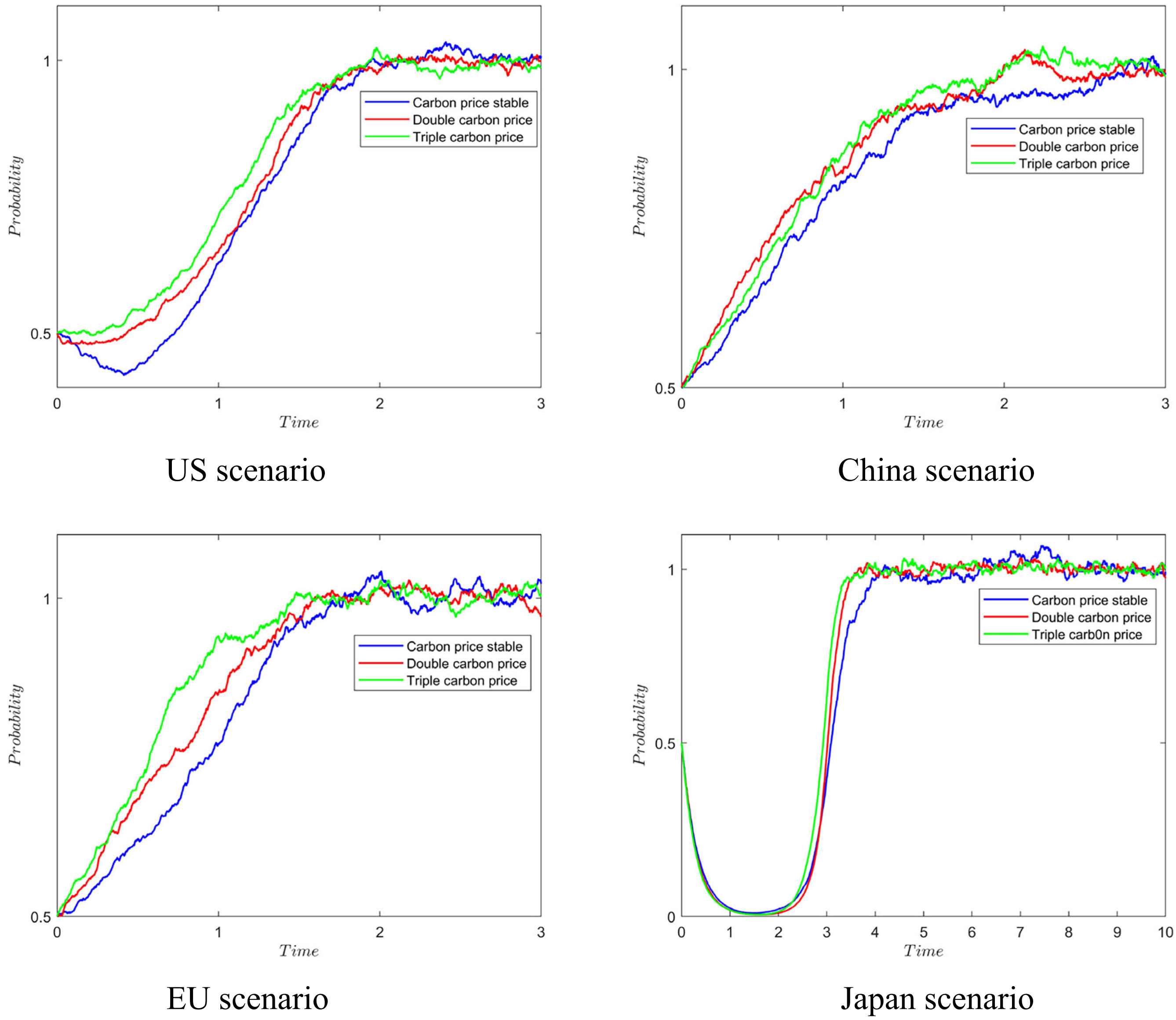


**Fig. 3** Impact of rising carbon prices on consumers' willingness to purchase.

differentials alter consumer preferences. However, heterogeneous impacts emerge across countries due to variations in economic development levels, energy mix heterogeneity, policy environments, and EV industrial foundations. We empirically test these heterogeneous impacts on EV industry game-theoretic outcomes.

As shown in Fig. 3, on the one hand, an increase in the carbon price enhances consumers' willingness to purchase new energy vehicles. With the rise in the carbon price, the evolutionary game cycle for consumers in various countries (regions) will be advanced. Compared with the stable evolution time of consumer strategies when carbon prices are stable and surge (tripling the carbon price), the increase in purchasing willingness among Chinese and EU consumers is most significant. The stable strategy for Chinese consumers to purchase new energy vehicles has evolved from a 2.7-times cycle when carbon prices are stable to less than 2.2 times, whereas for European consumers, the stable strategy has evolved from a 2-times cycle to less than 1.5 times, with both achieving stability 0.5 times earlier. In contrast, the willingness of Japanese consumers to purchase EVs is less affected by an increase in the carbon price.

The core mechanism hinges on carbon pricing dynamics. Price elasticity drives strategic interactions: Rising carbon prices amplify internal combustion vehicle operational costs (fuel, taxes) while enhancing EV competitiveness through stable, lower electricity costs. China's coal-dominated power mix sustains electricity-oil price differentials, intensifying consumer EV adoption incentives. Conversely, Japan's low baseline carbon pricing weakens multiplier effects on EV purchase intent despite policy escalation.

Moreover, cross-country heterogeneity exists in the relationship between carbon price escalation rates and consumer adoption growth rates. In Japan, a 1% carbon price increase corresponds to a 1% acceleration in EV adoption rates, whereas other regions exhibit decoupled growth patterns between carbon pricing rates and adoption rates. This disparity arises from Japan's comparatively low EV penetration, which diminishes the perceived cost impact of carbon pricing on conventional vehicle users, resulting in weaker consumer sensitivity to carbon price fluctuations relative to other markets.

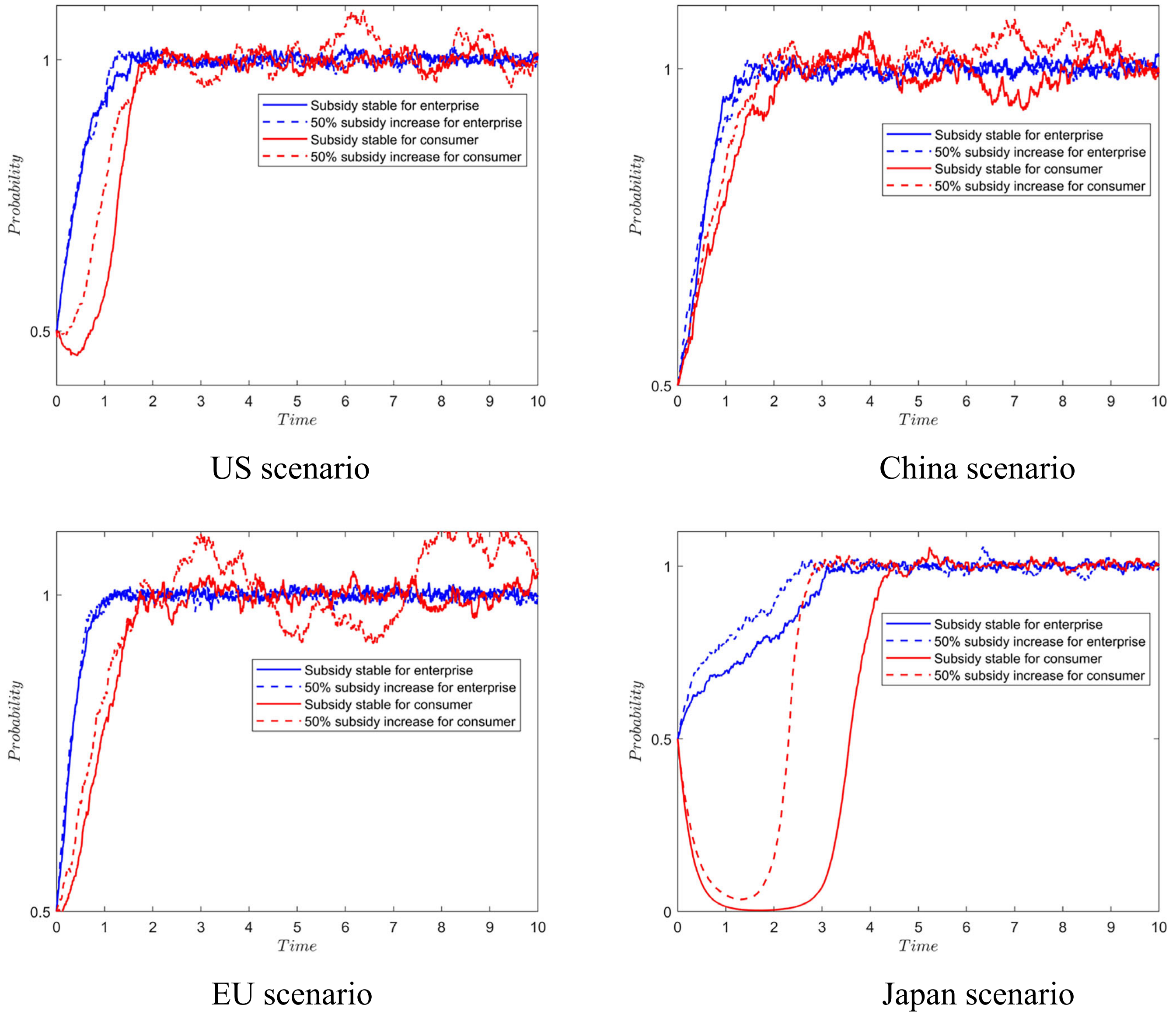


**Fig. 4** The strategic impact of subsidies on consumers and enterprises.

*Impact of subsidies*. The impact of government subsidies on new energy vehicle enterprises and consumers is multifaceted. For enterprises, government subsidies reduce their production costs and R&D risks, enhancing the market competitiveness of EVs. For consumers, government subsidies lower the cost of purchasing vehicles, increasing their willingness to purchase new energy vehicles. However, similar to the impact of carbon pricing, the market effects of government subsidies vary across different countries (regions).

Figure 4 reveals that subsidy adjustments primarily influence consumers: consumption subsidies (e.g., purchase incentives) increase EV adoption intent, whereas production subsidies show limited efficacy in stimulating high-quality EV R&D among the U.S., China and EU manufacturers. A cross-regional 50% subsidy increase accelerates equilibrium convergence (red dashed vs. solid trajectories) but has weaker effects than does carbon pricing. This stems from the subsidy policies' one-off transfers versus the carbon pricing's persistent operational cost restructuring. As markets mature, carbon-driven cost differentials dominate consumer decisions, surpassing transient subsidy impacts.

The empirical results indicate that across all regions except Japan, equilibrium convergence rates under stable production subsidies (blue solid trajectories) align closely with subsidy escalation scenarios (blue dashed trajectories). This demonstrates the limited efficacy of production subsidies in accelerating high-quality EV R&D commitments or inducing equilibrium convergence acceleration. The reason for this is cost, which is crucial. Subsidies in various countries (regions) are one-time, while the impact of carbon prices is long-lasting. As the market matures and the use of new energy vehicles extends, the impact of carbon prices on consumers is significantly greater than that of government subsidies. On the other hand, rising production subsidies in various countries (regions) will neither stimulate an increase in enterprisers' willingness to develop high-quality new energy EVs nor lead to an earlier arrival of the game equilibrium state. The reason for this is that production subsidies can directly reduce the production costs of new energy vehicles, allowing enterprisers to invest more funds into research and development activities while maintaining reasonable profits. However, it should be noted that in fierce market competition, technological

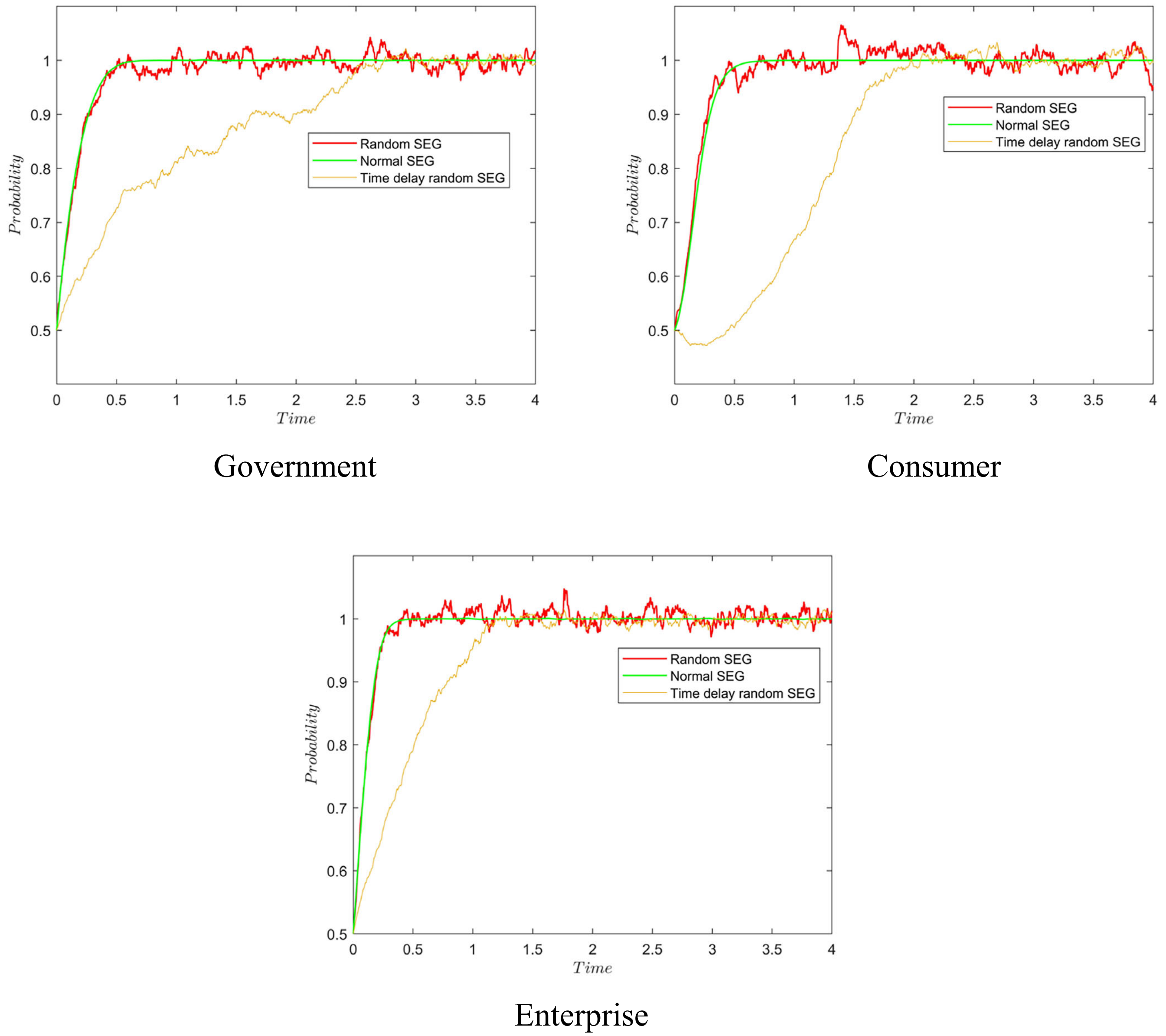


**Fig. 5** Robustness test of government-enterprise-consumer strategies in different evolutionary game models.

innovation is crucial for enterprisers to increase their competitiveness and seize market opportunities. Moreover, the effectiveness of research and development lags behind, which is reflected in the time required for technological breakthroughs, the cycle needed for the transformation of research results, and the slow increase in market acceptance. Therefore, companies choosing to develop high-quality new energy EVs are all manifestations of their long-term adaptation to market competition, and production subsidies will not affect their research and development strategies for high-quality new energy EVs. In addition, unclearly targeted production subsidies may also distract enterprises' resources and efforts from the research and development of high-quality new energy EVs, ultimately causing companies to abandon the research and development of high-quality new energy EVs. The results of this paper indicate that increasing subsidy levels will not change the strategic choices of companies in developing high-quality EVs. This result further verifies the conclusion of Zhao et al. (2024) that "government subsidies will hinder the high-quality research and development of EVs by companies".

**Robustness test**. To validate the stability of the stochastic delay evolutionary model, we replicate the EV industry evolutionary game outcomes using U.S. empirical market data under a 1-time information lag ($\tau = 1$), demonstrating model consistency across temporal parameterizations.

As shown in Fig. 5, both the stochastic evolutionary game model and the evolutionary game model with time delay exhibit evolutionary trends and convergence consistent with the standard evolutionary game model, with differences only in the evolutionary rate and stabilization time. The fluctuation in the rate of strategy changes caused by stochasticity is most pronounced during the consumer strategy selection game process, whereas the time delay has the most profound effect on the robustness of government strategies. Under the guidance of stochasticity, consumers may reach an equilibrium strategy for purchasing new energy vehicles earlier. Under the guidance of a time delay, the rate of enterprise R&D strategies is significantly higher than that of consumer new energy vehicle purchases and government subsidies, resulting in a shorter game time for the final stable state of R&D strategies. We can conclude that randomness does not change the outcome of the game, but affects only the rate during the game process; information delay does not change the outcome of the game, but affects only the game time. However, both randomness and time delay reflect the game process and do not affect the convergence of the final model. The evolutionary game model with time delay proposed in this paper is robust.

## Conclusion and policy recommendations

**Conclusion**. The development of the EV industry involves multiple aspects, such as technology, the market, policy, and infrastructure. When any country or region develops its EV industry, if there are shortcomings in policy, technology, the market, and infrastructure, its development of the EV industry will be affected. The results of this study indicate that the U.S., the EU, and China share strong similarities in terms of the development prospects of the EV industry. This similarity is attributed mainly to similar policy support, technological innovation, market demand, and cost control, to the extent that the governments of the three countries (regions) adopt the same strategies when facing information lag, consumers facing policy subsidy reductions, and enterprises facing market competition. Moreover, these similarities reflect the common trends and patterns of the development of the global EV industry, namely, policy support and promotion, technological innovation and iteration, market demand and growth, industrial chain collaboration and development, and low-carbon and sustainable development are the origins of promoting the continuous prosperity of the global EV industry. These findings align with those of Wu et al. (2021), Liu et al. (2023), Liu et al. (2024), and Nylund and Brem (2024) in identifying policy incentives, technological innovation cycles, market demand dynamics, supply-chain coordination, and low-carbon sustainability imperatives as foundational drivers of sustained growth of the EV industry.

In contrast, the development model of the EV industry in Japan tends to fluctuate between government-led and enterprise-led approaches. This is reflected in the intersection of EV research and development strategies and policy subsidy strategies during its stochastic evolutionary game, where the government's subsidy reduction strategy is more rapid than that of enterprises. Considering the current development status of EVs in Japan, owing to Japan's long-term focus on the research and development of hydrogen-powered vehicles in the field of new energy vehicles and its relatively lower investment in pure EVs and hybrid EVs, the lack of subsidy policies and the lag in the construction of charging infrastructure have caused Japanese automobile manufacturers to have a hesitant attitude about the EV revolution, preferring to continue the existing hybrid technology route. Moreover, although the development model of EVs in Japan is similar to that in China and the U.S., the price of EVs in Japan is still higher than that of traditional fuel vehicles, which inhibits consumers' desire to purchase EVs and hinders the popularization of EVs.

The research results of this paper further show that information timeliness, the carbon price and subsidies are the core factors that affect the decision-making of relevant subjects in the EV industry.

First, information timeliness affects the strategic choice and duration of government subsidy policies. The more significant the information lag is, the longer the evolution cycle of the subsidy policy, and the weaker the government's market regulation ability. Deng and Hao (2024) provided theoretical grounding: information lags induce policy inertia, where regulators extend existing policy cycles to minimize institutional adjustment costs from frequent revisions, systematically dampening market responsiveness.

Second, carbon prices affect consumers' willingness to buy EVs. The higher the carbon price is, the shorter the time to reach the purchase intention of EVs. However, there is no obvious proportional relationship between the time when the purchase strategy is reached and the carbon price. The results of this study show that the time of consumers' willingness to purchase EVs triggered by the quadruple carbon price is consistent with that triggered by the double carbon price. These empirical findings corroborate those of Bhat et al. (2025), who reported that carbon abatement policy implementation accelerated EV adoption rates.

Third, subsidies not only affect consumers' EV purchase strategies but also affect enterprisers' choice of high-quality EV R&D strategies, but the impact is limited. This finding corroborates Sun et al.'s (2019) conclusion that consumer subsidies outperform manufacturer subsidies in promoting EV adoption and technological breakthroughs. Furthermore, we demonstrate that while production and consumption subsidies temporarily increase consumers' purchase intentions and manufacturers' R&D incentives for high-quality EVs, they do not ultimately alter the equilibrium strategy outcomes for either party. Especially for EV enterprisers, in the current fierce market competition, the profits brought by high-quality new energy vehicles are not enough to offset the decline in profits brought by high R&D costs. Therefore, the profit and market share demand of enterprisers is higher than the R&D demand for high-quality EVs. It is difficult for production subsidies to promote the research and development of high-quality new energy and new energy vehicles.

**Policy recommendations**. Our findings reveal that convergent development pathways across China, the U.S. and the EU accelerate technology diffusion and cost reduction in the EV industry. However, achieving exponential economic growth through the "economies of scale-technological innovation-policy iteration" virtuous cycle requires addressing the following challenges.

First, the information lag of the government should be reduced. The market is the wind vane of industrial development, and changes in the market signal can reflect the supply and demand situation, competition situation and other important information of the industry. The EV industry is highly competitive, with a high market growth rate and fast technology update speed. Rapidly responding to market changes and technological progress, and formulating policies and measures that meet actual needs are highly important for industry development. If the government information lags behind, it may miss the best time for the introduction of the policy, resulting in a great discount on the effect of the policy. Therefore, when formulating a reasonable EV industry policy, we should first improve the timeliness of information, accurately understand the current situation of the industry in a timely manner and predict the development trend.

Second, carbon price tools can be reasonably used to improve the penetration of new energy vehicles. The use of a carbon price tool is a complex but important strategy to improve the penetration of new energy vehicles. The carbon price can provide a clear price signal to guide enterprises and consumers to transfer to low-carbon products (such as EVs). By increasing the cost of high-carbon products (such as traditional fuel vehicles), the relative price of low-carbon products can be reduced, and consumers can be encouraged to buy EVs. Moreover, we should optimize the allocation of resources, guide funds to the field of low-carbon technologies and products and promote the development of the EV industry. However, the factors influencing the carbon price are complex, and the requirements for policymaking are high. Therefore, a reasonable carbon price level should be formulated according to national conditions and actual industrial development. We should not only consider the affordability of enterprises but also ensure that carbon prices can play an effective incentive role.

Third, a precise subsidy policy and a perfect subsidy exit mechanism should be designed. In the current market-oriented global EV industry environment, government subsidies should avoid the traditional "flood irrigation" form, guide enterprises to strengthen technological innovation and product research and development and promote industrial transformation and upgrading through the precise positioning of subsidy objects, the refinement of subsidy standards and the innovation of subsidy means. First, subsidies should focus on EV enterprises and projects with technological innovation capabilities, broad market prospects and strong industrial chain operations. Second, differentiated subsidy standards should be formulated according to key performance indicators such as the EV range, energy consumption level and battery energy density. Third, in addition to direct subsidies, we can also consider various ways to support the development of the EV industry, such as tax relief, loan preferences, and charging facility construction subsidies. Third, the government should gradually reduce the subsidy standards and scope according to industrial development and market changes until it finally withdraws completely. However, it should be noted that the withdrawal of subsidies should be carried out in stages to avoid excessive impacts on the market caused by a one-time withdrawal. In the process of subsidy withdrawal, an effective market incentive mechanism should be established to encourage enterprises to rely on their own technical strengths and market competitiveness.

Despite the model's attempt to simulate the consequences of EV development paths from a realistic perspective, there are inherent limitations. First, while the model captures dynamic strategy evolution, its probabilistic nature restricts precise prediction of the exact timing of stable equilibria, yielding only trend-based projections. Second, the simplified consumer decision rules inadequately represent heterogeneous preferences (e.g., brand loyalty, charging infrastructure concerns), potentially deviating from real-world market behaviors. Third, the aggregated data standards across countries/regions and the binary comparison between premium EVs and conventional vehicles overlook performance variations across price segments (e.g., economy vs. luxury EVs), limiting insights into submarket competition. Future research will enhance the model by integrating Bayesian networks to address nonlinear and abrupt influencing factors, improving practical simulation capabilities. We will also incorporate segmented cost data (low/mid/high-tier EVs) to examine heterogeneous carbon pricing impacts across consumer tiers.

## Data availability
No datasets were generated or analyzed during the current study.

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## Author contributions
Yazhi Song conceived of the study idea, supported the formation of manuscript drafts, and provided guidance on the vision. Yin Li compiled and summarized the literature on the carbon price influence. Jingjing Jiang contributed to the manuscript drafts and assisted in paper edits. Bin Ye initiated this research and contributed to the idea formation, foundation and editing of the manuscript. All authors contributed to and reviewed the manuscript.

## Competing interests
The authors declare no competing interests.

## Ethical approval
This article does not contain any studies with human participants performed by any of the authors.

## Informed consent
This article does not contain any studies with human participants performed by any of the authors.

## Additional information
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