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Product development strategies of electric vehicle manufacturers: Considering government subsidy and consumers' environmental preferences

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ABSTRACT

Governments worldwide have promulgated greenness-based electric vehicle subsidy (GEVS) policies to encourage electric vehicle (EV) manufacturers to develop products with higher greenness (i.e., energy saving and emission reduction performance). Normally a GEVS policy would set a subsidy threshold to ensure that only EVs whose greenness meets the subsidy threshold requirement receive the subsidy. By considering consumers' environmental preferences (CEPs), this paper develops game-theoretical models to investigate the impacts of the GEVS policy on EV manufacturers' product development strategies and profits, as well as on the environment. The findings show that the product development strategies highly depend on subsidy thresholds, and three equilibrium product development strategies are obtained in equilibrium. Besides, it is intuitive to find that, in the absence of CEP, a low subsidy threshold can increase both EV manufacturers' profits and reduce the environmental impact of EVs simultaneously. However, the opposite results emerge when consumers have strong environmental preferences; that is, a low subsidy threshold would hamper both EV manufacturers' profits, and meanwhile increase EVs' environmental impacts. Surprisingly, as CEP increases, the GEVS policy is more likely to reduce EV manufacturers' profits and increase EVs' environmental impacts.

1. Introduction

Increasing energy consumption and carbon dioxide emissions from the transport sector have imposed serious threats to the environment (Degirmenci and Breitner, 2017). Studies show that the fuel combustion of traditional gasoline vehicles is a main contributor to carbon dioxide emissions (Li et al., 2020). Therefore, the development of green product, such as electric vehicle (EV), has been adopted as a strategy to save energy consumption and reduce carbon dioxide emissions (Li et al., 2018; Li et al., 2022). Compared with gasoline vehicles, EVs can reduce carbon emissions by 30 % to 50 % (Wang et al., 2017). With advanced green technology, vehicle manufacturers can achieve further improvement on energy saving and carbon reduction (referred to as greenness) of EVs (Hafezi and Zolfagharinia, 2018). However, there are many barriers affecting the development of EVs, such as high research and development (R&D) cost of EVs. Among various influential factors, the government subsidy policy and consumer demand are critical drivers (Hafezalkotob, 2017; Wu et al., 2020).

Government subsidy policies can be effective in alleviating vehicle manufacturers' cost pressure and promoting EV development (Zhu et al., 2022). At present many countries have enacted such subsidy policies including Germany, Italy, France and China (Breetz and Salon, 2018; Kong et al., 2020). In the initial stage of EV development, some governments offer the same subsidy to EVs with different greenness to promote the sales of EVs. However, extant literature (for instance, Liu et al., 2023) posits that subsidy policies can inadvertently engender adverse effects on product innovation and technological upgrading among EV manufacturers. With the development of EV market, the subsidy policy begins to take the greenness as a critical measurement, and a greenness-based EVs subsidy (referred to as GEVS) policy has been formulated to encourage EV manufacturers to develop products with higher greenness. Nowadays, the GEVS policy has been widely adopted

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in many countries (e.g., France, Italy, China). It is noticed that the GEVS policy has two characteristics: the first is that there is a subsidy threshold eligible for a subsidy, and the second is that EVs of higher greenness can obtain higher subsidies. For example, according to the Chinese GEVS policy in 2022, a plug-in hybrid EV with a charging power of 10 kW can obtain a subsidy only when the energy-saving rate is not lower than 60 %, and more subsidies can be obtained when the energy-saving rate increases. For convenience, in this paper, the vehicle with a greenness not lower (higher) than the subsidy threshold is referred to as high-greenness (low-greenness) products.

Studies show that consumers' environmental preferences (CEP) will significantly affect market demand and ultimately affect firms' decisions and profits (Ji et al., 2017; Zhang et al., 2019). In recent years, CEP has gradually improved, and a consumer with higher environmental preference is willing to pay a premium for products with higher greenness (Prakash et al., 2019; Su et al., 2021). A big data statistic has quantified the premium, revealing that the value of the average premium is about 33 %.[1] More recently, the empirical pieces of evidence show that CEP exhibit significant impacts on consumers' demand for EVs, thus motivating firms to develop products with higher greenness (Wu et al., 2022; Fan et al., 2022).

To response to the GEVS policy and increasing CEP, some EV manufacturers tend to develop high-greenness products. For example, BYD, a well-known EV company, chooses to develop high-greenness products, thus receiving a large amount of subsidy with more than 710 million yuan from 2016 to 2019 and achieving significant net profit growth of up to 578.11 %. Differently, some manufacturers choose to develop low-greenness products. It is reported that in China, 23 EV manufacturers failed to receive government subsidies,[2] because they develop low-greenness products that did not meet the subsidy threshold requirements.

Based on the above facts, it is obvious that different EV manufacturers will choose differentiated products development strategies (i.e., developing high-greenness or low-greenness products), and the driving force of these choices deserves further investigation. Intuitively, an EV manufacturer who develops high-greenness products can receive more subsidies from the government and enjoy the price premium from the consumers with CEP; meanwhile, developing high-greenness products incurs a substantial development cost. Therefore, the manufacturers need to weigh the revenue and cost when choosing products development strategies. For profit-oriented manufacturers, the GEVS policy and CEP would affect their products development strategies and consequently influence their profits. For environment-oriented governments, the GEVS policy and CEP would affect the production decision and the greenness decision of EV manufacturers, and ultimately affect the environment performance (i.e., energy consumption and carbon emission) of EVs. Therefore, investigating the effects of GEVS policy and CEP are crucial to manufacturers and governments. In this paper, the research questions are as follows:

> RQ1: How do the GEVS policy and CEP affect EV manufacturers' product development strategies?
> RQ2: How do the GEVS policy and CEP influence EV manufacturers' profits and the environment?

This study develops game-theoretic models to address the above questions. In this model setting, a competing supply chain involving a supplier and two ex-ante identical EV manufacturers is considered, and manufacturers can decide whether to develop high-greenness products or low-greenness products. First, two benchmark models without and with the GEVS policy (i.e., models N and C) are developed to investigate the impact of the GEVS policy in the absence of CEP. Subsequently, two models with the consideration of CEP are constructed, i.e., the models without and with the GEVS policy (models $N^{'}$ and $H^{'}$), and uncover the impacts of the GEVS policy and CEP on EV manufacturers' profits and the environment by comparing the two models.

The main contributions of this study can be outlined in four key dimensions. Firstly, the existing literature has mainly focused on fixed subsidies, neglecting the implications of subsidy thresholds and the greenness of EVs. In contrast, the study introduces a floating subsidy policy that depends on the subsidy threshold and the greenness of EVs. The findings highlight the significant influence of the threshold on the strategies, profitability, and environmental impacts of EV manufacturers, emphasizing their importance. Secondly, the research explores the CEP across different levels of greenness of EVs, expanding the scope of previous studies. While previous research has typically compared the environmental impacts of gasoline vehicles and EVs, this study specifically examines CEP within the EV category, considering various degrees of greenness. Thirdly, prior studies have primarily emphasized the technological aspects of EVs, such as battery lifespan, economic viability, and safety protocols. In contrast, this research delves into the potential for enhancing the greenness of EVs through technological innovation. This perspective provides new insights into the environmental benefits of EVs. Finally, the findings have practical implications by providing valuable recommendations for EV manufacturers regarding product development strategies. Additionally, governmental bodies can benefit from these insights in designing effective EV subsidy policies.

The rest of this paper is organized as follows. Section 2 reviews relevant literature. Section 3 depicts the model setting and assumptions. Section 4 develops game models without considering CEP. Section 5 constructs models by taking into account of CEP. Section 6 develops two extension models by relaxing the assumptions in the main models. Section 7 highlights the theoretical and practical contributions of this study. Section 8 concludes this paper.

2. Literature review

In this section, three streams of literature related to the topic of this paper are reviewed, including green product/green technology development, government policy in the EV market, and CEP.

2.1. Green technology/product development

Green technology refers to environmentally friendly technology that can save energy consumption and reduce environmental pollution (Braun and Wield, 1994). Previous studies have identified the typical factors affecting green technology development, including the success rate of investment in new technology, fuel price, the uncertainty of market demand, the power structure of players, consumer preference, and government policy (Wang et al., 2013; Selove, 2014; Meng et al., 2018). Among these factors, government policy is regarded as the main one, and many studies have investigated the impacts of different government policies on monopoly firms (see Krass et al., 2013; Drake et al., 2016), or competing firms (Drake, 2018; Zhou et al., 2019). Most literature intends to answer such a question: compared with the traditional high-pollution technology, whether the enterprise will adopt green technology or not (Cohen et al., 2016; Dong et al., 2019; Zhang and Huang, 2021; Zhong and Sun, 2022). Different from their studies, it is assumed that EV manufacturers have adopted green technology, and focus on how EV manufacturers should determine the greenness of products.

In previous studies on green product development, greenness is generally regarded as the "environmental quality" of products, and is commonly expressed by carbon dioxide emission reduction or energy-saving levels (Liu et al., 2012; Zhu and He, 2017). Prior studies have explored the greenness decision of manufacturers under different

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[1] http://i.aliresearch.com/file/20160803/20160803103534.pdf

[2] https://www.sohu.com/a/339885467_733088

scenarios. For example, Zhou and Huang (2016) have investigated the greenness decision of one firm under the government's various goals (i.e., reducing total energy consumption and average energy consumption). Other scholars have studied the greenness decision by considering different supply chain structures, such as one manufacturer and one supplier (Xie, 2015), two suppliers and a manufacturer (Xie, 2016), and two competing supply chains (Hafezalkotob, 2017). In contrast to these studies, this study considers a supply chain consisting of a supplier and two EV manufacturers in the EV market, and investigates EV manufacturers' product development strategies by considering both government subsidy policy and CEP.

2.2. The government policy in the EV market

Government policy is regarded as an important driver of the EV market development (Zhu et al., 2021; Zhu et al., 2022; Chen et al., 2022). There is extensive literature investigating government policy in the EV markets. Different government policies have been issued in practice, such as tax policy (Liu et al., 2017), subsidy policy (Gu et al., 2017; Cheng et al., 2022), and price discount scheme (Luo et al., 2014; Shao et al., 2017), dual credit policy (Li et al., 2020; Li et al., 2022). Among these policies, the government subsidy is regarded as effective and necessary, especially in the initial stage of EV market development (Gu et al., 2017; Zhu et al., 2021). It is found that the government subsidy plays an important role in improving the cost advantage of EVs and increasing the EV demand (Breetz and Salon, 2018; Sun et al., 2022). For example, Breetz and Salon (2018) found that federal and state incentives can improve the cost competitiveness of American EVs. Kong et al. (2020) established a system dynamics model, indicating that if China cancels the purchase subsidy plan, the market share of China's EVs will decline by 40.39 % by 2020. Some studies have investigated the optimal subsidy objects, such as EV consumers (Sun et al., 2019), EV manufacturers (Li et al., 2020), and EV infrastructure investors (Ledna et al., 2022).

Recently, a plethora of studies have begun to concentrate on how government policy interventions and consumer preferences collectively influence corporations' research and development as well as operational decisions (Jia and Chen, 2023; Choi and Koo, 2023; Feng et al., 2023; Shao et al., 2023; Li and Wang, 2023). For instance, Feng et al. (2023) evaluated consumer preferences towards battery range or charging intervals, along with the impact of green credit policies on investment decisions made by EV manufacturers. On the other hand, Choi and Koo (2023) explored how policy interventions and new market competition shape the optimal promotional strategies for manufacturers' new products. When it comes to policy, these studies primarily delve into fiscal subsidies and dual credit policies, yet they do not encompass the issue of government subsidy thresholds, i.e., only EVs that meet certain levels of greenness for government subsidies. In terms of consumer preferences, the research primarily focuses on consumer preferences regarding EV range, purchase costs, and operational costs, particularly addressing the issue of range anxiety (Choi and Koo, 2023; Feng et al., 2023; Shao et al., 2023). Some studies also pay attention to consumers' preferences for the environmental performance of EVs (Fan et al., 2022; Li and Wang, 2023). However, these studies only consider the difference in environmental performance between gasoline vehicles and EVs, without delving into consumer preferences for EVs at varying levels of eco-friendliness.

In a sum, the aforementioned policies overlook two crucial characteristics of the GEVS policy. The first characteristic is that there exists a subsidy threshold that determines the eligibility for receiving subsidies, and the second is that EVs of higher greenness are entitled to receive greater subsidies. As a consequence, the theoretical effectiveness of the GEVS policy is unknown. In addition, the effectiveness of subsidy policies have been investigated by most of the previous studies without considering CEP (Fan et al., 2022), which can be influential in affecting the effectiveness of government policies (Zhang et al., 2018). This paper intends to compensate previous studies by exploring the combined impact of government subsidies and CEP on the product development strategies in a competitive EV supply chain.

2.3. CEP

In the EV market, extensive studies have empirically investigated the impacts of CEP on EV demand or sales. Axsen and Kurani (2013) found that American families with stronger environmental preferences are more willing to buy EVs. It is found that the environmental benefits of EVs would significantly affect EV demand in Japan, and the United States (Krupa et al., 2014; Lim et al., 2015). Besides, Zhang et al. (2018) found that although the Chinese government offers substantial subsidies, consumers' willingness to buy EVs is still extremely low due to the lack of CEP. Recent literature tells that consumers' interests in energy-saving and environmental protection products are gradually rising, and CEP is found to significantly affect the sales of EVs (Prakash et al., 2019; Saari et al., 2020; Wang et al., 2020). All of these studies indicate that CEP will affect purchase intention, thus affecting demand. However, the above literature does not investigate the impact of CEP on the decisions of relevant enterprises in the EV supply chain. There are only a few studies investigating the impact of CEP on EV enterprises' decisions in the EV supply chain (Su et al., 2021; Wu et al., 2022; Fan et al., 2022).

Su et al. (2021) conducted an empirical study that highlighted the pivotal role of CEP. They proposed that the public's awareness of environmental conservation would constitute a significant proportion in the propagation of new energy vehicle sales. Wu et al. (2022) explored the influence of dual integral policies on the competitive market dynamics between traditional fuel vehicles and EVs. However, their research did not sufficiently depict the competition among EV manufacturers. In contrast, this paper delves further into the competitive landscape within the EV market and investigates the impact of subsidy policies on this competitive sphere. Fan et al. (2022) studied the diffusion of R&D innovations in EVs. They considered scenarios where EV manufacturers could enhance battery life, economic benefits, and safety of EVs, while concurrently reducing EV costs through R&D efforts. Unlike their research, this paper assumes scenarios in which EVs elevate their level of greenness via technological R&D.

3. The model

A competitive supply chain involving a supplier (denoted by subscript S) and two ex-ante identical EV manufacturers (denoted by subscript $i \in \{1,2\}$) that sell homogeneous products is considered. The supplier provides key parts of vehicles (such as engines or motors) to both two EV manufacturers. The two EV manufacturers are competing with each other in production quantities and product greenness. The government will offer a subsidy to the EV manufacturer who produces high-greenness EVs, which encourages two EV manufacturers to produce vehicles with higher greenness. In what follows, the assumptions from the perspective of consumers, EV manufacturers, government, and the environment, and conclude this section with the sequence of the events will be presented.

CEP is assumed to have significant impacts on the demand for EVs. In the absence of CEP, the two EV manufacturers are engaged in the Cournot competition (or the quantity competition). In this case, the inverse demand function is $p = a - q_1 - q_2$, where p is the market-clearing price of EV, a is the potential market demand, and q_i is the production quantity of the EV manufacturer i. This inverse demand function is based on the classical Cournot game model, also known as the quantity competition model, which has been widely acknowledged for its effectiveness in capturing the quantity competition between two distinct EV manufacturers within the EV market. This model suggests a linear price decrease of EVs with increased cumulative production, reflecting the inverse price-demand relationship in economics. Extensively used in low-carbon technology and EV market competition research, as proven by Sabzevar et al. (2017), Xu et al. (2017), and Liu et al. (2023), this Cournot model serves as this research benchmark. It's especially relevant in situations lacking greenness competition, allowing us to focus on pure quantity competition. However, when consumers have environmental preferences, the inverse demand function will be changed since they are willing to pay more for the products with higher greenness. Following Peng et al. (2018), and Zhou (2018), the inverse demand function is assumed to be $p_i = a - q_i - q_{3-i} + \theta(\tau_i - \tau_{3-i})$, where p_i is the market-clearing price of EV manufacturer i's products, τ_i denotes the greenness of EVs, and $\theta \in (0,1)$ depicts the average CEP and the intensity of greenness competition. In particular, a lower value of θ denotes lower CEP and weaker competition, and vice versa.

It is assumed that the cost of the two EV manufacturers includes the R&D cost and production cost. Following previous literature, e.g., Zhu and He (2017), and Hong and Guo (2019), it is assumed that the improvement in the greenness of EVs (i.e., τ_i) will incur high fixed R&D costs. A typical case in line with this assumption is as follows. EV manufacturers can improve the greenness (such as reducing the power consumption of 100 km) of EVs by developing the electric control system, which can improve the efficiency of the EV drive system, and ultimately reduce the power consumption of 100 km. This R&D method will incur extremely high fixed costs (including the construction cost of the R&D center, the wages of R&D personnel, etc.). Following Peng et al. (2018), Giri et al. (2019), Guo et al. (2020), and Zhu et al. (2022), the R&D cost of EVs (denoted by $C(\tau_i)$) is a quadratic function with respect to the greenness of EVs (denoted by τ_i), i.e., $C(\tau_i) = k{\tau_i}^2/2$, where k is the R&D cost coefficient reflecting the R&D cost efficiency. Following previous studies, e.g., Zhu and He (2017), and Liu et al. (2023), the unit production costs of two EV manufacturers are assumed to be zero. This assumption is mainly based on two reasons. First, previous studies have found that for products where greenness improvement primarily affects fixed R&D costs, production costs can be considered negligible compared to substantial development costs, and thus it can be ignored in modeling (Zhu and He, 2017; Feng et al., 2023). Second, the calculation shows that the positive production cost will not change the qualitative results of this study.

According to the GEVS policy, there is a subsidy threshold τ_0, which denotes the lowest greenness eligible for the government subsidy. Also, the GEVS policy declares that higher greenness can obtain more subsidies. Therefore, it is assumed that when $\tau_i \geq \tau_0$, the subsidy that the EV manufacturer i can obtain is $\lambda\tau_i$, where λ ($\lambda \geq 0$) stands for the subsidy intensity.

Now, the environmental impact (i.e., E), which depicts the carbon emissions of EVs at the use stage, is calculated. Following Zhou and Huang (2016), it is assumed that the initial unit energy consumption of each EV for the EV manufacturer i is κ_i. To focus on the impact of the GEVS policy, the difference in initial unit energy consumption of the two EV manufacturers is not considered. Therefore, it is assumed that $\kappa_1 = \kappa_2 = \kappa$. In line with methodologies applied in previous studies (e.g., Sim et al., 2019; Liu et al., 2023), the unit energy consumption of each EV is normalized to be 1 (i.e., κ=1). It is pertinent to note that while the qualitative findings of this study remain unchanged when $\kappa \neq 1$, the complexity of the model and associated mathematical formulations will increase if $\kappa \neq 1$. When the EV manufacturer develops green technology, the unit energy consumption of each EV can be reduced. Given the production quantity q_i and the greenness τ_i, the total energy consumption is $\sum_{i=1}^{2}(1-\tau_i)q_i$. Following Ouchida and Goto (2016), and Sim et al. (2019), it is assumed that one unit of energy consumption incurs per unit of carbon emission. Consequently, the total environmental impacts of EVs are $\sum_{i=1}^{2}(1-\tau_i)q_i$.

The sequence of the events is characterized as follows. First, the government decides whether to offer the GEVS policy, the subsidy threshold τ_0, and the subsidy intensity λ. Second, based on the GEVS policy, the two EV manufacturers determine the product development strategies, i.e., to develop high-greenness or low-greenness products. Third, the supplier decides the wholesale price w. Fourth, the two EV manufacturers decide on product greenness τ_i and production quantity q_i, simultaneously and independently. Finally, when the sales season is approaching and the market-clearing price is determined, consumers make the purchase decisions.

4. The equilibrium results without CEP

In this section, the impact of the GEVS policy in the absence of CEP will be investigated. A model without GEVS policy (i.e., model N), proceeded with a model incorporating the GEVS policy (i.e., model H) will be first developed, and consequently concluded with a comparison of EV manufacturers' profits and environmental impacts under two models (i.e., models N and H).

In model H, contingent on the product development strategy choice of EV manufacturers, there are three subgames, i.e., (i) neither EV manufacturer develops high-greenness products, denoted by HN; (ii) only one EV manufacturer (say manufacturer 1) develops high-greenness products, denoted by HO; (iii) both two EV manufacturers develop high-greenness products, denoted by HB. In a sum, the main models without CEP are shown as in Table 1.

4.1. The model without GEVS policy (model N)

In the model N, the two EV manufacturers determine product greenness τ_i and production quantity q_i to maximize their profits (denoted by $\prod_i^N$). The objective function of the EV manufacturer i is as follows:

$$\max_{q_1,\tau_1}\prod\nolimits_1^N = (p-w)q_1 - k{\tau_1}^2\Big/2, \max_{q_2,\tau_2}\prod\nolimits_2^N = (p-w)q_2 - k{\tau_2}^2\Big/2, \tag{1}$$

where $p = a - q_1 - q_2$. The supplier determines the wholesale price to maximize its profit ($\prod_S^N$), and the objective function is

$$\max_{w}\prod\nolimits_S^N = w(q_1+q_2). \tag{2}$$

Solving the model N via backward induction, the optimal greenness levels and product quantities of EV manufacturers in equilibrium can be obtained, which are $w^N = \frac{a}{2}$, $q_1^N = q_2^N = \frac{a}{6}$, $\tau_1^N = \tau_2^N = 0$. In line with the intuition, the result ($\tau_1^N = \tau_2^N = 0$) shows that in the case without CEP and GEVS policy, both two EV manufacturers lack the motivation to increase the greenness of products.

4.2. The model with GEVS policy (model H)

In this subsection, the model without CEP and with the GEVS policy (i.e., model H), will be developed. Three models in the three subgames (models HN, HO, HB) are developed, and the perfect Nash equilibrium of the above subgames is derived using backward induction. In what follows, the equilibrium results of each subgame are presented, and then the pure-strategy Nash equilibrium of the product development strategy for EV manufacturers is characterized.

4.2.1. Neither EV manufacturer develops high-greenness products (model HN)

In the model HN, the decision objective function of the EV manufacturer i is as follows:

$$\max_{q_i,\tau_i}\prod\nolimits_i^{HN} = (p-w)q_i - k{\tau_i}^2\Big/2, \text{s.t.}\tau_i \leq \tau_0, \tag{3}$$

where $p = a - q_1 - q_2$. The supplier's decision objective function is

Table 1
The main models without CEP.

Models	Whether to consider CEP	Whether to consider the GEVS policy	Does EV manufacturer 1 develop high-greenness products	Does EV manufacturer 2 develop high-greenness products	Decision variable of the supplier	Decision variables of EV manufacturer 1	Decision variables of EV manufacturer 2
Model *N*	×	×	×	×	w^N	q_1^N, τ_1^N	q_2^N, τ_2^N
Model *HN*	×	√	×	×	w^{HN}	q_1^{HN}, τ_1^{HN}	q_2^{HN}, τ_2^{HN}
Model *HO*	×	√	√	×	w^{HO}	q_1^{HO}, τ_1^{HO}	q_2^{HO}, τ_2^{HO}
Model *HB*	×	√	√	√	w^{HB}	q_1^{HB}, τ_1^{HB}	q_2^{HB}, τ_2^{HB}

$$\max_{w}\prod\nolimits_S^{HN} = w(q_1+q_2). \tag{4}$$

Solving the model *HN*, optimal wholesale price, product quantities, and greenness levels of EV manufacturers in equilibrium can be obtained, as shown in Lemma 1.

Lemma 1. In the subgame *HN*, the wholesale price, product quantities, and greenness levels are: $w^{HN} = a/2$, $q_1^{HN} = q_2^{HN} = a/6$, $\tau_1^{HN} = \tau_2^{HN} = 0$.

It can be seen from Lemma 1 that the equilibrium outcome in the model *HN* is the same as that in the model *N*. Specifically, in the model *HN*, both two EV manufacturers will not increase the greenness of EVs, and determine the same greenness levels and product quantities.

4.2.2. One EV manufacturer develops high-greenness products (model HO)

In the model *HO*, the decision objective function of the EV manufacturer *i* is as follows:

$$\begin{cases} \max\limits_{q_1,\tau_1}\Pi_1^{HO} = (p-w+\lambda\tau_1)q_1 - k{\tau_1}^2\Big/2, \ \ \text{s.t.}\tau_1 \geq \tau_0, \\ \max\limits_{q_2,\tau_2}\Pi_2^{HO} = (p-w)q_2 - k{\tau_2}^2\Big/2, \text{s.t.}\tau_2 \leq \tau_0, \end{cases} \tag{5}$$

where $p = a - q_1 - q_2$. The decision objective function of the supplier is as follows:

$$\max_{w}\prod\nolimits_S^{HO} = w(q_1+q_2), \tag{6}$$

Again, by solving the model *HO*, the optimal wholesale price, product quantities, and greenness levels in equilibrium can be obtained, which are summarized in Lemma 2.

Lemma 2. In the subgame *HO*, there exists a threshold of $L_1 = \left(4\lambda^2 - 6k + \sqrt{36k^2 - 42k\lambda^2 + 12\lambda^4}\right)\Big/\left[\lambda\left(3k - 2\lambda^2\right)\right]$ such that the wholesale price, product quantities, and the greenness levels in equilibrium are:

(i) if $\tau_0 \leq L_1$, *then* $w^{HO} = \frac{a}{2}$, $q_1^{HO} = \frac{ak}{2\left(3k-2\lambda^2\right)}$, $q_2^{HO} = \frac{a\left(k-\lambda^2\right)}{2\left(3k-2\lambda^2\right)}$, $\tau_1^{HO} = \frac{a\lambda}{2\left(3k-2\lambda^2\right)} > \tau_0$, $\tau_2^{HO} = 0$;

(ii) if $\tau_0 > L_1$, *then* $w^{HO} = \frac{2a+\lambda\tau_0}{4}$, $q_1^{HO} = \frac{2a+7\lambda\tau_0}{12}$, $q_2^{HO} = \frac{2a-5\lambda\tau_0}{12}$, $\tau_1^{HO} = \tau_0$, $\tau_2^{HO} = 0$.

Lemma 2 indicates that the wholesale price, greenness levels, and product quantities depend on the subsidy threshold. When the threshold is low ($\tau_0 \leq L_1$), EV manufacturer 1 will develop products whose greenness is higher than the subsidy threshold. However, when the threshold is high (i.e., $\tau_0 > L_1$), due to the high R&D cost, EV manufacturer 1 will develop products whose greenness is the same to the subsidy threshold. In addition, it can be inferred from Lemma 2 that the quantity of the EV manufacturer developing high-greenness products will be higher than that of the EV manufacturer developing low-greenness products (i.e., $q_1^{HO} > q_2^{HO}$). The reason is that the EV manufacturer developing high-greenness products can enjoy the subsidy offered by the government, which increases its cost advantage in producing EVs and ultimately promote EV sales.

4.2.3. Both two EV manufacturers develop high-greenness products (model HB)

In the model *HB*, the decision objective function of EV manufacturer *i* is as follows:

$$\begin{cases} \max\limits_{q_1,\tau_1}\Pi_1^{HB} = (p-w+\lambda\tau_1)q_1 - k{\tau_1}^2\Big/2, \ \ \text{s.t.}\tau_1 \geq \tau_0, \\ \max\limits_{q_2,\tau_2}\Pi_2^{HB} = (p-w+\lambda\tau_2)q_2 - k{\tau_2}^2\Big/2, \ \ \text{s.t.}\tau_2 \geq \tau_0, \end{cases} \tag{7}$$

where $p = 1 - q_1 - q_2$. The decision objective function of the supplier is

$$\max_{w}\prod\nolimits_S^{HB} = w(q_1+q_2). \tag{8}$$

Solving the model *HB*, optimal wholesale price, product quantities, and greenness levels in equilibrium can be obtained, as shown in Lemma 3.

Lemma 3. In the subgame *HB*, there exists a threshold L_2 (where $L_2 = \left(\lambda^2 - 3k + \sqrt{3k\left(3k - \lambda^2\right)}\right)\Big/\left[\lambda\left(3k - \lambda^2\right)\right]$) such that the wholesale price, product quantities, and the greenness levels in equilibrium are:

(i) $w^{HB} = \frac{a}{2}$, $q_1^{HB} = q_2^{HB} = \frac{ak}{2\left(3k-\lambda^2\right)}$, *and* $\tau_1^{HB} = \tau_2^{HB} = \frac{a\lambda}{2\left(3k-\lambda^2\right)} > \tau_0$ *if* $\tau_0 \leq L_2$;

(ii) $w^{HB} = \frac{a+\lambda\tau_0}{2}$, $q_1^{HB} = q_2^{HB} = \frac{a+\lambda\tau_0}{6}$, *and* $\tau_1^{HB} = \tau_2^{HB} = \tau_0$ *if* $\tau_0 > L_2$.

Lemma 3 shows that in the model *HB*, the supplier and EV manufacturers will set two different wholesale prices, product quantities, and greenness, depending on the subsidy threshold. From Lemma 3, it can be seen that when the subsidy threshold is low (i.e., $\tau_0 \leq L_2$), the supplier will set a low wholesale price. As a result, the two EV manufacturers invest more in green technology to increase the greenness of products, so that the greenness of products will be higher than the subsidy threshold ($\tau_1^{HB} = \tau_2^{HB} > \tau_0$). However, when the subsidy threshold is high (i.e., $\tau_0 > L_2$), the supplier will increase the wholesale price, thus two EV manufacturers face cost pressure from both the high R&D cost of high-greenness products and high wholesale price. As a result, both EV manufacturers will produce products with lower greenness equivalent to the subsidy threshold ($\tau_1^{HB} = \tau_2^{HB} = \tau_0$).

4.2.4. The product development strategies in equilibrium under the GEVS policy

In this subsection, the product development strategies of two EV manufacturers in equilibrium under the GEVS policy without considering CEP will be analyzed. Game theory is employed to systematically analyze the optimal product development strategy for two EV manufacturers. This analysis is conducted with the consideration of the potential strategies of the competitor, with the ultimate goal being the maximization of profits. During this process, two pivotal thresholds, L_3 and L_4 (see Proposition 1), are identified. These thresholds are depicted as situations where the profits, when varying product development strategies are adopted by the two EV manufacturers, are identical. This suggests that the product development strategies might be reconsidered by EV manufacturers when market conditions align with these two thresholds.

Proposition 1. *In the scenario without CEP, there exist two thresholds* (i.e., L_3 *and* L_4, *where*$L_3 = 28a\lambda/\left(72k + 21\lambda^2\right)$, $L_4 = 28a\lambda/\left(72k - 49\lambda^2\right)$) *such that the product development strategies for two EV manufacturers under the GEVS policy are*:

(i) both EV manufacturers develop high-greenness products when $0 \le \tau_0 \le L_3$;

(ii) only one EV manufacturer develops high-greenness products when $L_3 < \tau_0 \le L_4$;

(iii) neither EV manufacturers develop high-greenness products when $\tau_0 > L_4$.

The product development strategies in equilibrium under the GEVS policy are graphically illustrated in Fig. 1. It can be seen from Proposition 1 that the product development strategies mainly depend on the subsidy threshold. When the subsidy threshold is low (i.e., $0 \le \tau_0 \le L_3$), both EV manufacturers will develop high-greenness products. Because under this circumstance, the revenue from the subsidy can cover the R&D cost. When the subsidy threshold is moderate (i.e., $L_3 < \tau_0 \le L_4$), it is interesting to find that the symmetric EV manufacturers will choose the differentiated development strategy. That is, only one EV manufacturer will develop high-greenness products, while the other EV manufacturer will develop low-greenness products. The reason is that as the subsidy threshold increases, EV manufacturers need to pay higher R&D costs to reach the lowest greenness eligible for a government subsidy. Meanwhile, when both EV manufacturers develop high-greenness products, the quantities in the market will be extremely high so that the price is reduced, consequently reducing the profit of the two EV manufacturers. In line with intuition, when the subsidy threshold is high (i.e., $\tau_0 > L_4$), both EV manufacturers will forgo developing high-greenness products because of the high R&D expenditure and excessive wholesale price under this circumstance.

4.3. *The impact of the GEVS policy without CEP*

In Section 4.2, the equilibrium product development strategies of EV manufacturers under the GEVS policy have been derived. Correspondingly, the profits of EV manufacturers and environmental impact under the GEVS policy can be obtained. In this section, firstly, the impact of GEVS policy on EV manufacturers' profits by comparing the profits without and with GEVS policy will be investigated. Then, the impact of the GEVS policy on the environment will be investigated by comparing the environmental impacts without and with GEVS policy.

Proposition 2. In the scenario without CEP, compared with no GEVS policy, there exist three thresholds (i.e., L_2, L_3 and L_4) such that the GEVS policy creates the following impacts on the profits of two EV manufacturers:

(i) a positive impact on two EV manufacturers' profits when $\tau_0 \le L_2$, *denoted by (W, W);*

(ii) a negative impact on two EV manufacturers' profits when $L_2 < \tau_0 \le L_3$, *denoted by (L,L);*

(iii) a positive impact on EV manufacturer 1's profit, and a negative impact on EV manufacturer 2's profit when $L_3 < \tau_0 \le L_4$, *denoted by (W, L);*

(iv) no impact on two EV manufacturers' profits when $\tau_0 > L_4$, *denoted by (U, U).*

The impact of the GEVS policy on two EV manufacturers' profits is graphically illustrated in Fig. 2. Recall that when the subsidy threshold is exceedingly high (i.e., $\tau_0 > L_4$), both EV manufacturers will forgo developing high-greenness products and thus fail to obtain the government subsidy. In this case, the profits of the two EV manufacturers are the same in the case with and without the GEVS policy, which means the GEVS policy creates no impact on the two EV manufacturers' profits. However, when the subsidy threshold is high ($L_3 < \tau_0 \le L_4$), the GEVS policy can make the EV manufacturer who develops high-greenness products better off, and make the EV manufacturer who develops low-greenness products worse off. The reason is that the EV manufacturer who develops high-greenness products can obtain a government subsidy, which consequently increases its cost advantage and ultimately raises its profit.

When the subsidy threshold is low ($\tau_0 \le L_3$), there exists a specific lower threshold value, L_2. Only when the subsidy threshold reaches or falls below this lower threshold (i.e., $\tau_0 \le L_2$), can the GEVS policy benefit both EV manufacturers. Interestingly, when the subsidy

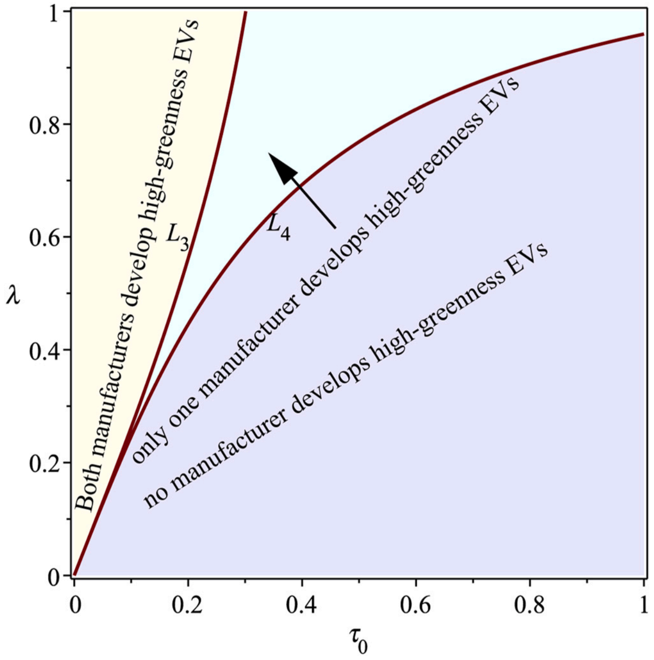


Fig. 1. The products development strategies in equilibrium without CEP.

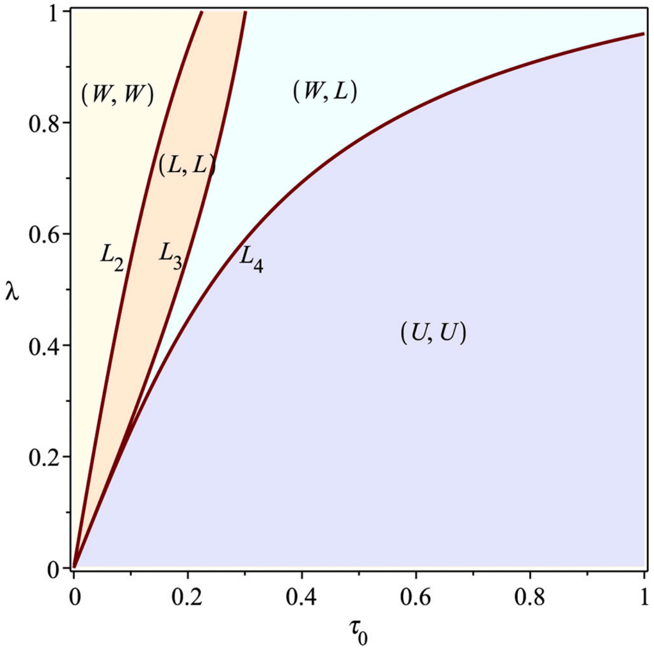


Fig. 2. The impact of the GEVS policy on EV manufacturers' profits without CEP.

threshold is moderate ($L_2 < \tau_0 \le L_3$), the GEVS policy will incur the profits losses for both EV manufacturers. This result can be understood as follows. When the subsidy threshold is moderate, the two EV manufacturers will get involved in a *prisoner's dilemma*, in which the Pareto optimal strategy is that both EV manufacturers develop low-greenness products, but developing high-greenness products will be the equilibrium. That is to say, compared with developing low-greenness products, the profits of two EV manufacturers will be lower when both EV manufacturers develop the high-greenness product. The reason for the profit losses in developing high-greenness is threefold. First, two EV manufacturers have to afford high R&D expenditure to obtain the government subsidy. Second, under this circumstance, the wholesale price will be high, which subsequently increases the cost pressure for the two EV manufacturers. Third, as stated earlier, the quantities in the market will be extremely high so that the price is reduced, which consequently reduces the profits of the two EV manufacturers.

Proposition 3. In the scenario without CEP, compared with no GEVS policy, there exists one threshold of L_4 such that the GEVS policy creates the following impacts on the environment:

(i) a positive impact on the environment when $\tau_0 \le L_4$;

(ii) no impact on the environment when $\tau_0 > L_4$.

The environmental impact of the GEVS policy is shown in Proposition 3. Proposition 3 shows that in the case without CEP, the impact of the GEVS policy on the environment heavily depends on the subsidy threshold. It should be noted that the GEVS policy will always have a positive impact on the environment when the subsidy is low, i.e., $\tau_0 \le L_4$ (while this result will not hold when considering CEP, see Section 5). Recall that one or two EV manufacturers will develop high-greenness products when the subsidy is low, thereby increasing the greenness of unit products and ultimately reducing the negative impact of products on the environment. However, when the subsidy threshold is high (i.e., $\tau_0 > L_4$), the GEVS policy has no impact on the environment. Because under this circumstance, the GEVS policy will not affect the greenness and product quantity decisions of EV manufacturers. As a result, the environmental impacts of EVs will keep unchanged.

5. The equilibrium results with CEP

In this section, the impact of the GEVS policy by considering CEP will be explored. Similar to Section 4, first, the model without the GEVS policy (i.e., model N') is established; then, the model with GEVS policy (i.e., model H') is developed; ultimately, the impact of the GEVS policy by comparing EV manufacturers' profits and the environmental impacts of EVs under models N' and H' will be uncovered.

In model H', there are three subgames: (i) neither EV manufacturer develops high-greenness products, denoted by $H'N$; (ii) only one EV manufacturer (e.g., manufacturer 1) develops high-greenness products, denoted by $H'O$; (iii) both two EV manufacturers develop high-greenness products, denoted by $H'B$. In a sum, the main models with CEP are in Table 2.

5.1. *The model without GEVS policy (model N')*

In the model N', the government does not offer subsidies to EV manufacturers. The decision objective function of the EV manufacturer i is as follows:

$$\max_{q_1,\tau_1}\prod\nolimits_1^{N'} = (p_1 - w)q_1 - k{\tau_1}^2 \Big/ 2, \max_{q_2,\tau_2}\prod\nolimits_2^{N'} = (p_2 - w)q_2 - k{\tau_2}^2 \Big/ 2, \tag{9}$$

where $p_i = a - q_i - q_{3-i} + \theta(\tau_i - \tau_{3-i})$, $i = 1, 2$. The supplier's decision objective function is

$$\max_{w}\prod\nolimits_S^{N'} = w(q_1 + q_2). \tag{10}$$

The greenness levels and product quantities in equilibrium are derived by solving the model N', i.e., $w^{N'} = \frac{a}{2}$, $q_1^{N'} = q_2^{N'} = \frac{a}{6}$, $\tau_1^{N'} = \tau_2^{N'} = \frac{a\theta}{6k}$. It can be seen from the equilibrium result that when consumers have environmental preferences, two EV manufacturers will improve the greenness levels (i.e., $\tau_i^{N'} > 0$), even without government subsidy.

5.2. *The model with GEVS policy (model H')*

In this subsection, the model with both CEP and the GEVS policy (i.e., model H') is developed. Three models in the three subgames, i.e., models $H'N$, $H'O$, $H'B$ are developed, and the perfect Nash equilibrium of the above subgames is derived by backward induction. In what follows, the equilibrium results of each subgame are first presented. Then, the pure-strategy Nash equilibrium of the development strategy for EV manufacturers is characterized.

5.2.1. *Neither EV manufacturer develops high-greenness products (model $H'N$)*

In the model $H'N$, the decision objective function of EV manufacturers is

$$\max_{q_i,\tau_i}\prod\nolimits_i^{H'N} = (p_i - w)q_i - k{\tau_i}^2 \Big/ 2, \text{s.t.}\tau_i \le \tau_0, \tag{11}$$

where $p_i = a - q_i - q_{3-i} + \theta(\tau_i - \tau_{3-i})$, $i = 1, 2$. The supplier's decision objective function is as follows:

$$\max_{w}\prod\nolimits_S^{H'N} = w(q_1 + q_2). \tag{12}$$

The equilibrium results in model $H'N$ by solving $H'N$ (see Lemma 4) can be obtained.

Lemma 4. In the subgame $H'N$, the wholesale price, product quantities, and the greenness levels in equilibrium are:

(i) if $\tau_0 < \frac{a\theta}{6k}$, then $w^{H'N} = \frac{a}{2}$, $q_1^{H'N} = q_2^{H'N} = \frac{a}{6}$, $\tau_1^{H'N} = \tau_2^{H'N} = \tau_0$;

(ii) if $\tau_0 \ge \frac{a\theta}{6k}$, then $w^{H'N} = \frac{a}{2}$, $q_1^{H'N} = q_2^{H'N} = \frac{a}{6}$, $\tau_1^{H'N} = \tau_2^{H'N} = \frac{a\theta}{6k}$.

Table 2

The main models with CEP.

Models	Whether to consider CEP	Whether to consider the GEVS policy	Does EV manufacturer 1 develop high-greenness products	Does EV manufacturer 2 develop high-greenness products	Decision variable of the supplier	Decision variables of EV manufacturer 1	Decision variables of EV manufacturer 2
Model N'	√	×	×	×	$w^{N'}$	$q_1^{N'}$, $\tau_1^{N'}$	$q_2^{N'}$, $\tau_2^{N'}$
Model $H'N$	√	√	×	×	$w^{H'N}$	$q_1^{H'N}$, $\tau_1^{H'N}$	$q_2^{H'N}$, $\tau_2^{H'N}$
Model $H'O$	√	√	√	×	$w^{H'O}$	$q_1^{H'O}$, $\tau_1^{H'O}$	$q_2^{H'O}$, $\tau_2^{H'O}$
Model $H'B$	√	√	√	√	$w^{H'B}$	$q_1^{H'B}$, $\tau_1^{H'B}$	$q_2^{H'B}$, $\tau_2^{H'B}$

Lemma 1 shows that EV manufacturers will not improve the greenness of products (i.e., $\tau_1^{HN} = \tau_2^{HN} = 0$) in the case without CEP. Different from Lemma 1, Lemma 4 tells that both EV manufacturers will improve the greenness of products $\tau_1^{H'N} = \tau_2^{H'N} > 0$ when consumers have environmental preferences. This result uncovers the important role of CEP in promoting green product innovation and carbon reduction.

5.2.2. One EV manufacturer develops high-greenness products (model $H'O$)

In the model $H'O$, the decision objective function of EV manufacturers is

$$\begin{cases} \max\limits_{q_1,\tau_1} \Pi_1^{H'O} = (p_1 - w + \lambda\tau_1)q_1 - k{\tau_1}^2 \Big/ 2, \ \text{s.t.}\tau_1 \geq \tau_0, \\ \max\limits_{q_2,\tau_2} \Pi_2^{H'O} = (p_2 - w)q_2 - k{\tau_2}^2 \Big/ 2, \ \text{s.t.}\tau_2 \leq \tau_0, \end{cases} \tag{13}$$

where $p_i = a - q_i - q_{3-i} + \theta(\tau_i - \tau_{3-i})$, $i = 1, 2$. The supplier's decision objective function is as follows:

$$\max_w \prod\nolimits_S^{H'O} = w(q_1 + q_2). \tag{14}$$

By solving the model $H'O$, the wholesale price, product quantities, and greenness levels in equilibrium are obtained. The expressions of the equilibrium results are quite complex, thus they are provided in the appendix.

5.2.3. Both two EV manufacturers develop high-greenness products (model $H'B$)

In the model $H'B$, the decision objective function of EV manufacturers is

$$\begin{cases} \max\limits_{q_1,\tau_1} \Pi_1^{H'B} = (p_1 - w + \lambda\tau_1)q_1 - k{\tau_1}^2 \Big/ 2, \ \ \text{s.t.}\tau_1 \geq \tau_0, \\ \max\limits_{q_2,\tau_2} \Pi_2^{H'B} = (p_2 - w + \lambda\tau_2)q_2 - k{\tau_2}^2 \Big/ 2, \ \ \text{s.t.}\tau_2 \geq \tau_0, \end{cases} \tag{15}$$

where $p_i = a - q_i - q_{3-i} + \theta(\tau_i - \tau_{3-i})$, $i = 1, 2$. The supplier's decision objective function is as follows:

$$\max_w \prod\nolimits_S^{H'B} = w(q_1 + q_2). \tag{16}$$

Solving the model $H'B$, optimal wholesale price, product quantities, and greenness levels in equilibrium can be obtained, which are: (i) $w^{H'B} = \frac{a}{2}$, $q_1^{H'B} = q_2^{H'B} = \frac{ak}{2(3k-\lambda(\lambda+\theta))}$, and $\tau_1^{H'B} = \tau_2^{H'B} = \frac{a(\lambda+\theta)}{2(3k-\lambda(\lambda+\theta))}$ if $\tau_0 \leq L_7$, and (ii) $w^{H'B} = \frac{a+(\lambda+\theta)\tau_0}{2}$, $q_1^{H'B} = q_2^{H'B} = \frac{a+(\lambda+\theta)\tau_0}{6}$, $\tau_1^{H'B} = \tau_2^{H'B} = \tau_0$ if $\tau_0 > L_7$, where $L_7 = \frac{a\left(\lambda(\lambda+\theta)-3k+\sqrt{3k(3k-\lambda(\lambda+\theta))}\right)}{(\lambda+\theta)(3k-\lambda(\lambda+\theta))}$.

5.2.4. The product development strategies in equilibrium under the GEVS policy

In this section, the product development strategies of two EV manufacturers in equilibrium under the GEVS policy are analyzed by considering CEP. The product development strategies of two EV manufacturers can be obtained by analyzing the profit matrix. Given the strategic space of the two EV manufacturers is {low-greenness products, high-greenness products}, the profit matrix can be shown in Fig. 3.

		EV manufacturer 2	
		Low-greenness products	High-greenness products
EV manufacturer 1	Low-greenness products	$\Pi_1^{H'N}$, $\Pi_2^{H'N}$	$\Pi_1^{H'\tilde{O}}$, $\Pi_2^{H'\tilde{O}}$
	High-greenness products	$\Pi_1^{H'O}$, $\Pi_2^{H'O}$	$\Pi_1^{H'B}$, $\Pi_2^{H'B}$

Fig. 3. Two EV manufacturers' profits matrix with CEP.

The profit matrix in Fig. 3 is a symmetric matrix, in which the strategy choices of the two EV manufacturers are the same. Therefore, EV manufacturer 1's product development strategies are analyzed by comparing the profit in four different scenarios. Due to the complexity of the profits expression of two EV manufacturers, the strategy choices of EV manufacturer 1 are analyzed through numerical simulation., and thus obtain the development strategies in equilibrium under the GEVS policy.

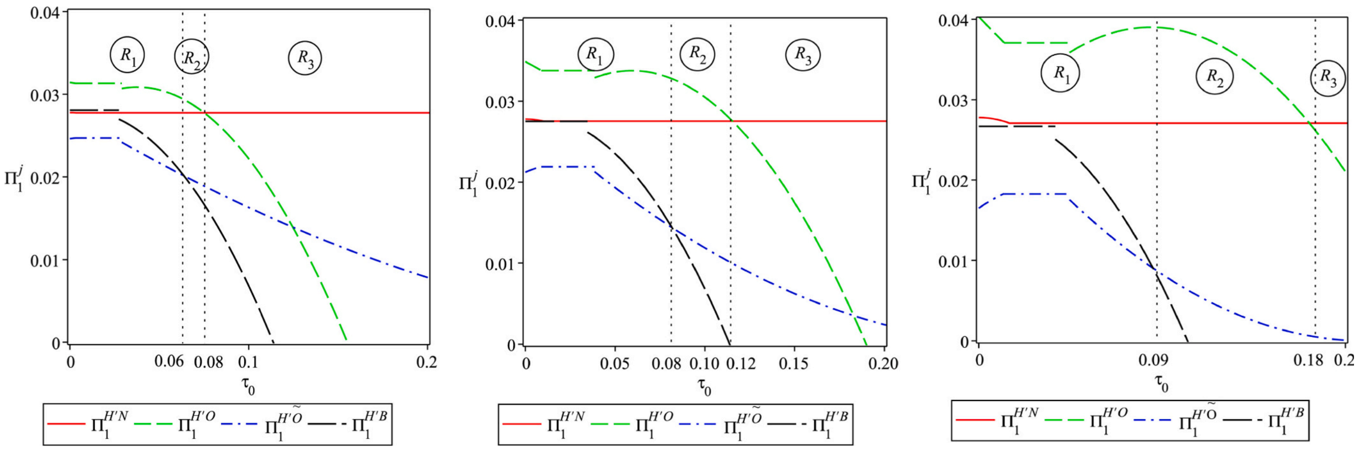
Following Shao et al. (2017), Zhang and Huang (2021), and Liu et al. (2023), the potential market demand is normalized to be 1. To ensure the practical significance of all models in this study, it is necessary to ensure that the production quantities of EVs from EV manufacturer 1 and EV manufacturer 2 are positive in different models (i.e., model N', $H'N$, $H'O$, $H'B$). In other words, for $i = 1, 2$ and $j = N', H'N, H'O, H'B$, the production quantities EVs should be greater than zero (i.e., $q_i > 0$). The corresponding equation $k > 2\theta^2 + \lambda^2 + 3\lambda\theta$ is assumed, which can meet the constraint of production quantities EVs. Besides, by solving the two equations, i.e., $k > 2\theta^2 + \lambda^2 + 2\lambda\theta$ and $\lambda \geq 0$, where $\theta > 0$ and $k > 0$, the equation $\lambda < \left(\sqrt{4k + \theta^2} - 3\theta\right) \Big/ 2$ can be derived. Let $\left(\sqrt{4k + \theta^2} - 3\theta\right) \Big/ 2 = \overline{\lambda}$, it can be seen that there exists a subsidy ceiling $\overline{\lambda}$, which is in line with the GEVS policy. This assumption ($\lambda < \left(\sqrt{4k + \theta^2} - 3\theta\right) \Big/ 2$) reflects the fact that the government will reduce the subsidy ceiling under two conditions, i.e., when the technology level increases (or equivalently, k decreases), and when CEP increase (or equivalently, θ increases).

To guarantee that the production quantities of the two EV manufacturers are non-negative and the constraint of subsidy ceiling, it is assumed that $k = 5, \lambda = 0.7, \theta = 0.1/0.3/0.5$. Then, the profits of EV manufacturer 1 under four scenarios (see Fig. 4(a/b/c)) can be obtained. It can be seen from Fig. 4(a) that EV manufacturer 1's development strategy heavily depends on the development strategy of his competitor (i.e., EV manufacturer 2) and the subsidy threshold. When the subsidy threshold is low (i.e., $\tau_0 < 0.06$), EV manufacturer 1's profit in developing high-greenness products is always higher than that in developing low-greenness products ($\prod_1^{H'O} > \prod_1^{H'N}$, $\prod_1^{H'B} > \prod_1^{H'\tilde{O}}$), regardless of EV manufacturer 2's development strategy. Thus when the subsidy threshold is low (i.e., $\tau_0 < 0.06$), EV manufacturer 1 will develop high-greenness products.

However, when the subsidy threshold is high ($\tau_0 > 0.08$), EV manufacturer 1's profit in developing high-greenness is always lower than that in developing low-greenness products ($\prod_1^{H'O} < \prod_1^{H'N}$, $\prod_1^{H'B} < \prod_1^{H'\tilde{O}}$), regardless of EV manufacturer 2's development strategy. Thus when the subsidy threshold is high (i.e., $\tau_0 > 0.08$), EV manufacturer 1 will develop low-greenness products.

Interestingly, when the subsidy threshold is moderate (i.e., $0.06 < \tau_0 < 0.08$), if EV manufacturer 2 chooses to develop low-greenness products, EV manufacturer 1's profit in developing high-greenness products is higher than that in developing low-greenness products ($\prod_1^{H'O} > \prod_1^{H'N}$); otherwise, if EV manufacturer 2 chooses to develop high-greenness products, the profit of EV manufacturer 1 in developing high-greenness will be lower ($\prod_1^{H'B} < \prod_1^{H'\tilde{O}}$). Therefore, it can be inferred that in this case, EV manufacturer 1 will make the differentiated development strategy to his competitor, i.e., to develop high-greenness (low-greenness) products when his competitor develops low-greenness (high-greenness) products.

The development strategy of EV manufacturer 2 is the same to EV manufacturer 1. Therefore, it can be obtained that there are three development strategies in equilibrium, i.e., both EV manufacturers develop high-greenness products when $\tau_0 < 0.06$ (region R1), only one EV manufacturer develops high-greenness products when $0.06 < \tau_0 < 0.08$ (region R2), and neither EV manufacturers develop high-greenness



(a) $\theta = 0.1$ (b) $\theta = 0.3$ (c) $\theta = 0.5$

Fig. 4. Two EV manufacturers' profits under the GEVS policy.

products when $\tau_0 > 0.08$ (region R3). The results in Fig. 4(b/c) are similar to that in Fig. 4(a), except for the thresholds of τ_0.

The results in Fig. 4 are summarized in Result 1.

Result 1. *In the scenario with CEP, the development strategies for two EV manufacturers under the GEVS policy are: (i) both EV manufacturers develop high-greenness products when τ_0 is small (region R1); (ii) only one EV manufacturer develops high-greenness products when τ_0 is moderate (region R2); (iii) neither EV manufacturers develop high-greenness products when τ_0 is large (region R3).*

In addition, Result 2 can be obtained from Fig. 4. It can be inferred from Fig. 4 that developing high-greenness products may hamper two EV manufacturers' profits under certain conditions. That is to say, there is a region in which $\prod_1^{H'N} > \prod_1^{H'B}$, and $\prod_2^{H'N} > \prod_2^{H'B}$ in region R1. The results tell that both EV manufacturers are involved in a *prisoner's dilemma,* in which both EV manufacturers choose to develop high-greenness products, but their profits in the case of developing low-greenness products are higher. Additionally, it can be seen from Fig. 4 (a/b/c) that with an increase in the CEP, the prisoner's dilemma area will be enlarged. This result can be explained as follows. As CEP increases, the competition will be tougher. As a result, there are more production quantities in the market, resulting in a lower price of vehicles, which further hamper the profits of both two EV manufacturers.

Result 2. *There exists a prisoner's dilemma for two EV manufacturers, in which two EV manufacturers develop high-greenness products in equilibrium, but their profits in the case of developing low-greenness products are higher. In addition, two EV manufacturers are more likely to get involved in the prisoner's dilemma with an increase in the CEP.*

Our further numerical simulation shows that Results 1 and 2 still hold when some parameters change. It is found that when the value of k is within the range of 6 to 20, while other parameters remain unchanged, Results 1 and 2 are still valid. Moreover, when the value of λ is within the range $\lambda \in \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6\}$ while other parameters remain unchanged, Results 1 and 2 are still valid.

5.3. *The impact of the GEVS policy with CEP*

In Section 5.2, the equilibrium development strategy of EV manufacturers under the GEVS policy have been derived. Correspondingly, the profits of EV manufacturers and environmental impacts under the GEVS policy can be obtained. In this section, the impact of GEVS policy on EV manufacturers' profits and the environment with the consideration of CEP is investigated. Similarly, numerical simulations are used to observe the effects of the GEVS policy.. The parameters setting is the same to that in Section 5.2, i.e., $a = 1, k = 5, \lambda = 0.7, \theta = 0.1/0.3/0.5$. Main variables and results with CEP are in Table 3.

The profits of two EV manufacturers with and without GEVS policy are graphically illustrated in Fig. 5(a/b/c). Fig. 5(a/b) indicates that when CEP is not strong, the impact of GEVS policy on EV manufacturers' profits is the same to that without CEP. Specifically, the GEVS policy increases both EV manufacturers' profits if the subsidy threshold is low (see region R1), decreases both EV manufacturers' profits if the subsidy threshold is moderate (see region R2), increases one EV manufacturer's profit if the subsidy threshold is high (see region R3), and creates no impact if the subsidy threshold is sufficiently high (see region R4).

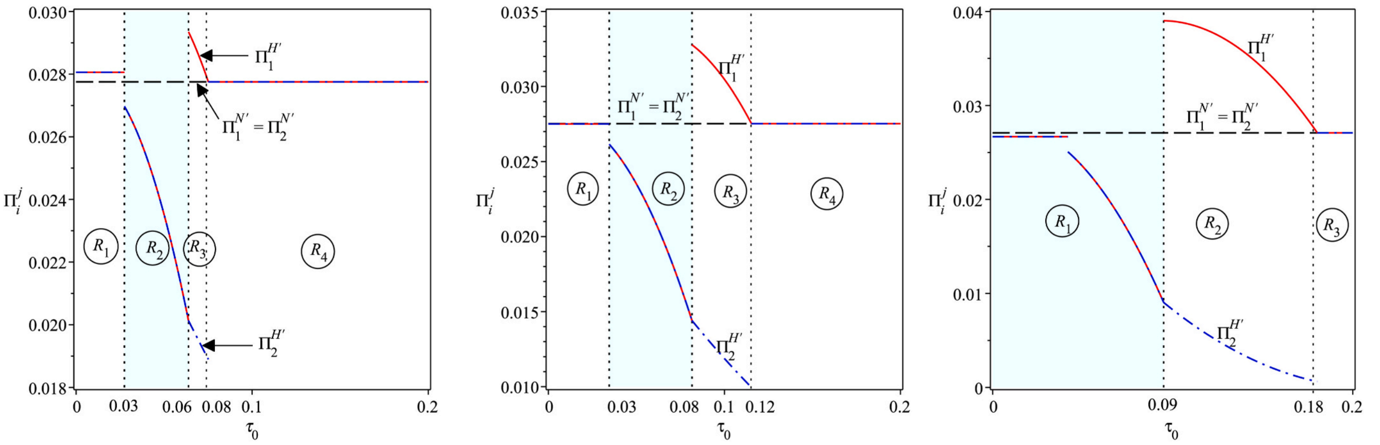
However, when CEP is strong, Fig. 5(c) indicates that a low subsidy threshold will hamper both two EV manufacturers' profits. The reason is that an increase in CEP will intensify the competition among two EV manufacturers, which leads to a sharp increase in the quantity under the GEVS policy. As a result, the price of EVs will decrease, and consequently, the profits of the two EV manufacturers are hampered by the GEVS policy.

It can be seen from Fig. 5(a/b/c) that, the region (i.e., region R2) in which the GEVS policy creates a negative impact on the two EV manufacturers' profits will increase. It implies that the two EV manufacturers are more likely to be hampered by the GEVS policy as the CEP increase. The reason is that when CEP increase, the two EV manufacturers are more likely to fall into a prisoner's dilemma, which leads to more production quantities and lower EV prices.

The main results in Fig. 5(a/b/c) are summarized in Result 3.

Table 3
The main variables and results with CEP.

Figures	The value of variables	The content of the analysis	Results of the analysis
Fig. 4	$a = 1, k = 5, \lambda = 0.7,$ $\theta = 0.1/0.3/0.5$	The products development strategies in equilibrium with CEP; The impact of developing high-greenness products on EV manufacturers' profits with CEP	Result 1 Result 2
Fig. 5	$a = 1, k = 5, \lambda = 0.7,$ $\theta = 0.1/0.3/0.5$	The impact of the GEVS policy on EV manufacturers' profits with CEP	Result 3
Fig. 6	$a = 1, k = 5, \lambda = 0.7,$ $\theta = 0.1/0.3/0.5$	The impact of the GEVS policy on the environment with CEP	Result 4



(a) $\theta = 0.1$ (b) $\theta = 0.3$ (c) $\theta = 0.5$

Fig. 5. Two EV manufacturers' profits without and with the GEVS policy.

Result 3. *In the scenario with strong CEP, a low subsidy threshold will reduce the profits of two EV manufacturers, and the profits of two EV manufacturers are more likely to suffer from the GEVS policy with an increase in CEP.*

The environmental impacts of EVs with and without GEVS policy are graphically illustrated in Fig. 6(a/b/c). Recall that in the case without CEP, a low subsidy threshold always make the environment better off. Differently, Fig. 6(a/b/c) indicates that the result will be opposite when considering CEP. Specifically, Fig. 6(a/b/c) shows that a low subsidy threshold will increase the environmental impacts of EVs when the subsidy threshold is low (region R1). Besides, in line with the case without CEP, when the subsidy threshold is prohibitively high (region R3), the GEVS policy has no impact on the environment because it does not affect unit carbon emission and quantities of EVs.

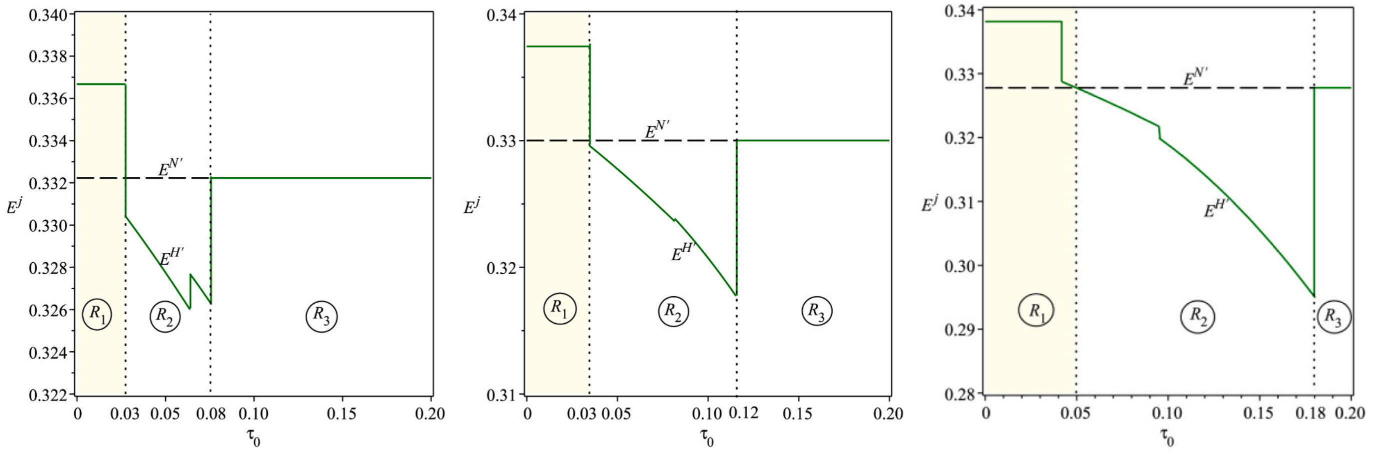
In addition, Fig. 6(a/b/c) also tells that the GEVS policy can make the environment better off when the subsidy threshold is moderate (region R2). Two opposite effects lead to these results. On the one hand, in regions R1 and R2, two EV manufacturers will develop high-greenness products, which will reduce unit carbon emission (referred to as the unit-carbon-emission-decreasing effect). On the other hand, the quantity of EVs will also increase in these regions (referred to as the quantity-increasing effect). The unit-carbon-emission-decreasing effect will reduce the environmental impacts, while the quantity-increasing effect will increase the environmental impacts. When the subsidy threshold is low, the unit-carbon-emission-decreasing effect will be dominated by the quantity-increasing effect, thereby increasing the environmental impact. However, when the subsidy threshold is moderate, the quantity-increasing effect will be dominated by the unit-carbon-emission-decreasing effect, and thus the environment is better off.

In addition, it can be seen from Fig. 6(a/b/c) that, the region (i.e., region R1) in which the GEVS policy creates a negative impact on the environment will increase as CEP increases. The reason is that with an increase in CEP, the competition between two EV manufacturers is more intense. As a result, the quantity-increasing effect becomes more dominant, leading to serious damages to the environment.

The main results in Fig. 6(a/b/c) are summarized in Result 4.

Result 4. *In the scenario with CEP, a low subsidy threshold will have a negative impact on the environment, and the GEVS policy is more likely to increase the environmental impacts of EVs with an increase in CEP.*

To verify the robustness of Results 3 and 4, further numerical analysis is conducted. It is found that (i) when the value of k is within the range of 6 to 20 and other parameters remain unchanged, Results 3 and 4 are still valid. (ii) When the value of λ is within the range of



(a) $\theta = 0.1$ (b) $\theta = 0.3$ (c) $\theta = 0.5$

Fig. 6. The environmental impacts without and with GEVS policy.

$\lambda \in \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6\}$and other parameters remain unchanged, Results 3 and 4 are still valid.

6. Model extensions

6.1. *Extension model 1: considering the greenness-based unit production cost of EVs*

In the preceding section of this manuscript (Sections 3–5), it is assumed that the unit production cost of EVs was zero. To further substantiate the robustness of the results in previous sections, the previous models are extended to encompass scenarios with a greenness-based unit production cost of EVs. The unit cost of EVs is denoted as c, and after the adoption of green technology, the unit production cost of EVs is represented as $c(1+r\tau_i)$. Here, r is the unit production cost increase coefficient correlated with the degree of greenness, signifying that an enhancement in greenness will result in an escalation in unit production cost. This escalation is directly proportional to the degree of greenness. A situation that corresponds to this unit production cost assumption is as follows: EVs minimize energy loss through optimized body design to reduce wind resistance and decrease energy loss in driving by substituting power devices with lower switch losses. However, power devices with lower switch losses are usually more costly, thus escalating the unit production cost in this scenario.

Given this cost assumption, the model becomes highly intricate and cannot be analytically resolved. Nonetheless, through numerical examples, it is discovered that the qualitative results derived from the previous sections remain valid.

The impact of CEP and the GEVS policy on the profits of EVs is utilized as an illustration. By setting the parameter a=1, k=5, λ=0.7, c=0.3, r=0.3 the effects of CEP and government subsidy threshold on the profits of EV manufacturers can be intuitively perceived, as depicted in Fig. 7. The setting of other parameters does not alter the qualitative outcomes of this figure. The variables and results for the numerical examples in this section are presented in Table 4.

As inferred from Fig. 7, when considering the production cost of EV manufacturers and assume that an increase in greenness will escalate the unit production cost, the result that “a low subsidy threshold will reduce the profits of two EV manufacturers, and the profits of two EV manufacturers are more likely to suffer from the GEVS policy with an increase in CEP” (see Result 3) remains valid. For instance, from Fig. 7(b), it is ascertained that when CEP is strong (i.e., θ=0.3) and the government subsidy threshold is low (i.e., $\tau_0 \leq 0.05$), as demonstrated in region R_1, the profits of the two EV manufacturers under the GEVS policy are less than the profits without the GEVS policy. Clearly, the region R1 increases as CEP increases from 0.1 to 0.5, which indicates that two EV manufacturers are more likely to suffer from the GEVS policy.

Table 4
The main variables and results in extension model 1.

Figures	The value of variables	The content of the analysis	Results of the analysis
Fig. 7	$a = 1, k = 5, \lambda = 0.7,$ $c = 0.3, r = 0.3,$ $\theta = 0.1/0.3/0.5$	The impact of the GEVS policy on two EV manufacturers' profits	In line with Result 3
Fig. 8	$a = 1, k = 5, \lambda = 0.7,$ $c = 0.3, r = 0.3,$ $\theta = 0.1/0.3/0.5$	The impact of the GEVS policy on the EVs' environmental impacts	In line with Result 4

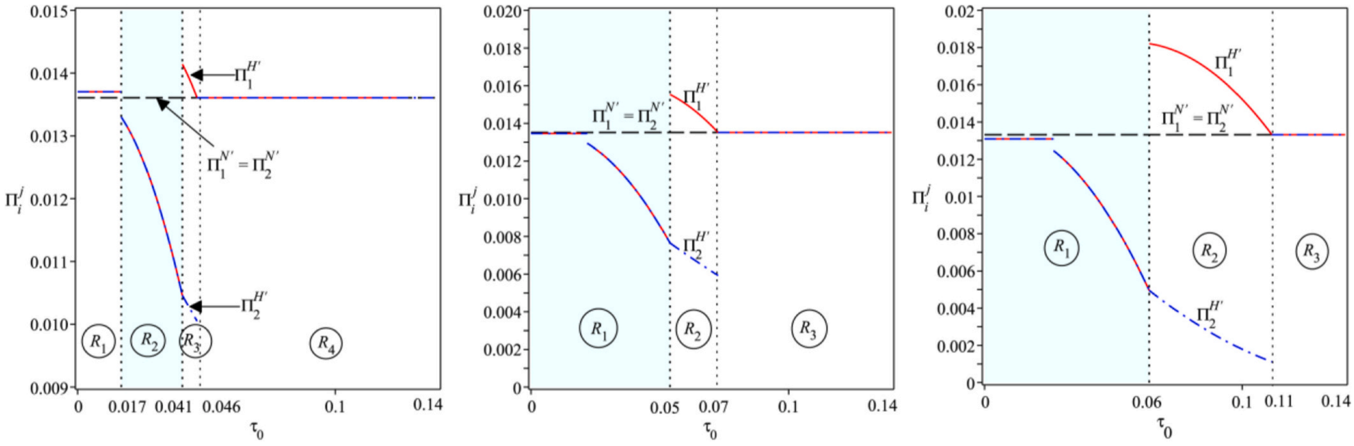
By setting the parameter $a = 1, k = 5, \lambda = 0.7, c = 0.3, r = 0.3$, it can be examined how CEP and government subsidy thresholds influence the total environmental impact of EVs, as depicted in Fig. 8(a/b/c). Setting other parameters will preserve the qualitative outcomes illustrated in this figure. Analogous to Result 4, Fig. 8 reveals that, in the scenario with CEP, a low subsidy threshold will detrimentally impact the environment. The GEVS policy is more inclined to exacerbate the environmental impacts of EVs as CEP increases.

6.2. *Extension model 2: considering the competition of EVs and traditional gasoline vehicles (GVs)*

In the preceding section (i.e., Sections 3–5), the models focused exclusively on the competition between two EV manufacturers, neglecting to consider the rivalry between GV and EV manufacturers. This subsection broadens this purview by integrating a scenario where both EVs and GVs coexist in the market, as depicted in Fig. 9.

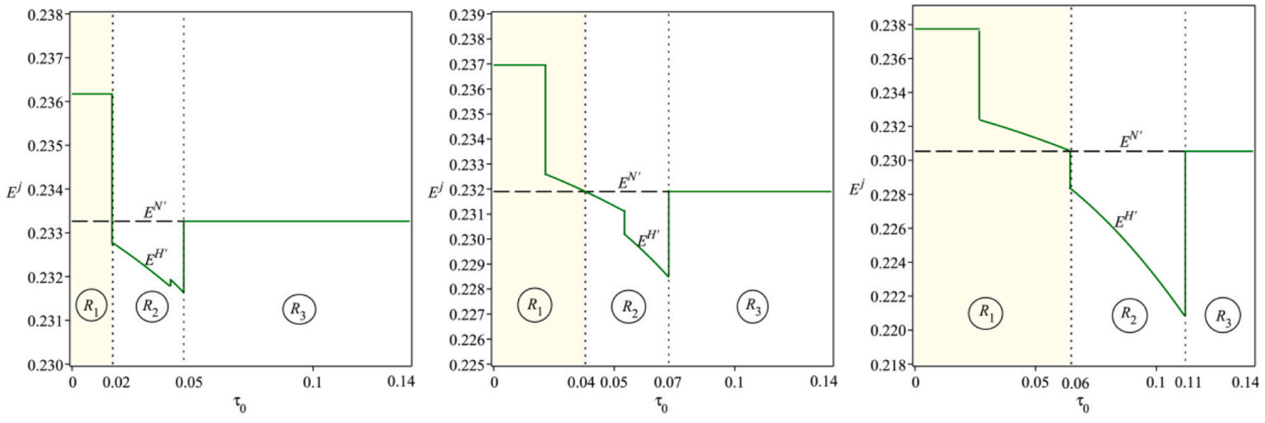
In this context, an additional GV supply chain is integrated into the pre-existing supply chain structure, composed of a GV manufacturer and an engine supplier (designated as Supplier 2). The EV manufacturer i, i=1,2 procures key components for EVs from supplier 1 at a wholesale price w, subsequently selling the assembled EVs to consumers at a price p_i. In a similar vein, the GV manufacturer acquires key components (engines) for GVs from Supplier 2 at a wholesale price w_G and sells the GVs to consumers at a price p_G. Consumers are presented with three alternatives: purchasing an EV from EV manufacturer 1, purchasing an EV from EV manufacturer 2, or buying a GV from GV manufacturer 3.

Under this supply chain structure, the prices at which consumers procure vehicles from EV manufacturer 1, EV manufacturer 2, and GV manufacturer 3 are $p_1 = a - q_1 - q_2 - mq_G + \theta(\tau_1 - \tau_2 - m \times 0), p_1 =$



(a) $\theta = 0.1$ (b) $\theta = 0.3$ (c) $\theta = 0.5$

Fig. 7. Two manufacturers' profits with CEP in extension model 1.



(a) $\theta = 0.1$ (b) $\theta = 0.3$ (c) $\theta = 0.5$

Fig. 8. The environmental impacts with CEP in extension model 1.

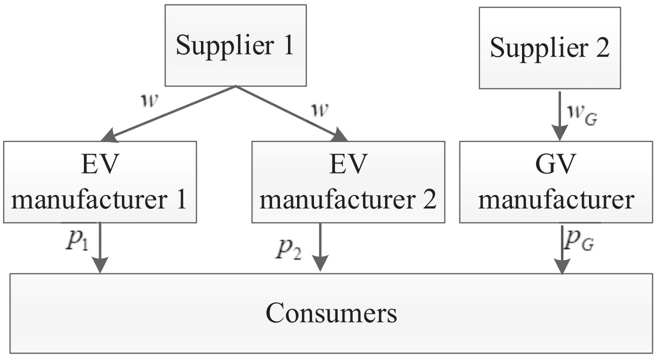


Fig. 9. The supply chain structure of the extension model 2.

$a - q_2 - q_1 - mq_G + \theta(\tau_2 - \tau_1 - m \times 0)$, and $p_G = a - q_G - mq_1 - mq_2 + \theta(m \times 0 - \tau_1 - \tau_2)$, respectively. Here, q_G and p_G signify the production quantity and price of GVs, while $m \in (0, 1]$ represents substitutability coefficient between EVs and GVs. A smaller value of m suggests lower substitutability between EVs and GVs, indicating that consumers discern significant differences between the two vehicle types and exhibit a wide disparity in their willingness to pay for them, and vice versa.

In this scenario, the total environmental impact of all EVs and GVs in the market is represented by $\sum_{i=1}^{2} e_0(1 - \tau_i)q_i + e_g q_G$. Here, e_0 signifies the per-unit environmental impact of an EV, and e_g denotes the per-unit environmental impact of a GV. Consistent with Section 3, the e_0 is normalize to be 1, i.e., $e_0 = 1$. The remaining assumptions of the model align with those in Section 3.

In this scenario, the complexity of the model escalates significantly, rendering it unsolvable analytically. Therefore, this subsection employs numerical examples to evaluate how CEP and government subsidy thresholds influence the profitability of EV manufacturers and the total environmental impact of EVs and GVs. By setting the parameter $a = 1$, $k = 5, \lambda = 0.7, m = 0.1/0.9, \theta = 0.1/0.3/0.5$, the impact of CEP and government subsidy thresholds on the profitability of EV manufacturers can be intuitively observed, as depicted in Fig. 10. Modifying other parameters does not alter the qualitative outcomes of this figure. As gleaned from Fig. 10, in the extended model 2, the profits of both EV manufacturers are more susceptible to the GEVS policy as CEP increases. The result of Fig. 10 is summarized in Result 5. The numerical values and results for this part are illustrated in Table 5.

Result 5. *In the extension model 2, (1) the profits of two manufacturers are more likely to suffer from the GEVS policy with an increase in CEP. (2) In the scenario with a low substitutability coefficient (m) between EVs and GVs and a strong CEP, a low subsidy threshold will reduce the profits of two EV manufacturers.*

The parameters $a = 1, k = 5, \lambda = 0.7, m = 0.9, e_0 = 1, e_g = 1.2/2.5$, $\theta = 0.1/0.3/0.5$ are set to monitor alterations in total environmental impact, encompassing both EVs and GVs, under varying CEP and government subsidy thresholds (see Fig. 11). Setting other parameters will preserve the qualitative outcomes illustrated in Fig. 11.

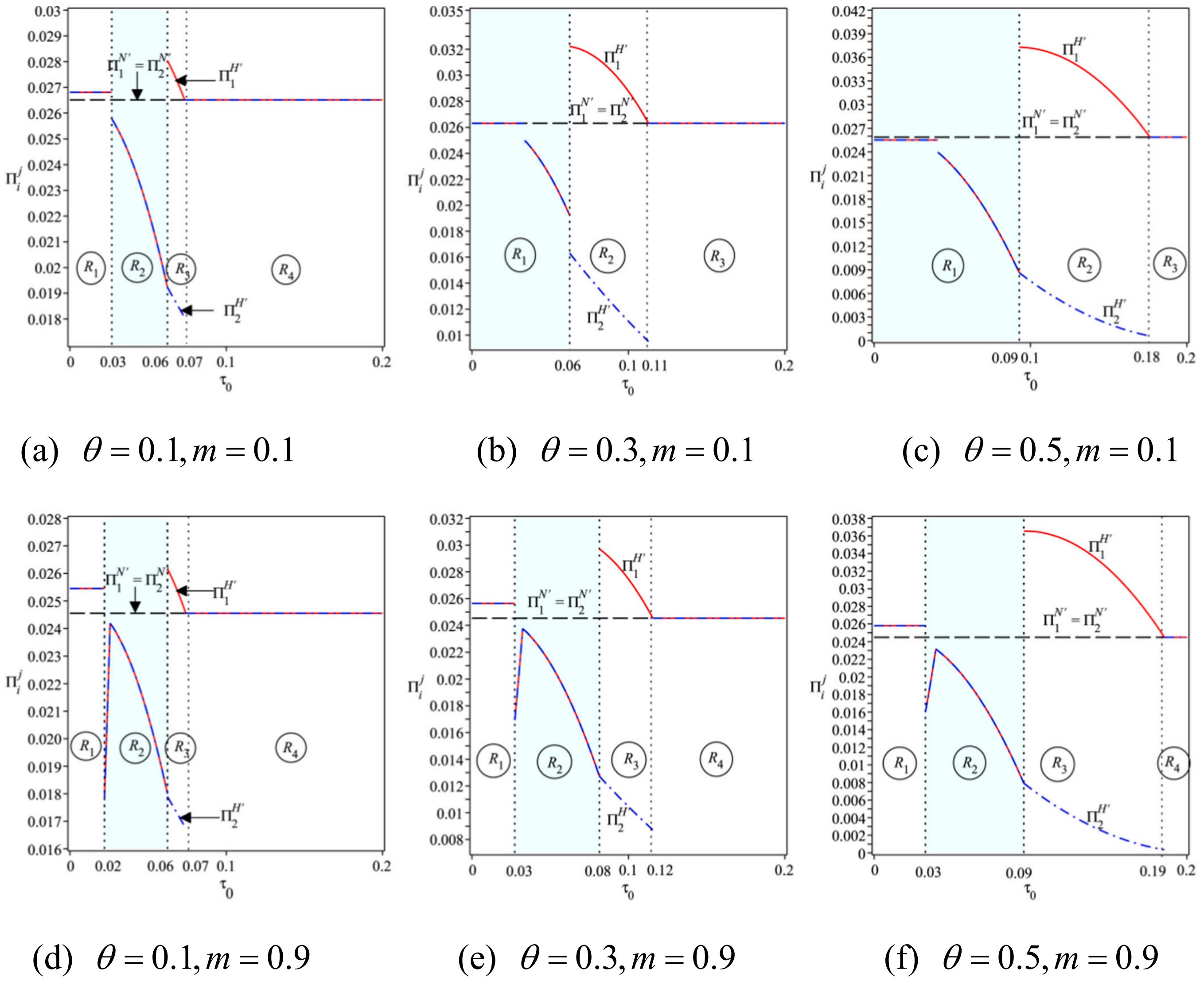
Fig. 11 tells that when the per-unit environmental impact of GVs is relatively minor, the total environmental impact of vehicles mirrors the scenario that omits GVs (lower subsidy thresholds escalate environmental impact). Conversely, when the per-unit environmental impact of GVs is relatively substantial, the conclusion diverges, suggesting that the GEVS policy invariably benefit the environment and a lower subsidy threshold ameliorate environmental impact. This is attributable to the fact that the total environmental impact encapsulates the environmental impact of both EVs and GVs. Although a lower subsidy threshold increases the quantity of EVs, thereby escalating the environmental impact of EVs (environmental-impact-increase effect), the quantity of GVs concurrently diminishes, which culminates in a reduction in the environmental impact of GVs (environmental-impact-decrease effect). When the per-unit environmental impact of GVs is relatively significant, the environmental-impact-decrease effect predominates over the environmental-impact-increase effect, culminating in a decrease in total environmental impact. The results of Fig. 11 are summarized in Result 6.

Results 6. *In the extension model 2, (1) When the unit environment impact of a GV is low, a low subsidy threshold will have a negative impact on the environment, and the GEVS policy is more likely to increase the environmental impacts of both EVs and GVs with an increase in CEP. (2) When the unit environment impact of a GV is high, a low subsidy threshold will have a positive impact on the environment.*

7. Theoretical and practical contributions

7.1. Theoretical contributions

The main theoretical contributions lie in the following three aspects. Firstly, this research complements previous literature on EV subsidy policy by expanding the EV subsidy way and subsidy dimension. Most literature focuses on the fixed subsidy that does not consider the subsidy threshold and the greenness of EVs (see Luo et al., 2014; Shao et al., 2017; Zhu et al., 2021; Zhu et al., 2022). Differently, a greenness-based floating EV subsidy policy with a subsidy threshold is considered. The results show that the subsidy threshold significantly affects EV



(a) $\theta = 0.1, m = 0.1$ (b) $\theta = 0.3, m = 0.1$ (c) $\theta = 0.5, m = 0.1$

(d) $\theta = 0.1, m = 0.9$ (e) $\theta = 0.3, m = 0.9$ (f) $\theta = 0.5, m = 0.9$

Fig. 10. Two manufacturers' profits with CEP in extension model 2.

Table 5
The main variables and results in extension model 2.

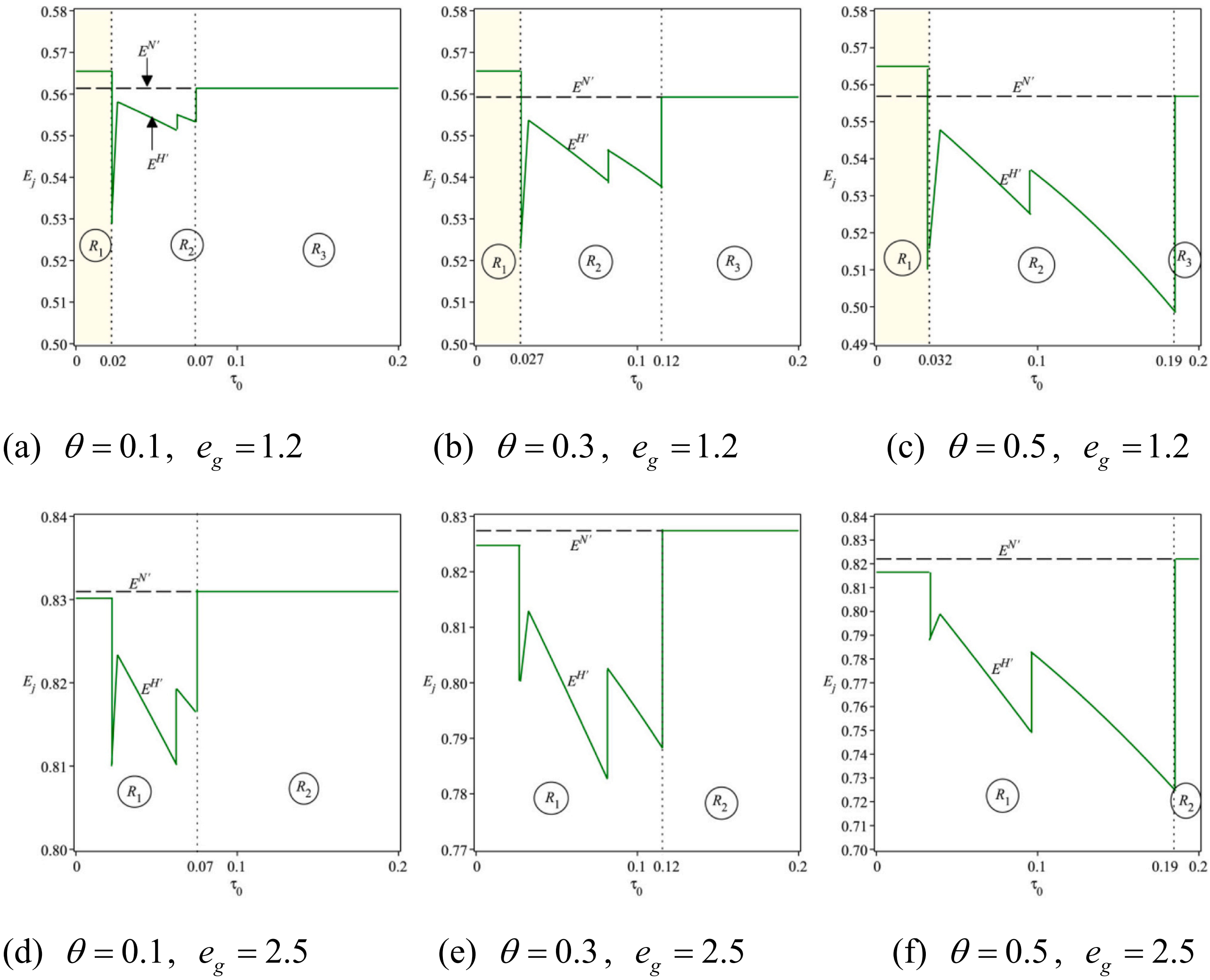
Figures	The value of variables	The content of the analysis	Results of the analysis
Fig. 10	$\theta = 0.1, m = 0.1$	The impact of the GEVS policy on two EV manufacturers' profits	Result 5
Fig. 11	$\theta = 0.1, m = 0.1$	The impact of the GEVS policy on all the EVs' and GVs' environmental impacts	Result 6

manufacturers' product development strategies, profits and the environment, and thus cannot be ignored.

Secondly, the research enriches previous literature from a theoretical perspective.

This research takes a unique perspective by delving into consumer preferences for EVs based on varying greenness of EVs. While previous studies have primarily drawn comparisons between the environmental impact of GVs and EVs, this research innovatively extends the scope by investigating consumer preferences within the EV category itself, based on their varying levels of greenness or eco-friendliness. By examining preferences for different levels of eco-friendliness within the EV category, this research provides valuable insights into the nuanced consumer behavior in the EV market. The study further explores how these preferences can influence EV manufacturers' decisions in terms of the greenness development and production of EVs. This study, therefore, makes it a highly valuable contribution to the existing body of knowledge on EVs.

Thirdly, this study complements previous studies by focusing on the greenness of EVs. The prevailing body of research predominantly concentrates on aspects such as the longevity of battery life, economic viability, and safety measures associated with EVs, underscoring the role of technological R&D by EV manufacturers in bolstering these facets (refer to Fan et al., 2022; Choi and Koo, 2023; Feng et al., 2023; Shao et al., 2023). In contrast, the present study investigates the potential for EVs to augment environmental sustainability of EVs through technological innovations. EVs, capable of sourcing energy from renewable resources, are widely perceived as an eco-friendly mode of transportation. However, it is crucial to acknowledge that the electricity utilized by EVs could originate from coal-fired power plants. Consequently, in regions such as China, where coal-fired power generation holds a significant share in the energy mix, the environmental implications of EVs become notably substantial. In circumstances where altering the country's power generation structure proves to be challenging, the exploration and development of strategies to curtail the energy consumption of EVs emerge as an efficacious approach to



(a) $\theta = 0.1,\ e_g = 1.2$ (b) $\theta = 0.3,\ e_g = 1.2$ (c) $\theta = 0.5,\ e_g = 1.2$

(d) $\theta = 0.1,\ e_g = 2.5$ (e) $\theta = 0.3,\ e_g = 2.5$ (f) $\theta = 0.5,\ e_g = 2.5$

Fig. 11. The environmental impacts with CEP in extension model 2.

ensuring their environmental benefits. Hence, the examination of how EV manufacturers can bolster the environmental sustainability of EVs through research and development introduces a novel and invaluable perspective to the existing body of research.

7.2. Practical implications

Our findings contribute to the practice by providing insightful commendations to the EV manufacturers in terms of product development strategies, and to the government when designing EV subsidy policies.

For the EV manufacturers, the results show that EV manufacturers should flexibly adjust their product development strategies according to the government subsidy threshold and competitors' product development strategies. For example, when the subsidy threshold is low, EV manufacturers can choose to develop high-greenness products, thus obtaining the government's subsidy. When the subsidy threshold is moderate, manufacturers should pay attention to the competitor's product development strategy and produce differentiated products to avoid intense competition. Moreover, it is suggested that EV manufacturers should cooperate with their competitors to develop low-greenness products under two conditions. That is, (i) when there are weak CEP and a moderate subsidy threshold, or (ii) when there are strong CEP and a low subsidy threshold. Because under these two circumstances, both parties will choose to develop high-greenness products in the absence of cooperation, and the profits of both parties under this choice are lower than that in the case of developing low-greenness products.

For the government, the results are helpful in understanding the impact of the GEVS policy on the environment, and providing insights into the design of the subsidy policy. It is found that the effectiveness of the GEVS policy is significantly affected by CEP. Thus, CEP should be considered when making the subsidy policy. Specifically, it is suggested that when consumers have no environmental preference, the government should set a low subsidy threshold since the environmental impacts of vehicles can be reduced in this way. However, as CEP increase, a low subsidy threshold will increase the impacts of vehicles, thus the government should set a higher subsidy threshold in this case. More importantly, when CEP is extremely strong, the GEVS policy will have negative impacts on the environment in most cases, thus the government is recommended to cancel the subsidy.

8. Conclusions

In this paper, the importance of two key drivers affecting the development of EVs is highlighted, i.e., the GEVS policy with a subsidy threshold, together with CEP. Eight game-theoretical models (see Table 6) are developed to analyze the impact of both GEVS policy and CEP on EV manufacturers' product development strategy, EV manufacturers' profits, and the environment. Some interesting results have been obtained, which are summarized as follows.

The results show that EV manufacturers' product development strategies highly depend on the subsidy threshold. The traditional

Table 6
The main models in this paper.

Models	Whether to consider CEP	Whether to consider the GEVS policy	Number of EV manufacturers developing high-greenness products
Model N	×	×	0
Model HN	×	√	0
Model HO	×	√	1
Model HB	×	√	2
Model N'	√	×	0
Model $H'N$	√	√	0
Model $H'O$	√	√	1
Model $H'B$	√	√	2

wisdom tells that symmetrical EV manufacturers will choose the same product development strategy (Meng et al., 2018). The results are in line with this wisdom when the subsidy threshold is low or high, but differentiate from it when the subsidy threshold is moderate. Specifically, contingent on the subsidy threshold, there are three different product development strategies in equilibrium. That is, both EV manufacturers develop high-greenness (low-greenness) products when the subsidy threshold is low (high), and only one EV manufacturer develops high-greenness products when the subsidy threshold is moderate.

As for the impacts of the GEVS policy on the profits of EV manufacturers, the results uncover the significant role of the subsidy threshold and CEP. Specifically, in the case without CEP, the GEVS policy will make both EV manufacturers better off when the subsidy threshold is low. However, when consumers have strong environmental preferences, a low threshold can make both EV manufacturers worse off. In addition, the numerical simulation indicates that an increase in CEP will enlarge the parameter regions hampering both EV manufacturers' profits.

In terms of the environmental impacts (which is denoted by the carbon emission of vehicles), the results in the absence of CEP is in line with intuition, i.e., the GEVS policy will not make the environment worse off, and a low subsidy threshold will make the environment better off. However, CEP will incur a counterintuitive result, i.e., a low threshold subsidy can hamper the environment. The reason for this unexpected result is a tradeoff between two effects (i.e., unit-carbon-emission-decreasing effect, and quantity-increasing effect). Besides, another counterintuitive result emerges when CEP increase, that is, the environment is more likely to be hampered by the GEVS policy with CEP increasing. The reason is that higher CEP will lead to fiercer competition and larger quantities of EVs. Consequently, the environment is more likely to be hampered by the GEVS policy as CEP increase.

There are several avenues in future research directions. First, two symmetric EV manufacturers are considered in this study. The asymmetric EV manufacturers with differentiated R&D cost or quality can be further explored. Second, the focus is on the product development of EV manufacturers, but the product development of the supplier can also be investigated. Third, this study mainly investigates the competition between EV manufacturers, while the competition between traditional gasoline vehicles and EVs can be incorporated into the model in future research, which can reflect the practice better.

CRediT authorship contribution statement

Jing Liu: Formal analysis, Funding acquisition, Writing – original draft. **Jiajia Nie:** Conceptualization, Methodology, Validation. **Wenjie Zhang:** Funding acquisition, Methodology, Software. **Lingyue Li:** Funding acquisition, Visualization. **Hongping Yuan:** Conceptualization, Writing – review & editing.

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.

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