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Research Article

Standard Setting with Considerations of Energy Efficiency Evolution and Market Competition

Rui Dai,[1] **Jianxiong Zhang**,[2] **and Shichen Zhang**[2]

[1] *Glorious Sun School of Business and Management, Donghua University, Shanghai 200051, China*
[2] *College of Management and Economics, Tianjin University, Tianjin 300072, China*

Correspondence should be addressed to Shichen Zhang; sczhang@tju.edu.cn

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EE (energy efficiency) level, an indispensable index reflecting the environmental performance of products, can be improved by the EE innovating effort of the producer. Considering both the evolution of EE level and market differentiation, we develop a Stackelberg differential game between a policy maker who sets the EE standard and multiple competing producers with different initial EE levels who decide the EE innovation simultaneously. As there exist numerous possible reactions for each producer under a given EE standard about whether to meet the EE standard or not, whether there exists an equilibrium is what we pay special attention to. We find that, under a given EE standard, there indeed exists a unique optimal reaction for each producer, and there exists an equilibrium. Moreover, we find that as green awareness or initial EE level increases, both the EE standard and EE innovation increase. Additionally, if policy maker pays more attention to consumer welfare and environmental performance rather than profit of producer, a more strict EE standard would be set. Also, both less information about the initial EE level and more competition among producers induce lower EE standard and social welfare.

1. Introduction

Environmental issues have drawn serious attentions from both the public and governments over the world [1]. From the perspective of the public, customers' purchasing behavior has turned greener tremendously as a result of the ever-increasing consumers' environmental awareness (CEA). The BBMG Conscious Consumer Report shows that 51% of Americans are willing to pay more for eco-friendly products and 67% are aware of the importance to buy products with more environmental benefits [2]. OECD [3] points out that 27% of consumers in OECD countries can be labeled as "green consumers". European Commission shows that 75% of Europeans prefer environmentally friendly products even if they cost a little bit more [4]. From the standpoint of governments, a variety of energy policies have been enforced over the world, aiming to cut emission and improve the environmental quality of products.

Considering the pressures from both stringent environmental regulations and the increase of CEA in the market, researchers have spotted that environmental quality of a product acts as a paramount factor which influences company strategies and eventually profits [5–7]. Hence, an increasing number of producers began to put more concern on eco-friendliness of products. In the household appliance industry, manufacturers specially focus on the product's energy efficiency (EE) level which increasingly influences consumers' purchasing decisions. In addition, for producers, effective EE innovating measures, such as cycled equipment recondition, process control investment, material reclaim, environmental technology development, and efficient production structure development can be employed to enhance EE level of final products [8–10]. Specifically, in the electrical appliance industry, consumers have began to weigh heavily on an essential index of "energy efficiency (EE)" level which measures the environmental performance of the products [11].

Despite the growing CEA among consumers, such awareness enjoys different levels and is subject to be influenced by many factors, e.g., demographics, regions, values, lifestyles, and such [12, 13]. As a result, in general, there simultaneously exist highly green-sensitive consumers and consumers with relatively low environmental awareness in a market.

Following such observation, we assume that a market is divided into two segments: a traditional one in which consumers are less green-sensitive, and a green one in which consumers highly concern about the environmental performance (e.g., the EE level of household appliance). Similar assumption can be found in Chen [14] which simultaneously considers the ordinary market and the green one. In response to market segmentation, different energy regulations may apply.

Therefore, products allowed to be sold in the green group usually take higher environmental performance: they sometimes need to meet a certain standard (of their EE levels) enforced by the policy maker. As pointed by Tanaka [10] and Shi [15], the EE standard is mandatorily set by policy maker in the green market, aiming to outdate low-performance products below the standard. In practice, such standards refer to "Minimum Energy Performance Standards (MEPS)". The MEPS are widely adopted over the world: by 2012, most European countries have announced MEPS [16]; also, China has implemented MEPS for over 40 products [17].

One important thing to note is that the comparative advantages of EE levels of products decay over time. Such decay of EE levels mainly results from competitive market environment. That is, the competitive environment in the market forces producers selling similar products to compete to improve the environmental quality of their respective products. Those who cannot keep their technology advantages will soon be left behind. For instance, after upgrading production and advancing technology, the energy efficiency ratio (EER) of a unitary air conditioner labeled level 2 by the "China Energy Label" today should achieve 3.10 [18]; however, it only needs to achieve 2.90 in 2004 [19]. As a result, it is necessary for us to capture the evolution of EE level from a dynamic viewpoint.

Based on such practical observations, producers need to consider three main facts when making their production strategies: the MEPS set by the policy maker (government), the decay of EE levels, and the competition in the market. MEPS lead to a complex problem of whether and when to open the green market, decay of EE levels of products asks producers to consider dynamic strategies, and the market competition complicates the decision-making problem for the firms. The government, anticipating the firms' reactions, should take serious policy-making so as to set a proper MEPS. Accordingly, this paper aims to characterize EE standard setting and EE innovating equilibrium strategies of a policy maker and numerous competing producers, taking into consideration both a market differentiation framework and the evolving EE level. We establish a game between a policy maker and several producers in a vertical green supply chain [20, 21]. Specifically, the game is played à la Stackelberg with the policy maker acting as the leader and all the producers as the followers, and then the producers to decide the respective EE innovating strategy. One thing to note is that the producers play a Nash game where all of them determine their respective strategies simultaneously, by anticipating others' reactions to the given policy.

In this paper, we raise the following research questions: (1) As there exist multiple reactions for each producer under a given EE standard, is there an equilibrium for the Stackelberg game or not? (2) If there exists an equilibrium, what are the equilibrium EE innovating strategy for each producer and equilibrium EE standard setting strategy for the policy maker? (3) What are the impacts of key factors, such as the policy maker's focuses, consumer green awareness, and initial EE level on the innovation decision of the producer and the standard setting decision of the policy maker? (4) How do the information about the initial EE level and the industry competition intensity affect the EE standard and the total social welfare?

We consider the possible case(s) for a producer under a given EE standard about whether and when to enter the green market and investigate the respective optimal investment strategy via the approach of optimal control [20, 22, 23]. The study relates and contributes to researches of complex system from three aspects. First, from the perspective of each producer, market differentiation induces a piecewise demand function and thus results in a complicated nonsmooth optimal control problem which cannot be addressed by standard optimal control method. We provide a systematical method on basis of optimality principle to solve such problem. Second, for all the competing producers, market competition among them adds to another dimension of complexity to their optimal decision-making problem. We are able to analyze the strategies of producers under market competition. Finally, the government faces a complex policy-making problem which is even more complicated to consider the profit of producers and the environmental impacts as well as consumer surplus. We are capable of providing policy-setting supports by solving the complex welfare-maximizing problem for the government. Main result demonstrates the existence of a unique optimal reaction for each producer, and the producer will enter into and further stay at the green market when facing a relatively low EE standard. According to the optimal response of the producers, the equilibrium EE standard setting strategy for the policy maker can also be obtained. Besides, the impacts of CEA, initial EE levels of producers, and the policy maker's weighting factors on equilibrium strategies are discussed.

The remainder of this paper is organized as follows. Section 2 reviews the literature. In Section 3, a Stackelberg game between a policy maker and multiple producers with different initial EE levels under competition is formulated. In Section 4, the model is solved by a systematical method on the basis of optimality principle. Section 5 provides numerical examples to illustrate the main results and analyze the sensitivity of key parameters. Finally, conclusions and future research directions are summarized in Section 6.

2. Literature Review

Literature related to our work is generalized from three perspectives: one introduces and investigates the energy efficiency (EE) of products, one discusses the market differentiation concerning the green and traditional market segmentations, and the other one is related to the EE standard setting for the policy maker.

Energy efficiency (EE) is first generally defined as the ratio of useful output and energy input in a process [24]. It has become an indispensable index demonstrating the environment performance of products, especially house appliances. EE improvement is considered as an incredible mean for conserving energy, reducing emissions, increasing the use of renewable energy sources, and achieving other energy policy goals [25–27]. Due to the driving forces from both the government and consumer green demand, investment is applied by firms to support EE innovation aiming at improving EE levels of the products technically. Based on above considerations, a couple of researches have emerged to focus on mathematical models involving EE levels and relative policies. Nouira et al. [28] considered the environmental impacts of manufacturing activities and developed models where the greenness of the output product was regarded as a decision variable along with others. In addition, there are a couple of literatures focusing on EE level in a framework of green supply chain. Xie [29] discussed how the threshold value of energy saving levels set by the policy maker affected energy saving levels and price of environmentally friendly products (EFP), respectively, controlled by the manufacturer and the retailer in both integrated and decentralized settings of green supply chain. Note that all the above-mentioned researches analyzed EE level in static settings; however, studies with regard to the dynamic EE evolution are sparsely discussed. Bahn et al. [30] proposed a stochastic control model for optimal timing of climate policies where the evolution of energy efficiency was considered and the growth rate of the EE level decayed exponentially. Lambertini and Mantovani [31] provided a dynamic model capturing the evolution of product performance and considered linear depreciation rate to describe a producer's investment behavior in process innovation.

With an increasing green demand, researches related to market segmentation have been substantially growing, which mainly distinguishes market segments based on the different consumers' green awareness. Several empirical studies about the consumer segmentation upon environmental consciousness have been discussed. For instance, Chan [32] conducted an intercept sample survey of 704 shoppers in Hong Kong to segment the market based on the past purchase of environmentally friendly as well as not-so-friendly products. Jain and Kaur [33] explored to capture variations present in the environmental consciousness of the consumers in India. Zhang and Wu [34] investigated the purchase willingness of green-electricity from various aspects in Jiangsu province in China and showed that consumer green behaviors varied due to household incomes, education levels, and so on. On another front, several researchers contribute via theoretical studies on the formation and application of marketing differentiation. A comprehensive study of market segmentation refers to Chen [14] where a quality-based model was developed to analyze the policy issues concerning the development of products. The research considered that the market was divided into ordinary and green segments, since consumers valued environmental quality of products differently. Liu et al. [6] employed two-stage Stackelberg game models to investigate the dynamics between the supply chain players and found that as consumers' environmental awareness increased, retailers and manufacturers with more eco-friendly operations would benefit. Hafezalkotob [35] considered market competition of one green supply chain and one regular supply chain under government's financial interventions. Du et al. [36] involved both green and traditional consumer segments to investigate whether a firm, in monopoly and in duopoly cases, should provide green products only to the green segment or to both segments. Madani and Rasti-Barzoki [37] studied the influence of the governmental regulations on the green supply chain by incorporating market demands of both green and non-green products and found that subsidies have significantly more impact than taxes on profits and sustainability.

To distinguish the green and traditional markets, an EE standard set by the policy maker is employed in this paper. Consistent with Tanaka [10] and Shi [15], the products not achieving the EE standard will not be permitted into the green market. Most of the researches related to the EE standard focus on the impact of implementing EE standard. Lu [38] and Mahlia et al. [39], respectively, reported the impacts of implementing EE standard on potential energy savings and CO2 reduction. Mahlia and Yanti [40] calculated the cost efficiency analysis and emission reduction by implementing EE standards for electric motor in Malaysia. Comparatively, less amount of studies pay attention to the EE standard setting for the policy maker, most of which are empirical studies. Li et al. [41] demonstrated that the current EE standard implemented in Chinese cities should be tightened further in order to achieve a socially optimal level via a Case for Tianjin. Shi [15] indicated that clear liabilities, authoritative administration, open principles for technical systems, and enforceable mechanisms were indispensable components for setting energy efficiency standards and labeling regulations. Shi [42] employed a case study of air conditioners in Brunei to demonstrate application of the best practice of setting minimum energy performance standards (MEPS) in technically disadvantaged countries (TDCs).

Different from the above studies, our paper considers a Stackelberg game between a policy maker and multiple producers with consideration of the EE evolution and the market segmentation to discuss the EE standard setting problem for the policy maker facing a group of producers with different initial EE levels and competition, which offers valuable guidance to enforce environmental policies. To our best knowledge, there is no similar model which studies the game between a policy maker and producers determining EE standard and EE innovation, respectively, in a two-market framework. In addition, our work is related to the recent work of Zhang et al. [43] where both dynamic EE level and market segmentation are involved. However, they focus on the optimal joint EE investing and pricing strategies of a producer under a given EE standard, and we extend and complement their research with allowing for the EE standard setting problem for the policy maker by incorporating all the possible behaviors of multiple producers.

3. The Model

In this section, we first formulate a benchmark model consisting of one policy maker and one producer. By characterizing the respective problem, we briefly introduce and explain the nonsmooth optimal control problem for the producer and the policy-making problem for the government. Afterwards, we extend the benchmark to a more practical and complicated condition where one policy maker governs multiple competing producers.

3.1. Benchmark: Only One Producer Is Involved. This subsection looks into a Stackelberg game between a welfare-maximizing policy maker as the leader who needs to set the EE standard and a profit-seeking producer who acts as the follower. The producer decides the EE innovation to control its EE level and faces customer demand from two differentiated market segments: one refers to the traditional market where consumers are less green-sensitive, and the other is described as a green one where eco-friendliness of products is highly appreciated. When the MEPS set by the government come into force, however, those products below the standard will not be permitted to enter the green market.

Consider a finite planning horizon $[0, T]$ for the producer and denote $u(t)$ as its EE innovation and $x(t)$ as the EE level at time t. Taking into account the decay of EE level, we formulate the evolution of the product's EE level as follows:

$$\dot{x}(t) = u(t) - \delta x(t), \quad x(0) = x_0, \tag{1}$$

where $\delta > 0$ captures the depreciation rate of the EE level and $x_0 > 0$ denotes the initial EE level. Equation (1) is proposed based on the following considerations. For one thing, the first term of the RHS (right hand side) describes the linear impact of EE innovation on pulling up the corresponding EE level of the product. For another thing, the second term of the RHS captures the decay (depreciation) of EE level due to the advanced technology in the market. Modelling of the dynamics of EE level associated with EE innovation in (1) is similar to Lambertini and Mantovani [31] and Chenavaz [44], both of which describe the evolution of the product quality by considering product innovation. Specifically, in the aforementioned two papers, the product quality is increased by product innovation in a linearly dynamic fashion and evolves autonomously according to a linear decay rate due to technological obsolescence over time. Moreover, in a relative paper of Zhang et al. [43], the linear depreciation of the EE level is also considered due to competition and/or technology advancement.

What complicates the producer's decision-making lies in the fact that a possible demand increase may generate a complex nonsmooth optimal control problem. First of all, we assume that consumer demand $D(x)$ depends on the EE level in the market and the producer gets a margin profit of π per unit sale. Secondly, consider that the product can be permitted to open the green market only when its EE level $x(t)$ achieves the MEPS $\overline{x}$ set by the policy maker. Without loss of generality, we assume $x_0 < \overline{x}$. When the EE level is lower than the standard ($x < \overline{x}$), the demand only covered the traditional market, which is modeled by αx. Once the standard is met, additional demand from the green market occurs as βx, generating a total demand of $(\alpha + \beta)x$. To summarize, the demand function is modelled as

$$D(x(t)) = \left(\alpha + \mu(x(t))\beta\right) x(t), \tag{2}$$

where the index function is

$$\mu(x(t)) = \begin{cases} 0, & x(t) < \overline{x}, \\ 1, & x(t) \geq \overline{x}. \end{cases} \tag{3}$$

Parameters α and β both reflect consumers' willingness to pay (WTP) towards the EE level of the product. Particularly, α is the basic WTP for green products among the consumers in the traditional market, while β denotes an increment of the overall WTP for greener products after some consumers from the green segment make purchases. The index function $\mu(x(t))$ indicates that when the EE standard $\overline{x}$ set by the policy maker is met, the green market is opened up and some consumers are willing to buy the products; otherwise, the products could only be sold among the traditional segment.

The cost function of EE innovation is assumed to take a quadratic form as follows:

$$C(u) = \frac{k}{2}u^2, \tag{4}$$

where $k > 0$ is a measure value of EE innovation cost, which implies increasing marginal cost of EE innovation. The cost function in (4) captures the reality that each subsequent improvement of EE level becomes more difficult and costly. Also, the quadratic form ensures that the EE innovation cannot go too high; otherwise, the cost burden gets overwhelming and investing in EE innovation is never optimal. Such quadratic and convex cost function is widely applied, e.g., in Zhang et al. [43], Taleizadeh et al. [45], and many others.

The objective functional of the profit-maximizing producer J_f can be expressed as

$$\begin{aligned} J_f &= \int_0^T \left(\pi D(x(t)) - C(u)\right) \mathrm{d}t \\ &= \int_0^T \left(\pi\left(\alpha + \mu(x(t))\beta\right) x(t) - \frac{k}{2}u^2(t)\right) \mathrm{d}t. \end{aligned} \tag{5}$$

Next, we delve into the problem of the policy maker whose objective is to maximize total social welfare. The social welfare usually consists of three parts: the producer's profit, consumer surplus, and the environmental performance [46]. Following the work of van Long [47], we describe total consumer surplus (CS) over the whole planning horizon as

$$\mathrm{CS} = \frac{1}{2}\int_0^T D^2(x(t))\,\mathrm{d}t. \tag{6}$$

Besides, similar with Zhang et al. [43], we measure the environmental performance (EP) by the final state of the EE level at time T, i.e.,

$$\mathrm{EP} = x(T). \tag{7}$$

As a result, the objective functional J_g of the policy maker is computed as

$$\begin{aligned} J_g &= \gamma_f J_f + \gamma_c \mathrm{CS} + \gamma_e \mathrm{EP} \\ &= \int_0^T \left(\gamma_f \left(\pi \left(\alpha + \mu \left(x \left(t \right) \right) \beta \right) x \left(t \right) - \frac{k}{2} u^2 \left(t \right) \right) \right. \\ &\quad \left. + \frac{\gamma_c}{2} \left(\alpha + \mu \left(x \left(t \right) \right) \beta \right)^2 x^2 \left(t \right) \right) \mathrm{d}t + \gamma_e x \left(T \right), \end{aligned} \tag{8}$$

where γ_f, γ_c, and γ_e, respectively, reflect the weight coefficient of the producer's profit, consumer surplus, and the environmental performance.

Taking the dynamic relationships (1)-(8) together, we develop a differential game involving a policy maker and a producer as follows:

$$\begin{aligned} &\max_{\overline{x}} \\ &\qquad \int_0^T \left(\gamma_f \left(\pi \left(\alpha \right. \right. \right. \\ &\quad \left. \left. + \mu \left(x \left(t \right) \right) \beta \right) x \left(t \right) - \frac{k}{2} u^2 \left(t \right) \right) + \frac{\gamma_c}{2} \left(\alpha + \mu \left(x \left(t \right) \right) \beta \right)^2 \\ &\quad \left. \cdot x^2 \left(t \right) \right) \mathrm{d}t + \gamma_e x \left(T \right), \\ &\max_{u(\cdot)} \quad \int_0^T \left(\pi \left(\alpha + \mu \left(x \right) \beta \right) x \left(t \right) - \frac{k}{2} u^2 \left(t \right) \right) \mathrm{d}t, \\ &\text{s.t.} \quad \dot{x} \left(t \right) = u \left(t \right) - \delta x \left(t \right), \\ &\qquad x \left(0 \right) = x_0. \end{aligned} \tag{9}$$

3.2. Multiple Competing Producers. In practice, the policy maker should consider all the related producers in the market when setting a proper and effective EE standard. A remarkable fact is that the high observation costs impede the policy maker from accurately obtaining every initial EE level of all the producers. Therefore, the policy-setting is mainly based on the government's estimation of the EE states in the market. Additionally, there exists competition among multiple companies due to the substitution of products, which should also be taken into consideration. Hence, in this subsection, we consider a Stackelberg game between a policy maker and multiple competing producers with different initial EE levels. In line with reality, we assume that the policy maker acts as the leader and all of the producers act as the followers who decide EE innovation simultaneously. This introduces a Nash game among producers.

Without loss of generality, we consider n producers with different initial EE levels x_{j0} $(j = 1, 2, \ldots, n)$ in the market. Considering that the policy maker cannot accurately obtain the initial EE level of each producer, we assume that the initial EE levels x_{j0} $(j = 1, 2, \ldots, n)$ are independent random variables to the policy maker. Denote the probability density function of x_{j0} as $f_j(\cdot)$ and the interval in which all of the initial EE levels x_{j0} $(j = 1, 2, \ldots, n)$ fall as $(\underline{x}_{j0}, \tilde{x}_{j0})$, both of which can be acquired by the policy maker via historical data or investigation. Considering competition among the n producers, we formulate the demand of each producer $D_j(t)$ as

$$D_j \left(t \right) = \left(\alpha + \mu \left(x_j \left(t \right) \right) \beta \right) x_j \left(t \right) - \frac{\eta}{n-1} \sum_{k \neq j, k=1}^{n} x_k \left(t \right), \tag{10}$$

where $\eta < \alpha$ measures the degree of substitution among final products, and

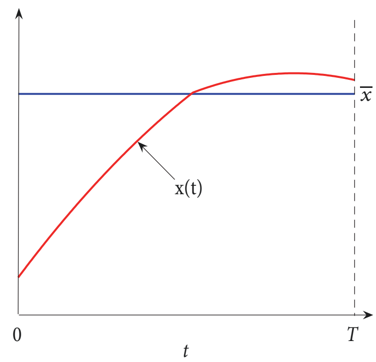
$$\mu \left(x_j \left(t \right) \right) = \begin{cases} 0, & x_j \left(t \right) < \overline{x}, \\ 1, & x_j \left(t \right) \geq \overline{x}. \end{cases} \tag{11}$$

The objective functional for each producer J_{fj} can be expressed as follows:

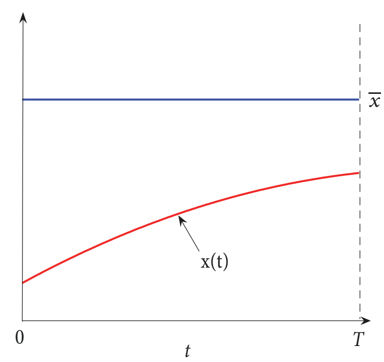
$$\begin{aligned} J_{fj} = \int_0^T & \left(\pi \left(\alpha + \mu \left(x_j \right) \beta \right) x_j \left(t \right) - \frac{k}{2} u_j^2 \left(t \right) \right. \\ & \left. - \frac{\pi \eta}{n-1} \sum_{k \neq j, k=1}^{n} x_k \left(t \right) \right) \mathrm{d}t. \end{aligned} \tag{12}$$

For producer j with initial EE levels x_{j0}, the optimal EE innovating strategy $u_j(t)$ and the EE level dynamic $x_j(t)$ under a given EE standard $\overline{x}$ can be described as $u_j(x_{j0}, \overline{x}, t)$ and $x_j(x_{j0}, \overline{x}, t)$, respectively. Correspondingly, the total profit J_{fj}, the demand D_j, and the terminal value of the EE level $x_j(T)$ can be denoted by $J_{fj}(x_{j0}, \overline{x}, t)$, $D_j(x_{j0}, \overline{x}, t)$, and $x_{jT}(x_{j0}, \overline{x})$, respectively. The social welfare J_{gj} associated with the producer j depends on both the initial EE levels x_{j0} and the given EE standard $\overline{x}$, namely, $J_{gj}(x_{j0}, \overline{x})$. Note that x_{j0} is a random variable for the policy maker; thus $J_{gj}(x_{j0}, \overline{x})$ is also a random variable. Thus, the optimization problem for the policy maker is to maximize the total expected social welfare by setting an EE standard, which can be formulated as

$$\begin{aligned} &\max_{\overline{x}} \sum_{j=1}^{n} \mathbb{E} \left[J_{gj} \left(x_{j0}, \overline{x} \right) \right] = \max_{\overline{x}} \sum_{j=1}^{n} \int_{\underline{x}_{j0}}^{\tilde{x}_{j0}} J_{gj} \left(v, \overline{x} \right) f \left(v \right) \mathrm{d}v \\ &\quad = \max_{\overline{x}} \sum_{j=1}^{n} \int_{\underline{x}_{j0}}^{\tilde{x}_{j0}} \left\{ \int_0^T \left(\gamma_f \left(\pi \left(\alpha + \mu \left(x_j \left(v, \overline{x}, t \right) \right) \beta \right) x_j \left(v, \overline{x}, t \right) - \frac{k}{2} u_j^2 \left(v, \overline{x}, t \right) - \frac{\pi \eta}{n-1} \sum_{k \neq j, k=1}^{n} x_k \left(x_{k0}, \overline{x}, t \right) \right) + \frac{\gamma_c}{2} \left(\left(\alpha + \mu \left(x_j \left(v, \overline{x}, t \right) \right) \beta \right) x_j \left(v, \overline{x}, t \right) - \frac{\eta}{n-1} \sum_{k \neq j, k=1}^{n} x_k \left(x_{k0}, \overline{x}, t \right) \right) \right)^2 \mathrm{d}t \right. \\ &\quad \left. + \gamma_e x_{jT} \left(v, \overline{x} \right) \right\} f \left(v \right) \mathrm{d}v. \end{aligned} \tag{13}$$



(a) Case 1



(b) Case 2

Figure 1: Two possible cases of optimal reaction for the producer.

Similar to the formation process of model (9), we model the following Stackelberg game between a policy maker and multiple competing producers:

$$\max_{\bar{x}} \quad \sum_{j=1}^{n} \int_{\underline{x}_{j0}}^{\bar{x}_{j0}} J_{gj}(v, \bar{x}) f(v)\, dv$$

$$\max_{u_j(\cdot)}$$

$$\int_0^T \Bigg(\pi \left(\alpha + \mu\left(x_j\right) \cdot \beta\right) x_j(t) - \frac{k}{2} u_j^2(t) - \frac{\pi\eta}{n-1} \sum_{k\neq j, k=1}^{n} x_k\left(x_{k0}, \bar{x}, t\right) \Bigg) dt, \tag{14}$$

$$\text{s.t.} \quad \dot{x}_j(t) = u_j(t) - \delta x_j(t),$$

$$x_j(0) = x_{j0},$$

$$j = 1, 2, \ldots, n.$$

4. Solution Method

In this section, we first deal with the benchmark model in (9), based on which the game model in (14) can be similarly solved. Note that before obtaining the equilibrium solution, we first need to address the problem of whether there exists an equilibrium for both the models (9) and (14), as each producer has several possible reactions about whether and when to open the green market under a given EE standard. Our finding indicates that there indeed exists an equilibrium no matter how many producers are involved and obtains the equilibrium solutions for the two models in (9) and (14), respectively.

4.1. Solution to the Benchmark Model. The benchmark model describes the following: at first, the policy maker (as the leader) determines the EE standard, and then the producer (as the follower) chooses EE innovation to maximize the total profit, subject to the state equation (1) for the EE level. According to the backward induction method, we first consider the producer's optimal reaction under a given EE standard $\bar{x}$ decided by the policy maker. It can be proved that there only exist two candidate cases of the optimal reaction of the producer under a given EE standard, as depicted by Figure 1. Specifically, Case 1 indicates that the producer increases the EE level to meet the standard at time τ and keep it above the standard thereafter. Case 2 states that the product's EE level never reached the standard; thus the producer merely carries out product sale in the traditional market.

One thing to note is that intuitively, the producer has several choices about whether and when to open the green market, which can be described by the intersection conditions between $x(t)$ and $\bar{x}$. In Appendix B, we conclude all the other possible cases in Figure 8 and compare the corresponding profit differences between Cases 3–7 and Case 1 or 2, giving proofs of why those cases are excluded from optimal reaction of the producer.

As a result, we sequentially describe Cases 1 and 2 and solve for each case the optimal strategies of the producer and the policy maker.

Case 1. One intersection of $x(t)$ and $\bar{x}$ at time τ, with $x(T) > \bar{x}$.

This case derives from the situation when the demand increment from the green market drives the producer to enhance EE innovation to open the green market. Starting from x_0, the EE level climbs up until the the standard $\bar{x}$ is reached at a trigger time τ and the product wins additional demands from the green market. Accordingly, we can divide the optimization problem of the producer under a given EE standard $\bar{x}$ into two subproblems: one ranging from $[0, \tau)$ which only focuses on the traditional market and the one from $[\tau, T]$ with market expansion. According to Bellman optimality principle, the optimality in both subproblems should be guaranteed.

Consider the first subproblem in the interval $[0, \tau)$ with state $x(t) < \overline{x}$ and $x(\tau) = \overline{x}$. The demand function can be rewritten as $D(x) = \alpha x$. Therefore, the optimization problem for the producer is given by

$$\begin{aligned} \max_{u(\cdot)} \quad & J_{f1} = \int_0^\tau \left(\pi\alpha x(t) - \frac{k}{2}u^2(t)\right) \mathrm{d}t, \\ \text{s.t.} \quad & \dot{x}(t) = u(t) - \delta x(t), \\ & x(0) = x_0, \\ & x(\tau) = \overline{x}, \end{aligned} \tag{15}$$

where J_{f1} is the profit corresponding to the first subproblem.

Applying the optimal control theory and introducing one costate variable λ_1 associated with the state variable x, we get the Hamiltonian function as follows:

$$\begin{aligned} H(x, u, \lambda_1, t) = {} & \pi\alpha x(t) - \frac{k}{2}u^2(t) \\ & + \lambda_1(-\delta x(t) + u(t)). \end{aligned} \tag{16}$$

Lemma 1 characterizes the optimal EE innovation u^* for the producer and the corresponding EE level x^* in the time interval $[0, \tau)$. All the proofs of propositions and lemmas can be obtained in Appendix A.

Lemma 1. *Under a given EE standard $\overline{x}$, the optimal EE innovation u^* of the producer in the interval $[0, \tau)$ in Case 1 is given by*

$$u^*(t) = \frac{c_1}{k}e^{\delta t} + \frac{\pi\alpha}{k\delta}, \tag{17}$$

and the EE level is

$$x^*(t) = \frac{c_1}{2k\delta}e^{\delta t} + c_2 e^{-\delta t} + \frac{\pi\alpha}{k\delta^2}, \tag{18}$$

where $c_1 = (2\pi\alpha(1 - e^{\delta\tau}) + 2k\delta^2(\overline{x}e^{\delta\tau} - x_0))/\delta(e^{\delta\tau} - 1)(e^{\delta\tau} + 1)$ *and* $c_2 = (\pi\alpha(1 - e^{\delta\tau}) + k\delta^2(\overline{x}e^{\delta\tau} - x_0))/k\delta^2(e^{\delta\tau} - 1)(e^{\delta\tau} + 1)$.

Since the standard $\overline{x}$ is met from τ, the total demand is enlarged to $D(x) = (\alpha + \beta)x$ in the time interval $[\tau, T]$. Thus the second subproblem for the producer is

$$\begin{aligned} \max_{u(\cdot)} \quad & J_{f2} = \int_\tau^T \left(\pi(\alpha + \beta)x(t) - \frac{k}{2}u^2(t)\right) \mathrm{d}t, \\ \text{s.t.} \quad & \dot{x}(t) = u(t) - \delta x(t), \quad x(\tau) = \overline{x}, \end{aligned} \tag{19}$$

where J_{f2} is the profit over time period $[\tau, T]$.

Similar to the solution process of the first subproblem, we compute the Hamiltonian function as

$$\begin{aligned} H(x, u, \lambda_2, t) = {} & \pi(\alpha + \beta)x(t) - \frac{k}{2}u^2(t) \\ & + \lambda_2(-\delta x(t) + u(t)), \end{aligned} \tag{20}$$

where λ_2 is the costate of x. Lemma 2 characterizes the optimal EE innovation u^* and the optimal EE level dynamic x^* in the time interval $[\tau, T]$.

Lemma 2. *Under a given EE standard $\overline{x}$, the optimal EE innovation u^* of the producer in the time interval $[\tau, T]$ in Case 1 is given by*

$$u^* = \frac{c_3}{k}e^{\delta t} + \frac{\pi(\alpha + \beta)}{k\delta}, \tag{21}$$

and the EE level is

$$x^* = \frac{c_3}{2k\delta}e^{\delta t} + c_4 e^{-\delta t} + \frac{\pi(\alpha + \beta)}{k\delta^2}, \tag{22}$$

where $c_3 = -(\pi(\alpha + \beta)/\delta)e^{-\delta T}$ *and* $c_4 = \pi(\alpha + \beta)(e^{\delta(\tau - T)} - 2)/2k\delta^2 e^{-\delta\tau} + \overline{x}e^{\delta\tau}$.

Finally, the profit of each subproblem, J_{f1} and J_{f2}, can be calculated once a unique meeting time τ is determined. As a result, the optimization problem for the producer over the entire planning horizon can be transformed into

$$\max_\tau \left(J_{f1}(\tau) + J_{f2}(\tau)\right). \tag{23}$$

Lemma 3 characterizes the optimal τ^* based on which the total profit is maximized.

Lemma 3. *If* $m_1 > 0$, $n_1 > 0$, *and* $8n_2 - n_1\pi(\alpha + \beta)e^{2\delta T}(e^{2\delta T} - 1)^3 - 2m_1 e^{3\delta T}(e^{\delta T} - 1)^4 > 0$, *the total profit of the producer* J_f *is concave in the trigger time* τ. *Further, if* $m_2(e^{2\delta T} - 1)^2 + 4k^2\delta^4(\overline{x} - x_0)^2 e^{2\delta T} - 4m_1 e^{\delta T}(e^{\delta T} - 1)^2 < 0$, *there exists a unique optimal intersection time* τ^* *in the planning horizon* $[0, T]$, *which satisfies the following equation:*

$$\begin{aligned} & \left(e^{2\delta\tau^*} - 1\right)^2 \left(e^{\delta\tau^*}\pi(\alpha + \beta)\left(2n_1 e^{\delta T} - \pi(\alpha + \beta)e^{\delta\tau^*}\right)\right. \\ & \quad \left.- e^{2\delta T}\pi^2\beta^2 + 2\alpha\beta\right)) - 4m_1 e^{\delta(2T + \tau^*)}\left(e^{\delta\tau^*} - 1\right)^2 \\ & \quad + 4n_2 e^{2\delta\tau^*} = 0, \end{aligned} \tag{24}$$

where m_1, m_2, n_1, *and* n_2 *are characterized in the Appendix.*

Note that the conditions in Lemma 3 for the concavity of profit are sufficient conditions. The numerical examples indicate that the concavity of J_f with respect to τ still holds even if the sufficient conditions in Lemma 3 are not satisfied.

Case 2. No intersection of $x(t)$ and $\overline{x}$.

Case 2 refers to a trivial case in which $x(t)$ does not reach the standard $\overline{x}$ over the whole planning horizon. When a producer with a low initial EE level faces an exceedingly high EE standard, then the EE innovation cost to achieve the standard might be too high for producer to open the green market. Instead, the producer would rather stay in the traditional one, which generates the following optimization problem:

$$\begin{aligned} \max_{u(\cdot)} \quad & J_f = \int_0^T \left(\pi\alpha x(t) - \frac{k}{2}u^2(t)\right) \mathrm{d}t, \\ \text{s.t.} \quad & \dot{x}(t) = u(t) - \delta x(t), \\ & x(0) = x_0. \end{aligned} \tag{25}$$

Table 1: Total social welfare J_g with different $\overline{x}$.

		J_f^*	CS	EP	J_g
$\overline{x}$	12	290.0142	38391.93	18.4885	87.4406
	14	282.3125	39736.40	19.0299	87.7922
	16	272.2183	41558.42	19.8007	88.3314
	18	259.1557	43707.33	20.8135	88.8247
	20	242.5141	45988.38	22.0819	88.9901
	22	240.1497	46149.12	22.2487	88.8462
	24	238.8063	22348.17	16.4019	63.0897
	26	238.8063	22348.17	16.4019	63.0897

Similarly, the optimal EE innovation is obtained as

$$u^* = \frac{c_9}{k}e^{\delta t} + \frac{\pi\alpha}{k\delta}, \tag{26}$$

and the EE level is

$$x^* = \frac{c_9}{2k\delta}e^{\delta t} + c_{10}e^{-\delta t} + \frac{\pi\alpha}{k\delta^2}, \tag{27}$$

where $c_9 = -\pi\alpha/\delta e^{\delta T}$ and $c_{10} = (\pi\alpha - 2\pi\alpha e^{\delta T} + 2x_0 k\delta^2 e^{\delta T})/2k\delta^2 e^{\delta T}$. Also note that Case 2 can be regarded as a special case of Case 1 that the trigger time τ goes beyond the terminal time T, that is, $\tau^* > T$ holds.

Finally, we are able to find a definite threshold denoted by $\widehat{x}$ to distinguish Cases 1 and 2. Specifically, if the EE standard $\overline{x}$ is lower than the threshold value $\widehat{x}$, the producer is best to take more efforts, enhance EE innovation, and open the green market, which refers to Case 1. Otherwise, if a significantly high standard $\overline{x} > \widehat{x}$ enforces, the producer has no intention to open the green market and only focuses on the traditional one, which points to Case 2. For technology convenience, we assume that the system parameters satisfy

$$\begin{aligned} &2k\delta^2\overline{x}e^{2\delta\tau^*} - 2k\delta^2 x_0 e^{\delta\tau^*} + 2\pi\alpha e^{\delta\tau^*}\left(1 - e^{\delta\tau^*}\right) \\ &\quad + \pi\alpha e^{\delta(\tau^*-T)}\left(e^{2\delta\tau^*} - 1\right) \\ &\quad + \pi\beta\left(e^{2\delta\tau^*} - 1\right)\left(e^{\delta(\tau^*-T)} - 1\right) > 0, \end{aligned} \tag{28}$$

where τ^* is the optimal trigger time in Case 1 satisfying (24).

Proposition 4 characterizes the threshold $\widehat{x}$.

Proposition 4. *There exists a unique optimal reaction for the producer: if $\overline{x} < \widehat{x}$, the producer will choose the optimal EE innovating strategy in Case 1; otherwise, the producer will choose the optimal EE innovating strategy in Case 2, where $\widehat{x}$ is a unique threshold value satisfying (A.21).*

Next, we look into the optimization problem of the policy maker. According to Proposition 4, if the EE standard set by the policy maker is higher than $\widehat{x}$, the producer will merely stay at the traditional market (Case 2), which generates a total profit of J_f^* for the producer. Also, the consumer surplus CS and the environmental performance EP will be independent of the standard $\overline{x}$. Therefore, the EE standard $\overline{x}$ has no influence on the total social welfare J_g. As a result, we mainly focus on the situation $\overline{x} < \widehat{x}$ (Case 1) which introduces the following welfare-maximizing problem:

$$\begin{aligned} \max_{\overline{x}} \quad & J_g \\ &= \int_0^T \left(\gamma_f\left(\pi(\alpha + \mu(x(t))\beta)x(t) - \frac{k}{2}u^2(t)\right) + \frac{\gamma_c}{2}(\alpha + \mu(x(t)) \cdot \beta)^2 x^2(t)\right)dt + \gamma_e x(T), \\ \text{s.t.} \quad & \overline{x} > 0. \end{aligned} \tag{29}$$

According to Proposition 4, for a given EE standard $\overline{x}$, the optimal reaction of the producer can be obtained uniquely, and the optimal EE innovating strategy $u^*(t)$ and the corresponding EE level $x^*(t)$ both can be described as functions of $\overline{x}$. Thus, the optimization problem (29) actually is a static optimization problem involving only one decision variable $\overline{x}$. Although it is hard to analytically prove that the total social welfare J_g is concave in the EE standard $\overline{x}$, numerical results demonstrate such feature (see Table 1) so that the optimal $\overline{x}^*$ to maximize the total social welfare can be obtained via a one-dimensional search algorithm.

4.2. Solution to Condition of Multiple Competing Producers. Similarly, applying the backward induction, we first address the optimization problems for the n producers under a given EE standard and then solve the policy-making problem. Proposition 5 characterizes the optimal solutions for the n competing producers.

Proposition 5. *There exists a unique optimal reaction for each producer, and the optimal EE innovating strategy $u_j^*(t)$ and the corresponding EE level $x_j^*(t)$ of each producer j ($j = 1, 2, \ldots, n$) remain the same as that in the situation where only one producer is considered, as shown in Proposition 4.*

Substituting the optimal EE innovating strategy $u_j^*(t)$ and the corresponding EE level $x_j^*(t)$ into (12), the total profit for each producer can be obtained. It should be mentioned that if the producer chooses the optimal EE innovating

Table 2: Total social welfare J_g versus $\overline{x}$.

$\overline{x}$	16	18	20	22	24	26	28	30	32
J_g	60.66	62.55	62.16	59.01	54.43	48.40	43.96	43.01	43.01

strategy in Case 1, the optimal trigger time τ^* can be obtained as stated in (24). Hence we can address the optimization problem for each producer under a given EE standard $\overline{x}$. Next, we turn to the optimization problem (13) for the policy maker. Although the concavity of J_g with respect to $\overline{x}$ is hard to verify due to the complexity of the problem, numerical results indicate this feature, as shown in Table 2; thus there exists an equilibrium EE standard $\overline{x}^*$ and a one-dimensional search algorithm can be employed to effectively find it.

5. Numerical Study

In this section, we utilize numerical analysis to illustrate the strategies, profit, and social welfare for the producer(s) and the policy maker. Afterwards, we carry out sensitivity analysis to check the impacts of key parameters on the producer(s) and the policy maker.

Throughout this section, we take the following parameters as benchmark settings:

Planning horizon parameter: $T = 2$.

Demand parameters: $\alpha = 10$, $\beta = 2$.

EE parameters: $\delta = 0.1$, $x_0 = 10$.

Profit parameters: $k = 2$, $\pi = 1$, $\gamma_f = 0.15$, $\gamma_c = 0.001$, $\gamma_e = 0.3$.

5.1. Numerical Examples. In this subsection, we provide numerical examples for both the benchmark condition with one producer and the situation with multiple competing producers to demonstrate the effectiveness of the proposed method.

First, we look at examples of the benchmark condition. According to Proposition 4, the threshold value $\hat{x}$ can be obtained as $\hat{x} = 22.50$. Once $\overline{x}$ exceeds $\hat{x}$, the producer will select the optimal EE innovating strategy in Case 2 instead of that in Case 1. We first consider the equilibrium solution for the producer under the equilibrium EE standard $\overline{x}^* = 20$. Since $\overline{x}^* = 20 < \hat{x}$, the producer will choose the optimal EE innovating strategy in Case 1. The relationship between the total profit of the producer J_f and the intersection time τ is shown as Figure 2, which illustrates that the total profit of the producer J_f is concave in the intersection time τ. Therefore, the optimal intersection time and the maximum profit can be, respectively, obtained as $\tau^* = 1.03$ and $J_f^* = 259.2048$.

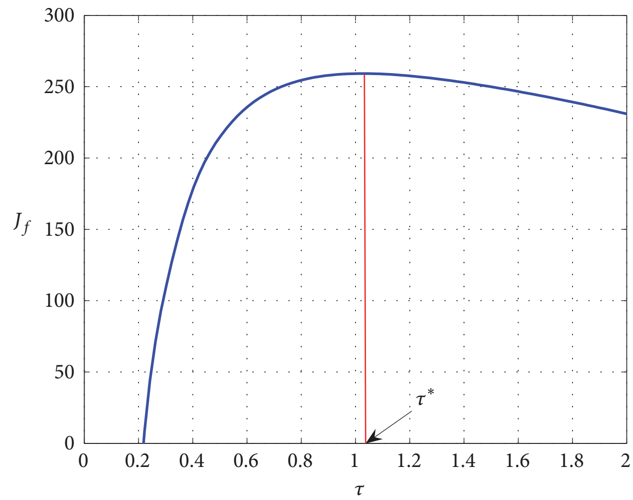


Figure 2: The total profit of the firm J_f versus the intersection time τ.

According to Lemmas 1 and 2, the equilibrium innovating policy u^* and the corresponding state curve x^* during the interval $[0, T]$, respectively, are given by

$$u^*(t) = \begin{cases} 50 - 36.79e^{0.10t}, & t \in [0, \tau^*], \\ 60 - 49.12e^{0.10t}, & t \in (\tau^*, T], \end{cases}$$

$$x^*(t) = \begin{cases} 500 - 183.9e^{0.10t} - 306.1e^{-0.10t}, & t \in [0, \tau^*], \\ 600 - 245.6e^{0.10t} - 341.1e^{-0.10t}, & t \in (\tau^*, T]. \end{cases} \quad (30)$$

In addition, the equilibrium EE innovation $u^*(t)$ and the corresponding EE level $x^*(t)$ are presented, respectively, in Figure 3.

Next, we consider the equilibrium EE standard setting strategy for the policy maker. The relationship between the EE standard $\overline{x}$ and the social welfare J_g is shown in Table 1. Note that once $\overline{x}$ is higher than $\hat{x}$, the producer will merely stay at the tradition market; thus EE standard $\overline{x}$ has no influence on total welfare J_g. Obviously, as long as $\overline{x}$ is higher than $\hat{x}$, no matter what the EE standard is, the producer's profit J_f^*, customer surplus CS, and the environment performance EP remain the same; hence the social welfare J_g always equals a fixed value 63.0897. Another important result concluded from Table 1 is that a higher EE standard $\overline{x}$ leads to a loss for the producer while generating benefits for both customer surplus and environment performance when $\overline{x} < \hat{x}$. All of our numerical examples support such result. Moreover, in this example, the equilibrium EE standard and the corresponding social welfare can be obtained as $\overline{x}^* = 20.0$ and $J_g^* = 88.9901$.

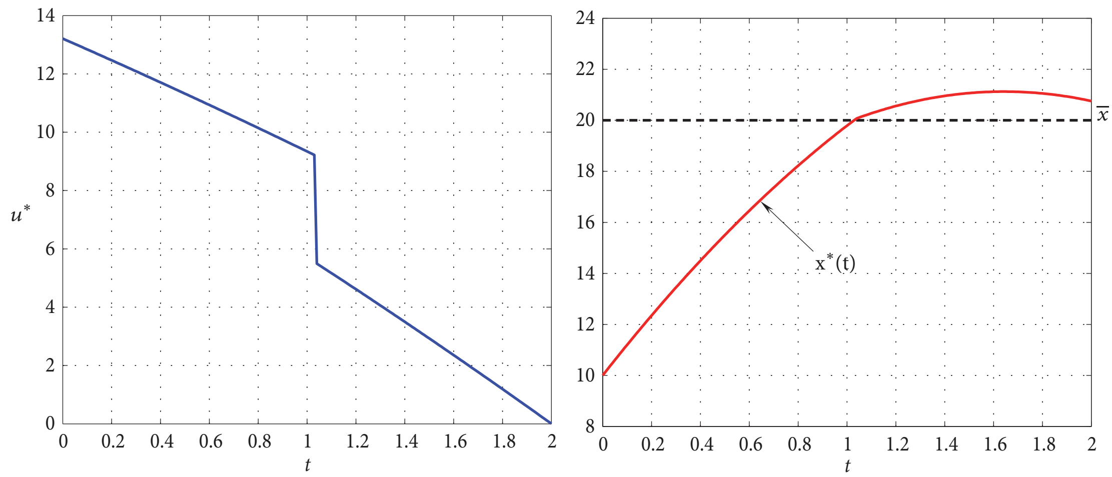


FIGURE 3: The optimal EE innovation $u^*(t)$ and corresponding EE level $x^*(t)$ when $\overline{x} = 20$.

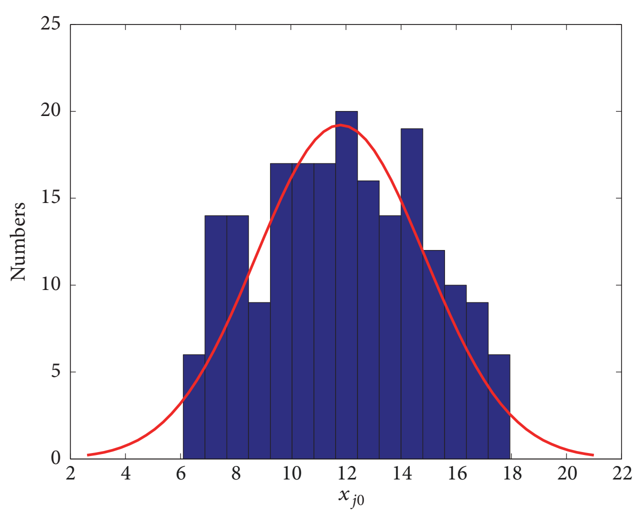


FIGURE 4: The histogram of the initial EE levels x_{j0}.

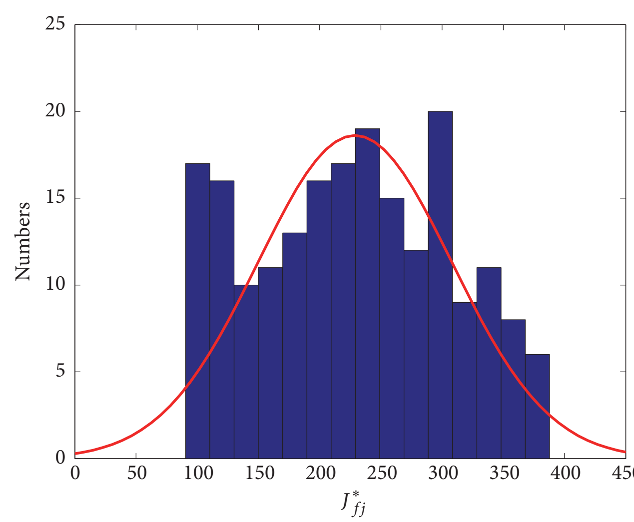


FIGURE 5: The histogram of total profit J_{fj}^*.

Second, we provide numerical example for the situation with a group of competing producers.

Consider that $n = 200$, $\eta = 2$ and that the initial EE level x_{j0} is a random variable with support (6.0, 18.0) which follows truncated normal distribution $N(\mu, \sigma^2)$ where $\mu = 12$ and $\sigma = 2$. Other parameters are the same as the benchmark setting. We first solve the optimization problem of each producer to maximize the total profit separately under the equilibrium EE standard $\overline{x}^* = 18.8$ based on Proposition 5. Figures 4 and 5, respectively, show the histograms of the initial EE levels x_{j0} $(j = 1, 2, \ldots, n)$ and the corresponding maximized total profit of each producer J_{fj}^* $(j = 1, 2, \ldots, n)$. From Figures 4 and 5, the numbers of producers winning relatively low profits (around 100) are unexpectedly large. The reason is that there exist a certain number of producers who only stay at the traditional market since their initial EE levels are too low to achieve the EE standard, which induces relatively low profits.

Next, we consider the equilibrium EE standard for the policy maker. It should be mentioned that when the EE standard $\overline{x}$ is relatively low, e.g., $\overline{x} = 16$, there exist some producers whose initial EE levels are already higher than the low EE standard. For these producers who have already hit the green market, the optimal EE innovating strategies can be obtained by solving the following optimization problem:

$$\begin{aligned} \max_{u(\cdot)} \quad & J_f = \int_0^T \left(\pi (\alpha + \beta) x(t) - \frac{k}{2} u^2(t) \right) dt, \\ \text{s.t.} \quad & \dot{x}(t) = u(t) - \delta x(t), \quad x(0) = x_0. \end{aligned} \tag{31}$$

The solving process of (31) is similar to that in Case 2; thus it is omitted here. The corresponding social welfare J_g for each level of EE standard can be obtained as in Table 2. In this example, the equilibrium EE standard $\overline{x}^*$ and the corresponding social welfare J_g^* can be further obtained as $\overline{x}^* = 18.8$ and $J_g^* = 63.0499$, respectively.

Table 3: Variations of total social welfare J_g.

J_g		$\overline{x}$ 12	14	16	18	20	22	24	26	28
β	1.0	75.25	73.73	75.37	75.44	63.09	63.09	63.09	63.09	63.09
	2.0	87.44	87.79	88.33	88.82	88.99	88.85	63.09	63.09	63.09
	3.0	101.1	99.88	103.8	102.9	102.4	104.7	102.8	104.0	63.09
	4.0	116.3	120.5	117.8	115.5	119.4	121.6	118.1	119.2	119.4
x_0	6.0	59.41	59.96	58.52	58.90	41.88	41.88	41.88	41.88	41.88
	10.0	87.44	87.79	88.33	88.82	88.99	88.85	63.09	63.09	63.09
	14.0	–	–	119.8	119.6	119.9	120.4	120.8	86.93	86.93
	18.0	–	–	–	–	156.4	155.6	155.8	156.2	156.4
γ_f	0.10	87.44	87.79	88.33	88.82	88.99	88.85	63.09	63.09	63.09
	0.15	125.8	127.5	129.9	132.5	135.0	135.0	85.44	85.44	85.44
	0.20	164.2	167.3	171.5	176.2	181.0	181.1	107.8	107.8	107.8
	0.25	202.6	207.0	213.0	220.0	227.0	227.3	130.1	130.1	130.1
γ_c	0.001	72.94	73.68	74.72	75.87	76.86	76.84	51.15	51.15	51.15
	0.002	87.44	87.79	88.33	88.82	88.99	88.85	63.09	63.09	63.09
	0.003	101.9	101.9	101.9	101.8	101.1	100.9	75.0	75.03	75.03
	0.004	116.4	116.0	115.6	114.7	113.2	112.9	86.97	86.97	86.97
γ_e	0.3	87.44	87.79	88.33	88.82	88.99	88.85	63.09	63.09	63.09
	0.7	94.84	95.40	96.25	97.15	97.82	97.75	69.65	69.65	69.65
	1.1	102.2	103.0	104.1	105.5	106.7	106.7	76.21	76.21	76.21
	1.5	109.6	110.6	112.1	113.8	115.5	115.5	82.77	82.77	82.77

Table 4: Impacts on equilibrium EE standard $\overline{x}^*$ and maximum social welfare J_g^*.

		$\overline{x}^*$	J_g^*			$\overline{x}^*$	J_g^*			$\overline{x}^*$	J_g^*
β	1.0	18.0	75.4363	x_0	6.0	14.0	59.9587	γ_e	0.3	20.0	88.9901
	2.0	20.0	88.9901		10.0	20.0	88.9901		0.7	20.0	97.8228
	3.0	22.0	104.731		14.0	25.4	131.4483		1.1	20.0	106.6556
	4.0	27.0	122.407		18.0	28.5	158.3972		1.5	22.5	116.6956
γ_f	0.10	22.5	77.8108	γ_c	0.001	20.0	88.9901				
	0.15	20.0	88.9901		0.002	22.5	136.9876				
	0.20	16.0	101.9423		0.003	22.5	184.2806				
	0.25	12.0	116.442		0.004	22.5	231.5736				

5.2. Sensitivity Analysis. In this subsection, we provide sensitivity analysis with regard to several essential parameters. First, we investigate how parameters β, x_0, γ_f, γ_c, and γ_e affect the equilibrium EE standard and maximum social welfare for the policy maker under the benchmark condition. Second, we examine how equilibrium EE innovating strategy and the producer's maximum profit change with different consumer green awareness β and initial EE level x_0 considering only one producer. Third, considering producers' competition, we explore the effects of the information about the initial EE level σ and the industry competition intensity η on the equilibrium EE standard $\overline{x}^*$ and the maximum social welfare J_g^*.

First, we conclude the impacts of β, x_0, γ_f, γ_c, and γ_e on the total social welfare J_g for various levels of $\overline{x}$ as in Table 3. Note that if $\overline{x}$ is quite high, the total social welfare J_g for the policy maker will keep the same, indicating that the producer only concerns traditional market. In addition, with enhancing values of $\overline{x}$, the total social welfare J_g may exhibit a trend of first increasing then decreasing. Via a one-dimensional search algorithm, the equilibrium EE standard $\overline{x}^*$ and the corresponding maximum social welfare J_g^* can both be obtained as shown in Table 4.

Results in Table 4 allow for the following comments. (1) The equilibrium EE standard $\overline{x}^*$ basically levels up with increasing β, x_0, γ_c, and γ_e but reduces with larger γ_f. This is consistent with the reality that more green-sensitive consumers compel the policy maker to set down a more strict standard for the producer to enter the green market. Also, a higher initial EE level of the producer will surely induce a higher EE standard to achieve. If the policy maker focuses more on the consumer surplus and environmental rather than the producer's profit, then apparently a more rigorous EE standard is called for to benefit consumer welfare and environment. (2) Social welfare J_g^* is positively impacted by β

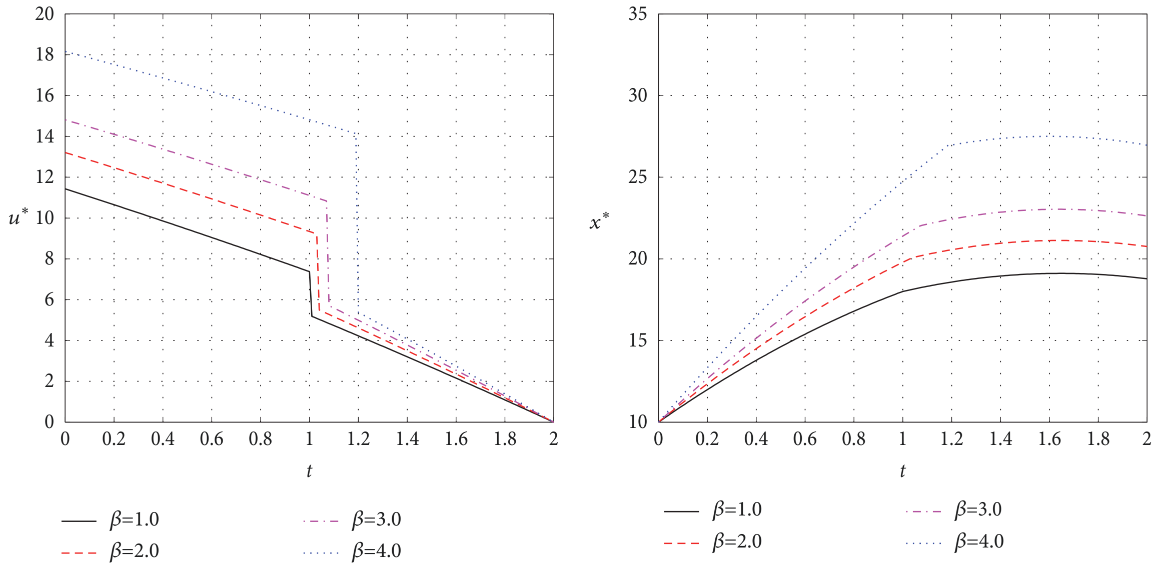


Figure 6: Impact of β on equilibrium EE innovation $u^*(t)$ and the corresponding EE level $x^*(t)$.

Table 5: Impacts of β and x_0 on threshold value $\hat{x}$.

β	1.0	2.0	3.0	4.0	x_0	6.0	10.0	14.0	18.0
$\hat{x}$	19.70	22.50	24.40	27.43	$\hat{x}$	19.07	22.50	25.80	28.80

Table 6: Impact of β and x_0 on the total profit J_f^*.

β	1.0	2.0	3.0	4.0	x_0	6.0	10.0	14.0	18.0
J_f^*	250.669	259.205	261.862	265.704	J_f^*	189.996	259.205	322.339	406.416

or x_0, indicating higher welfare can be generated if consumers get more green-sensitive or if the producer has a higher initial EE level.

Second, we examine how equilibrium EE innovating strategy and the producer's maximum profit change with different consumer green awareness β and initial EE level x_0 considering only one producer. The parameter β varies in the set $\{1.0, 2.0, 3.0, 4.0\}$ and x_0 is chosen from $\{6.0, 10.0, 14.0, 18.0\}$ while other parameters keep the same as that in numerical examples.

To distinguish whether the producer enters the green market or not, we explore the impacts of consumer green awareness β and initial EE level x_0 on the threshold value $\hat{x}$ as shown in Table 5. Comparing the equilibrium EE standard $\overline{x}^*$ in Table 4 and the threshold value $\hat{x}$ in Table 5, we notice that the equilibrium $\overline{x}^*$ is always smaller than $\hat{x}$ for each level of β and x_0. It indicates that, under the equilibrium EE standard $\overline{x}^*$, the producer will choose to enter the green market, namely, Case 1. The equilibrium EE innovation and the corresponding EE level for each level of β and x_0 are, respectively, shown in Figures 6 and 7. Figure 6 shows that a higher awareness of consumers gives rise to more exertion for the producer on the EE innovation, resulting in a higher EE investment. In response to such investment, the EE level also increases with consumer green awareness β increasing, as shown in Figure 6. In sum, higher consumer green awareness encourages more investment for the producer to enter the green market and results in a higher EE level.

Another important factor, the initial EE level, also has a substantial impact on the equilibrium EE innovating strategy of the producer. Figure 7 demonstrates that both the equilibrium EE innovation $u^*(t)$ and the corresponding EE level $x^*(t)$ basically increase as the initial EE level increases. As shown in Table 4, a higher initial EE level gives rise to a more strict EE standard for the policy maker; as a result, the producer should put more efforts on EE innovating to enter the green market. Additionally, the equilibrium EE standard increases by a smaller margin when the initial EE level is enough high, e.g., $x_0 = 18.0$, which incurs that the producer will spend a shorter time to enter the green market as shown in Figure 7.

The maximum profits J_f^* of the producer with different β and x_0 are shown in Table 6. It shows that J_f^* gets larger with β or x_0 increasing, indicating more benefits for the producer if consumers are highly green-sensitive or the initial EE level is exceedingly high. It should be mentioned that the above results in the case only one producer is considered are robust in the case involving multiple producers.

Third, we explore the effects of the information about the initial EE level and the industry competition intensity on the equilibrium EE standard $\overline{x}^*$ and the maximum social welfare J_g^*. Denote the standard deviation of the initial EE level

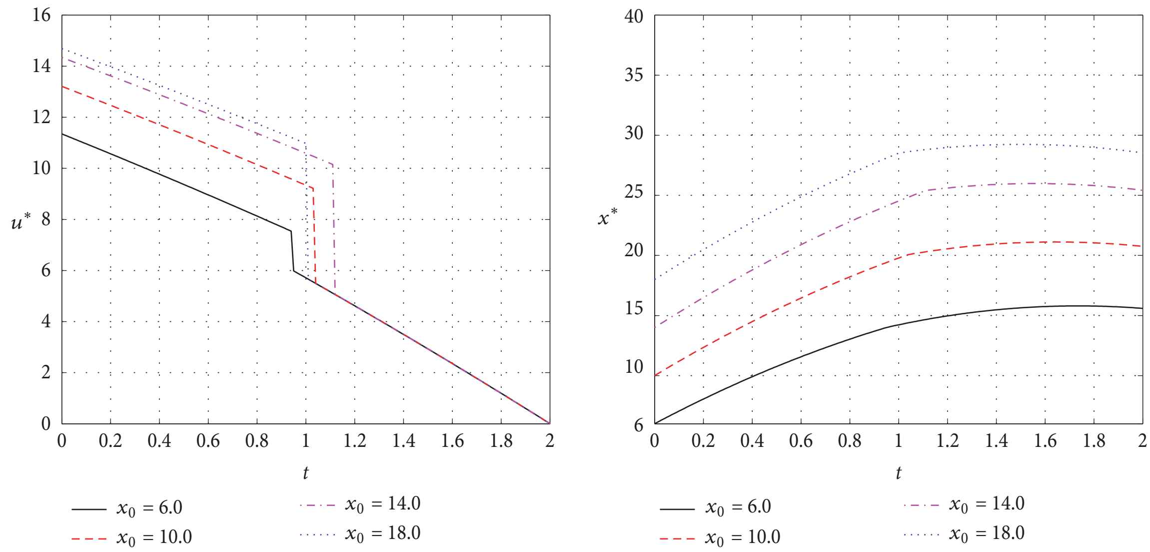
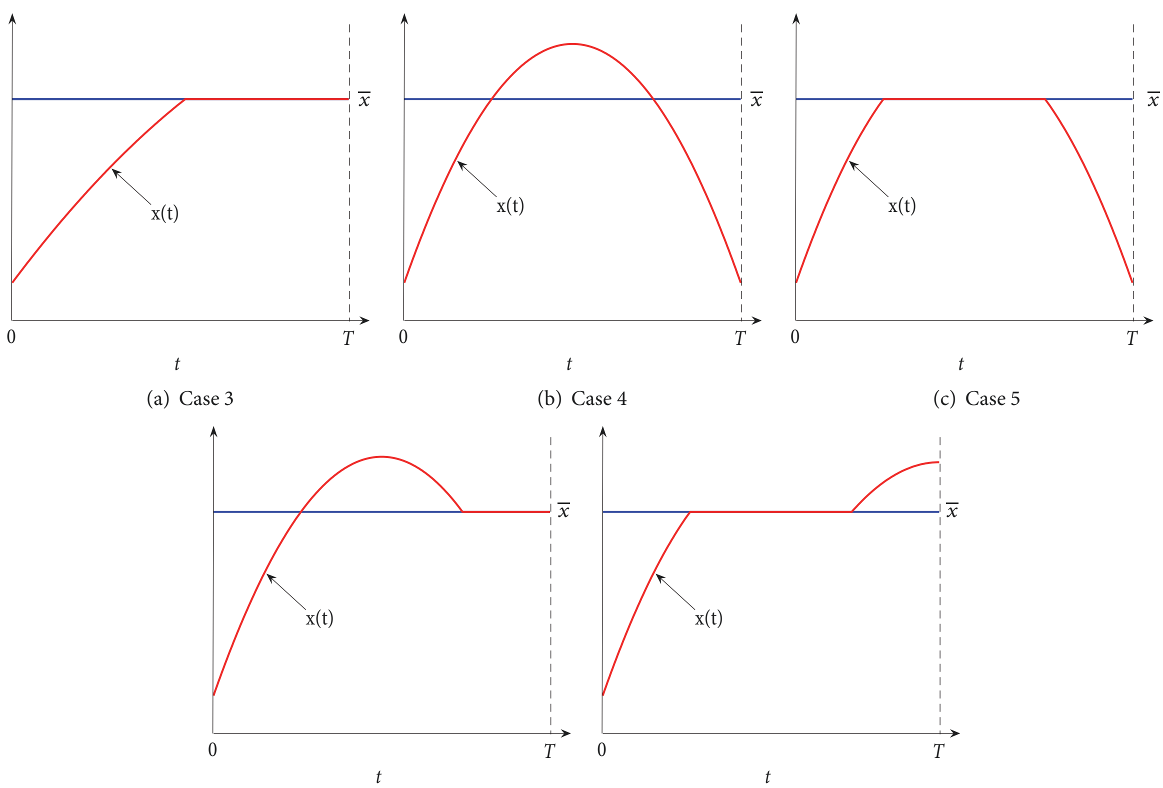


FIGURE 7: Impact of x_0 on equilibrium EE innovation $u^*(t)$ and the corresponding EE level $x^*(t)$.



(a) Case 3 (b) Case 4 (c) Case 5 (d) Case 6 (e) Case 7

FIGURE 8: Different cases for intersection of $x(t)$ and $\overline{x}$.

x_{j0} $(j = 1, 2, \ldots, n)$ as σ. Next, we focus on the sensitivity analysis of the key parameters σ and η. The parameter σ varies in the set $\{1, \sqrt{2}, \sqrt{3}, 2\}$ and η is chosen from $\{1.0, 2.0, 3.0, 4.0\}$ while other parameters keep the same as that in the above numerical example. The equilibrium EE standard $\overline{x}^*$ and the maximum social welfare J_g^* with different σ and η are shown in Table 7.

According to Table 7, we draw the following conclusions. (1) The equilibrium EE standard $\overline{x}^*$ decreases with σ and η increasing. Lower standard deviation of the initial EE level equips the policy maker with more information about the initial EE levels of the producers, which induces a higher EE standard. In addition, if the degree of substitution among final products is very high, i.e., the competition among

Table 7: Impacts of σ and η on the equilibrium EE standard $\overline{x}^*$ and the maximum social welfare J_g^*.

σ	1	$\sqrt{2}$	$\sqrt{3}$	2	η	1.0	2.0	3.0	4.0
$\overline{x}^*$	19.8	19.5	19.1	18.8	$\overline{x}^*$	20.0	18.8	17.5	16.0
J_g^*	63.95	63.66	63.27	63.05	J_g^*	70.36	63.05	56.05	48.98

the producers is exceedingly strong, a lower EE standard would be set down by the policy maker to encourage more producers to enter the green market and further to alleviate the competition. (2) The maximum social welfare reduces as σ and η increase. It means both less information and more competition have negative effects on the total social welfare.

6. Conclusions

This paper mainly models a Stackelberg game with a policy maker as the leader and a group of competing producers as the followers under market segmentation structure. The policy maker first announces an EE standard for the products, and then the producers decide their optimal EE innovating simultaneously. The market differentiation indicates two consumer segments: a traditional one where consumers care less about the environmental performance of the products, and a green group where consumers are much green-sensitive. Specifically, the EE standard set by the policy maker distinguishes the two segments, indicating that only when the EE standard is achieved can the products attract consumers in the green group. Meanwhile, the evolution of the EE level has been taken into consideration to reflect the additive effect by the EE innovation and damping effect due to advancing technology.

To solve the above model, we consider all the possible reactions for each producer and propose a systematical method on basis of optimality principle to solve the nonsmooth optimal control problem for the producers due to the market segmentation. Result indicates that, under a given EE standard, there exists a unique optimal reaction for each producer. Specifically, when the EE standard is lower than a threshold value, the producers may emphasize EE innovation to win an additional demand from the green segment market; otherwise, the producers will focus on the traditional group. Based on the above results for the producer, the equilibrium EE standard setting strategy for the policy maker can also be obtained. Moreover, this paper explores sensitivity analysis of the consumer green awareness, initial EE level, the emphases of the policy maker, the information about the initial EE level, and the competition among producers. Results are concluded in the following: (1) Both a higher consumer green awareness and a higher initial EE level provide incentives to more investment for the producer to enter the green market. (2) The equilibrium EE standard increases if consumers are highly green sensitive or the initial EE level is very high or the policy maker focuses more on consumer surplus and environmental performance rather than the profit of producer. (3) Both the producer and the policy maker welcome a higher consumer green awareness or a higher initial EE level. (4) Both more information about the initial EE level and less competition among producers generate higher EE standard and larger social welfare.

There are several future research directions based on our work. For example, our work only focuses on the EE investment of the producer and omits the pricing strategy due to the complexity of the problem. Future work points to joint EE innovating and pricing strategies for a producer. Additionally, in practice the consumer green awareness might be unknown for both producer and policy maker; thus it is better to be described as a random variable, besides, considering policy updating may be an interesting research subject which allows for the EE standard to be upgraded periodically.

Appendix

A. Proofs of Lemmas 1–3 and Propositions 4 and 5

Proof of Lemma 1. According to the Maximum principle, the optimal EE innovation u^* should maximize the Hamiltonian function H at each instant t. The first-order condition for optimality is

$$\frac{\partial H}{\partial u} = -ku + \lambda_1 = 0, \tag{A.1}$$

which yields the optimal investing policy as

$$u^* = \frac{\lambda_1}{k}. \tag{A.2}$$

Due to the adjoint equation $\dot{\lambda}_1 = -\partial H/\partial x$, we can get

$$\dot{\lambda}_1 = -\pi\alpha + \delta\lambda_1. \tag{A.3}$$

Solving (A.3), we can get from (A.2) that

$$u^* = \frac{\pi\alpha}{k\delta} + \frac{c_1 e^{\delta t}}{k}, \tag{A.4}$$

where c_1 is a constant to be determined.

Substituting (A.4) into (1) with the boundary conditions $x(0) = x_0$ and $x(\tau) = \overline{x}$, we can get

$$x^* = \frac{c_1}{2k\delta} e^{\delta t} + c_2 e^{-\delta t} + \frac{\pi\alpha}{k\delta^2}, \tag{A.5}$$

where $c_1 = (2\pi\alpha(1-e^{\delta\tau}) + 2k\delta^2(\overline{x}e^{\delta\tau} - x_0))/\delta(e^{\delta\tau}-1)(e^{\delta\tau}+1)$ and $c_2 = (\pi\alpha(1-e^{\delta\tau}) + k\delta^2(\overline{x}e^{\delta\tau} - x_0))/k\delta^2(e^{\delta\tau}-1)(e^{\delta\tau}+1)$. □

Proof of Lemma 2. According to the Maximum principle, the optimal EE innovation u^* should maximize the Hamiltonian function H at each instant t. The first-order condition for optimality is

$$\frac{\partial H}{\partial u} = -ku + \lambda_2 = 0, \quad (A.6)$$

which yields the optimal investing policy as

$$u^* = \frac{\lambda_2}{k}. \quad (A.7)$$

Due to the adjoint equation $\dot{\lambda}_2 = -\partial H/\partial x$, we can get

$$\dot{\lambda}_2 = -\pi(\alpha+\beta) + \delta\lambda_2, \quad (A.8)$$

with the terminal condition $\lambda_2(T) = 0$.

Solving (A.8), we can get from (A.7) that

$$u^* = \frac{\pi(\alpha+\beta)}{k\delta} + \frac{c_3 e^{\delta t}}{k}, \quad (A.9)$$

where $c_3 = -(\pi(\alpha+\beta)/\delta)e^{-\delta T}$.

Substituting (A.9) into (1) with the initial condition $x(\tau) = \overline{x}$, we can get

$$x^* = \frac{c_3}{2k\delta}e^{\delta t} + c_4 e^{-\delta t} + \frac{\pi(\alpha+\beta)}{k\delta^2}, \quad (A.10)$$

where $c_4 = (\pi(\alpha+\beta)(e^{\delta(\tau-T)} - 2)/2k\delta^2 e^{-\delta\tau}) + \overline{x}e^{\delta\tau}$. □

Proof of Lemma 3. According to Lemmas 1 and 2, we can get the state as follows:

$$x^*(t) = \begin{cases} \dfrac{\pi\alpha\left(1-e^{\delta\tau}\right) + k\delta^2\left(\overline{x}e^{\delta\tau} - x_0\right)}{k\delta^2\left(e^{\delta\tau}-1\right)\left(e^{\delta\tau}+1\right)}e^{\delta t} + \dfrac{\pi\alpha\left(1-e^{\delta\tau}\right) + k\delta^2\left(\overline{x}e^{\delta\tau} - x_0\right)}{k\delta^2\left(e^{\delta\tau}-1\right)\left(e^{\delta\tau}+1\right)}e^{-\delta t} + \dfrac{\pi\alpha}{k\delta^2}, & t \in [0,\tau), \\ \dfrac{-\pi(\alpha+\beta)e^{-\delta T}}{2k\delta^2}e^{\delta t} + \left(\dfrac{\pi(\alpha+\beta)\left(e^{\delta(\tau-T)}-2\right)}{2k\delta^2 e^{-\delta\tau}} + \overline{x}e^{\delta\tau}\right)e^{-\delta t} + \dfrac{\pi(\alpha+\beta)}{k\delta^2}, & t \in [\tau, T], \end{cases} \quad (A.11)$$

and the optimal EE innovation reaction for the producer is

$$u^*(t) = \begin{cases} \dfrac{\pi(\alpha+\beta)}{k\delta} + \dfrac{2\pi\alpha\left(1-e^{\delta\tau}\right) + 2k\delta^2\left(\overline{x}e^{\delta\tau} - x_0\right)}{k\delta\left(e^{\delta\tau}-1\right)\left(e^{\delta\tau}+1\right)}e^{\delta t}, & t \in [0,\tau), \\ \dfrac{\pi(\alpha+\beta)}{k\delta} + \dfrac{-\pi(\alpha+\beta)e^{-\delta T}}{k\delta}e^{\delta t}, & t \in [\tau, T]. \end{cases} \quad (A.12)$$

Then the corresponding demand can be given by

$$D(x^*) = \begin{cases} \alpha\left(\dfrac{\pi\alpha\left(1-e^{\delta\tau}\right) + k\delta^2\left(\overline{x}e^{\delta\tau} - x_0\right)}{k\delta^2\left(e^{\delta\tau}-1\right)\left(e^{\delta\tau}+1\right)}e^{\delta t} + \dfrac{\pi\alpha\left(1-e^{\delta\tau}\right) + k\delta^2\left(\overline{x}e^{\delta\tau} - x_0\right)}{k\delta^2\left(e^{\delta\tau}-1\right)\left(e^{\delta\tau}+1\right)}e^{-\delta t} + \dfrac{\pi\alpha}{k\delta^2}\right), & t \in [0,\tau), \\ (\alpha+\beta)\left(\dfrac{-\pi(\alpha+\beta)e^{-\delta T}}{2k\delta^2}e^{\delta t} + \left(\dfrac{\pi(\alpha+\beta)\left(e^{\delta(\tau-T)}-2\right)}{2k\delta^2 e^{-\delta\tau}} + \overline{x}e^{\delta\tau}\right)e^{-\delta t} + \dfrac{\pi(\alpha+\beta)}{k\delta^2}\right), & t \in [\tau, T]. \end{cases} \quad (A.13)$$

Substituting (A.11)-(A.13) into the objective functional (5) of the producer, we can get the first-order derivation $J_f'(\tau)$ and the second-order derivation $J_f''(\tau)$, respectively, as follows:

$$\begin{aligned} J_f'(\tau) = {} & \frac{e^{-2\delta T}}{2k\delta^2\left(e^{2\delta\tau}-1\right)^2}\left(\left(e^{2\delta\tau}-1\right)^2\right. \\ & \cdot\left(e^{\delta\tau}\pi(\alpha+\beta)\left(2n_1 e^{\delta T} - \pi(\alpha+\beta)e^{\delta\tau}\right)\right. \\ & \left. - e^{2\delta T}\pi^2\left(\beta^2 + 2\alpha\beta\right)\right) - 4m_1 e^{\delta(2T+\tau)}\left(e^{\delta\tau}-1\right)^2 \\ & \left. + 4n_2 e^{2\delta\tau}\right), \end{aligned} \quad (A.14)$$

and

$$\begin{aligned} J_f''(\tau) = {} & \frac{-e^{-2\delta T}}{k\delta\left(e^{2\delta\tau}-1\right)^3}\left(\pi(\alpha+\beta)\right. \\ & \cdot e^{\delta(\tau+T)}\left(e^{2\delta\tau}-1\right)^3\left(\pi(\alpha+\beta)e^{\delta(\tau-T)} - n_1\right) \\ & \left. - 2m_1 e^{\delta(\tau+2T)}\left(e^{\delta\tau}-1\right)^4 + 4\left(e^{2\delta\tau} + e^{4\delta\tau}\right)n_2\right), \end{aligned} \quad (A.15)$$

where $m_1 = (\pi\alpha - k\delta^2 x_0)(\pi\alpha - k\delta^2\overline{x})$, $n_1 = \pi(\alpha+\beta) - k\delta^2\overline{x}$, and $n_2 = e^{2\delta T}k^2\delta^4(\overline{x} - x_0)^2$.

It is obviously shown from (A.15) that $J_f''(\tau) < 0$ holds when conditions $n_1 > 0$, $m_1 > 0$, and $-n_1\pi(\alpha+\beta)e^{2\delta T}(e^{2\delta T} -$

$1)^3 - 2m_1 e^{3\delta T}(e^{\delta T}-1)^4 + 8n_2 > 0$ are simultaneously satisfied, which means that the total profit J_f is concave in the trigger time τ.

If $m_2(e^{2\delta T}-1)^2 + 4k^2\delta^4(\overline{x}-x_0)^2 e^{2\delta T} - 4m_1 e^{\delta T}(e^{\delta T}-1)^2 < 0$, we have

$$\begin{aligned}
&\lim_{\tau\longrightarrow 0} J_f'(\tau) \\
&\quad = \lim_{\tau\longrightarrow 0}\left\{\frac{e^{-2\delta T}}{2k\delta^2\left(e^{\delta\tau}-1\right)^2\left(e^{\delta\tau}+1\right)^2}\left(2\pi(\alpha+\beta)\right.\right. \\
&\quad\cdot n_1 e^{\delta(\tau+T)}\left(e^{2\delta\tau}-1\right)^2 - \pi^2(\alpha+\beta)^2 e^{2\delta\tau}\left(e^{2\delta\tau}\right. \\
&\quad\left.-1\right)^2 - \left(e^{\delta(T+2\tau)}-e^{\delta T}\right)^2\left(\pi^2\beta^2+2\alpha\beta\pi^2\right) \\
&\quad - 4m_1 e^{\delta(2T+\tau)}\left(e^{\delta\tau}-1\right)^2 + e^{2\delta(\tau+T)}4k^2\delta^4\left(x_0\right. \\
&\quad\left.\left.\left.+\overline{x}\right)^2\right)\right\} = \frac{e^{-2\delta T}}{2k\delta^2}\left(2\pi(\alpha+\beta)n_1 e^{\delta T} - \pi^2(\alpha\right. \\
&\quad\left.+\beta)^2 - e^{2\delta T}\left(\pi^2\beta^2+2\alpha\beta\pi^2\right) - m_1 e^{2\delta T}\right) \\
&\quad + \lim_{\tau\longrightarrow 0}\left\{\frac{2k\delta^2 e^{2\delta\tau}\left(x_0+\overline{x}\right)}{\left(e^{\delta\tau}-1\right)^2\left(e^{\delta\tau}+1\right)^2}\right\} \longrightarrow +\infty,
\end{aligned}\tag{A.16}$$

and

$$\begin{aligned}
&\lim_{\tau\longrightarrow T} J_f'(\tau) = J_f'(T) \\
&= \frac{m_2\left(e^{2\delta T}-1\right)^2 + 4k^2\delta^4\left(\overline{x}-x_0\right)^2 e^{2\delta T} - 4m_1 e^{\delta T}\left(e^{\delta T}-1\right)^2}{2\delta^2\left(e^{\delta T}-1\right)^2\left(e^{\delta T}+1\right)^2 k} \\
&< 0,
\end{aligned}\tag{A.17}$$

where $m_2 = \pi^2\alpha^2 - 2\pi(\alpha+\beta)k\delta^2\overline{x}$.

Thus, there exists a unique optimal intersection time τ^* satisfying the first-order condition $J_f'(\tau^*) = 0$, that is, (24) in the planning horizon $[0, T]$. □

Proof of Proposition 4. Denote the difference between the total profit of Case 1 and that of Case 2 by $\triangle_{1-2}$. We have

$$\begin{aligned}
\triangle_{1-2} &= -\frac{e^{-2\delta T}}{4k\delta^3}\left(\pi\alpha\left(2\pi\alpha\delta T e^{2\delta T} + \left(e^{\delta T}-1\right)\right.\right. \\
&\quad\cdot\left.\left.\left(4k\delta^2 x_0 e^{\delta T} + \pi\alpha\left(1-3e^{\delta T}\right)\right)\right) + \pi(\alpha+\beta)\right. \\
&\quad\cdot\left(2\pi(\alpha+\beta)\delta\left(\tau^*-T\right)e^{2\delta T} + \left(e^{\delta\tau^*}-e^{\delta T}\right)\right. \\
&\quad\cdot\left.\left.\left(4k\delta^2\overline{x}e^{\delta T} + \pi(\alpha+\beta)\left(e^{\delta\tau^*}-3e^{\delta T}\right)\right)\right)\right) \\
&\quad + \frac{1}{k\delta^3\left(e^{2\delta\tau^*}-1\right)}\left(\pi\alpha\left(k\delta^2\left(x_0+\overline{x}\right)-\pi\alpha\right)\left(e^{\delta\tau^*}\right.\right. \\
&\quad\left.-1\right)^2 + \frac{1}{2}\pi^2\alpha^2\delta\tau^*\left(e^{2\delta\tau^*}-1\right) - k^2\delta^4\overline{x}^2 e^{2\delta\tau^*} \\
&\quad\left.+ 2k^2\delta^4 x_0\overline{x}e^{\delta\tau^*} - k^2\delta^4 x_0^2\right),
\end{aligned}\tag{A.18}$$

where τ^* satisfying (24) is the optimal intersection time which maximizes the total profit of Case 1.

The derivation of $\triangle_{1-2}$ with respect to $\overline{x}$ is given by

$$\frac{d\triangle_{1-2}}{d\overline{x}} = \frac{\partial\triangle_{1-2}}{\partial\overline{x}} + \frac{\partial\triangle_{1-2}}{\partial\tau^*}\frac{\partial\tau^*}{\partial\overline{x}}.\tag{A.19}$$

Note that the total profit of Case 2 is independent of the intersection time τ^*. Hence, $\partial\triangle_{1-2}/\partial\tau^* = dJ_1/d\tau^* = 0$, where J_1 is denoted as the total profit of Case 1, and we can get

$$\begin{aligned}
\frac{d\triangle_{1-2}}{d\overline{x}} &= \frac{1}{\delta\left(1-e^{2\delta\tau^*}\right)}\left(2k\delta^2\overline{x}e^{2\delta\tau^*} - 2k\delta^2 x_0 e^{\delta\tau^*}\right. \\
&\quad + 2\pi\alpha e^{\delta\tau^*}\left(1-e^{\delta\tau^*}\right) + \pi\alpha e^{\delta(\tau^*-T)}\left(e^{2\delta\tau^*}-1\right) \\
&\quad\left.+ \pi\beta\left(e^{2\delta\tau^*}-1\right)\left(e^{\delta(\tau^*-T)}-1\right)\right),
\end{aligned}\tag{A.20}$$

which by virtue of (28) implies $d\triangle_{1-2}/d\overline{x} < 0$.

It can be verified that when $\overline{x}$ is very high, $\triangle_{1-2} < 0$ and oppositely, $\triangle_{1-2} > 0$. Due to $d\triangle_{1-2}/d\overline{x} < 0$, there only exists a unique threshold value $\widehat{x}$ satisfying $\triangle_{1-2} = 0$, i.e.,

$$\left.\triangle_{1-2}\right|_{\overline{x}=\widehat{x}} = 0.\tag{A.21}$$

□

Proof of Proposition 5. The producer j may choose the optimal EE innovating strategy in Case 1 or 2 as stated in Section 4. Similar to the method proposed in Section 4, we, respectively, address the optimization problem for producer j in each case. For Case 1, we divide the initial optimization problem into two subproblems, namely, the optimization of J_{fj1} in the time interval $[0, \tau)$ and the optimization of J_{fj2} in the time interval $[\tau, T]$, where τ is the intersection time.

We start with the first subproblem in Case 1. Applying the optimal control theory and introducing n costate variables λ_l' $(l = 1, 2, \ldots, n)$ associated with all the state variables x_j, we can get the Hamiltonian function as follows:

$$\begin{aligned}
H\left(x_j, u_j, \lambda_l', t\right) &= \pi\alpha x_j(t) - \frac{k}{2}u_j^2(t) \\
&\quad - \frac{\pi\eta}{n-1}\sum_{k\neq j,k=1}^{n} x_k(t) \\
&\quad + \sum_{l=1}^{n}\lambda_l'\left(-\delta x_l(t) + u_l(t)\right).
\end{aligned}\tag{A.22}$$

According to the Maximum principle, the optimal EE innovation u_j^* should maximize the Hamiltonian function H at each instant t. The first-order condition for optimality is

$$\frac{\partial H}{\partial u_j} = -ku_j + \lambda_j' = 0,\tag{A.23}$$

which yields the optimal investing policy as

$$u_j^* = \frac{\lambda_j'}{k}.\tag{A.24}$$

Due to the adjoint equation $\dot{\lambda}'_j = -\partial H/\partial x_j$, we can get

$$\dot{\lambda}'_j = -\pi\alpha + \delta\lambda'_j. \tag{A.25}$$

Obviously, the optimal investing policy (A.24) and the adjoint equation (A.25) are, respectively, the same as (A.2) and (A.3). Hence, finally, the optimal EE innovating strategy $u_j^*(t)$ and the corresponding EE level $x_j^*(t)$ of the first subproblem in Case 1, respectively, remain the same as (17) and (18).

Similarly, for the second subproblem in Case 1, we can get the optimal EE innovating strategy $u_j^*(t)$ and the corresponding EE level $x_j^*(t)$, respectively, as (21) and (22). Besides, the optimal EE innovating strategies and EE levels are all the same as the corresponding optimal solutions stated in Section 4 as in Case 2 and thus is omitted here. □

B. All the Possible Cases That Are Teased out and the Corresponding Proofs

Case 3. One intersection of $x(t)$ and $\overline{x}$ at time τ, with $x(t) = \overline{x}$ for any $t \in [\tau, T]$.

This case describes the following circumstance. The EE level $x(t)$ is enhanced by high investment until it meets the standard $\overline{x}$ at time τ and then it remains at such level in time plot $[\tau, T]$. The corresponding optimization problem for the producer can also be divided into two subproblems: the first subproblem ranging from $[0, \tau)$ with state $x(t) < \overline{x}$ and $x(\tau) = \overline{x}$ and the second subproblem ranging from $[\tau, T]$ with state $x(t) = \overline{x}$. We denote the profit of each subproblem as J_{f1} and J_{f2}, respectively.

Obviously, the first subproblem renders the same solution as that of Case 1, as stated in Lemma 1.

The second subproblem associated with J_{f2} indicates that the state $x(t)$ stays at $\overline{x}$ in the interval $[\tau, T]$. Hence, we can get $x^*(t) = \overline{x}$ and $\dot{x}(t) = 0$, inducing a constant investment $u^*(t) = \delta\overline{x}$. Thus, the objective function of the second subproblem can be calculated from

$$\begin{aligned} J_{f2} &= \int_\tau^T \left(\pi(\alpha+\beta)\overline{x} - \frac{k}{2}(\delta\overline{x})^2\right) dt \\ &= \left(\pi(\alpha+\beta)\overline{x} - \frac{k}{2}\delta^2\overline{x}^2\right)(T-\tau). \end{aligned} \tag{B.1}$$

Similarly, a unique optimal τ^* can be found to maximize the total profit $J_f = J_{f1} + J_{f2}$.

Comparing the maximized profit of Case 1 to that of Case 3, we obtain that the producer will never choose the optimal EE innovation in Case 3, since the maximized profit in Case 3 is always lower than that in Case 1.

Lemma B.1. *The maximized profit of Case 3 is always lower than that of Case 1.*

Proof of Lemma B.1. The difference between the total profit of Case 1 and Case 3 can be given by

$$\triangle_{1-3} = \frac{\pi(\alpha+\beta)\left(1-e^{\delta(\tau-T)}\right)\left(\pi(\alpha+\beta)\left(e^{\delta(\tau-T)}-3\right)+4k\delta^2\overline{x}\right)+2\delta(T-\tau)n_1^2}{4k\delta^3}. \tag{B.2}$$

Moreover, we can get its first-order derivation with respect to τ as follows:

$$\begin{aligned} &\frac{d\triangle_{1-3}}{d\tau} \\ &= \frac{\left(k\overline{x}\delta^2 - \pi\alpha - \beta\pi + \pi\alpha e^{\delta(-T+\tau)} + \pi\beta e^{\delta(-T+\tau)}\right)^2}{-2k\delta^2} \\ &\le 0, \end{aligned} \tag{B.3}$$

which indicates that $\triangle_{1-3}$ decreases with τ and reaches the minimum when $\tau = T$.

Due to $\triangle_{1-3}|_{\tau=T} = 0$, we have $\triangle_{1-3} \ge 0$. □

As a result, Case 3 is excluded in the optimal reaction of the producer for a given EE standard.

Case 4. Two intersections of $x(t)$ and $\overline{x}$ at time τ_1 and τ_2, respectively, with $x(t) > \overline{x}$ for any $t \in (\tau_1, \tau_2)$ and $x(t) < \overline{x}$ for any $t < \tau_1$ or $t > \tau_2$.

Intuitively, if the profit coming from the green market cannot offset the corresponding cost, the producer may quit the green market and return to the traditional one. Case 3 describes the following scenario. At the beginning, to enter the green market, the producer enhances the EE innovation; hence the EE level increases until time τ_1 where the EE standard is met, resulting in profit J_{f1}. Then the producer stays at the green market with the state $x > \overline{x}$ in the period (τ_1, τ_2), which leads to profit J_{f2}. Afterwards, the producer decides to quit the green market and return to the traditional one with the state $x(t)$ lower than $\overline{x}$ over $(\tau_2, T]$, which induces profit J_{f3}. Hence for the producer, the optimization problem is transformed into

$$\max_{u(\cdot)} J_f = \sum_{i=1}^{3} J_{fi}(u). \tag{B.4}$$

The first subproblem generates the same solution as that in Case 1, as stated in Lemma 1.

The second subproblem is similar to that in Case 1 except the terminal condition, and it can be formulated as

$$\begin{aligned} \max_{u(\cdot)} \quad & J_{f2} = \int_{\tau_1}^{\tau_2} \left(\pi(\alpha+\beta)x(t) - \frac{k}{2}u^2(t)\right) dt, \\ \text{s.t.} \quad & \dot{x}(t) = u(t) - \delta x(t), \\ & x(\tau_1) = \overline{x}, \end{aligned}$$

$$x(\tau_2) = \overline{x}. \tag{B.5}$$

Similarly, the optimal EE innovation is obtained as

$$u^* = \frac{c_5}{k} e^{\delta t} + \frac{\pi(\alpha+\beta)}{k\delta}, \tag{B.6}$$

and the EE level is

$$x^* = \frac{c_5}{2k\delta} e^{\delta t} + c_6 e^{-\delta t} + \frac{\pi(\alpha+\beta)}{k\delta^2}, \tag{B.7}$$

where $c_5 = -2(\pi\alpha+\pi\beta-k\delta^2\overline{x})/\delta(e^{\delta\tau_1}+e^{\delta\tau_2})$ and $c_6 = -(\pi\alpha+\pi\beta-k\delta^2\overline{x})e^{\delta(\tau_1+\tau_2)}/k\delta^2(e^{\delta\tau_1}+e^{\delta\tau_2})$.

The third subproblem resembles the first subproblem in Case 1 except the initial condition, and it takes the following form:

$$\begin{aligned} \max_{u(\cdot)} \quad & J_{f3} = \int_{\tau_2}^{T} \left(\pi\alpha x(t) - \frac{k}{2}u^2(t)\right) \mathrm{d}t, \\ \text{s.t.} \quad & \dot{x}(t) = u(t) - \delta x(t), \\ & x(\tau_2) = \overline{x}. \end{aligned} \tag{B.8}$$

Similarly, the optimal EE innovation is obtained as

$$u^* = \frac{c_7}{k} e^{\delta t} + \frac{\pi\alpha}{k\delta}, \tag{B.9}$$

and the EE level is

$$x^* = \frac{c_7}{2k\delta} e^{\delta t} + c_8 e^{-\delta t} + \frac{\pi\alpha}{k\delta^2}, \tag{B.10}$$

where $c_7 = -\pi\alpha/\delta e^{\delta T}$ and $c_8 = (-\pi\alpha e^{\delta\tau_2} + 2\pi\alpha e^{\delta T} - 2k\delta^2\overline{x}e^{\delta T})/-2k\delta^2 e^{\delta(T-\tau_2)}$.

Finally, for given intersection times τ_1 and τ_2, the corresponding optimal solutions in each substage can be obtained according to (17), (B.6), and (B.9), respectively, and the corresponding profit in each substage, namely, J_{f1}, J_{f2}, J_{f3}, is described as a function of τ_1 and τ_2. The profit can be maximized by solving the maximizer (τ_1, τ_2).

Similarly, comparing the maximized profit of Case 1 to that of Case 4, we can get the following result.

Lemma B.2. *The maximized profit of Case 4 is always lower than that of Case 1.*

Proof of Lemma B.2. Denote the difference between the total profit of Case 1 and Case 4 by $\triangle_{1-4}$. The first-order derivation with respect to τ_1 is calculated as

$$\frac{\partial\triangle_{1-4}}{\partial\tau_1} = \frac{-\left(\pi(\alpha+\beta)e^{\delta(\tau_1-T)}-n_1\right)^2\left(e^{\delta\tau_1}+e^{\delta\tau_2}\right)^2+\left(e^{\delta\tau_1}-e^{\delta\tau_2}\right)^2 n_1^2}{2k\delta^2\left(e^{\delta\tau_1}+e^{\delta\tau_2}\right)^2}. \tag{B.11}$$

Moreover, we get the derivation of $\partial\triangle_{1-4}/\partial\tau_1$ with respect to τ_2 as

$$\frac{\partial^2\triangle_{1-4}}{\partial\tau_1\partial\tau_2} = \frac{2e^{\delta(\tau_1+\tau_2)}\left(-\pi\alpha-\pi\beta+k\delta^2\overline{x}\right)^2\left(e^{\delta\tau_1}-e^{\delta\tau_2}\right)}{k\delta\left(e^{\delta\tau_1}+e^{\delta\tau_2}\right)^3} \le 0, \tag{B.12}$$

which indicates that $\partial\triangle_{1-4}/\partial\tau_1$ decreases with τ_2 and reaches the maximum when $\tau_2 = \tau_1$.

Noting that

$$\left.\frac{\partial\triangle_{1-4}}{\partial\tau_1}\right|_{\tau_2=\tau_1} = \frac{-\left(\pi(\alpha+\beta)e^{\delta(\tau_1-T)}-n_1\right)^2}{2k\delta^2} \le 0, \tag{B.13}$$

we have

$$\frac{\partial\triangle_{1-4}}{\partial\tau_1} \le 0, \tag{B.14}$$

which means $\triangle_{1-4}$ decreases with τ_1 and reaches the minimum when $\tau_1 = \tau_2$.

Denoting $\triangle_{1-4}|_{\tau_1=\tau_2}$ as $h(\tau_2)$, obviously we have $\triangle_{1-3} \ge h(\tau_2)$. The derivation of $h(\tau_2)$ with respect to τ_2 can be given by

$$\dot{h}(\tau_2) = \frac{-\pi\beta\left(\left(e^{\delta(\tau_2-T)}-1\right)^2+k\delta^2\overline{x}e^{\delta(\tau_2-T)}\right)}{\delta^2 k} < 0. \tag{B.15}$$

Due to $h(\tau_2)|_{\tau_2=T} = 0$, we have $h(\tau_2) \ge 0$. Finally, we can get $\triangle_{1-4} \ge 0$. □

As a result, Case 4 is also excluded in the optimal reaction of the producer for a given EE standard.

Case 5. Two intersections of $x(t)$ and $\overline{x}$ at time τ_1 and τ_2, respectively, with $x(t) = \overline{x}$ for any $t \in [\tau_1, \tau_2]$ and $x(t) < \overline{x}$ for any $t < \tau_1$ or $t > \tau_2$.

Case 5 is similar to Case 4 except the scenario in the interval $[\tau_1, \tau_2]$. At the beginning, the producer fuels EE innovation to enter the green market at time τ_1 so that the first period refers to profit J_{f1}, and at the end, the producer decides to quit the green market and the EE level $x(t)$ drops to a level below $\overline{x}$ over $(\tau_2, T]$, resulting in profit J_{f3}. Different from Case 4, in the second period $[\tau_1, \tau_2]$, the producer chooses to stay at the green market with the minimum cost, corresponding to profit J_{f2}. Obviously, the first and third subproblems associated with J_{f1} and J_{f3}, respectively, remain the same with that in Case 3, and the second subproblem associated with J_{f2} is similar to that in Case 2 except that the initial and terminal times in Case 4, respectively, are τ_1 and τ_2, which in Case 2, respectively, are τ and T. Finally, the optimal EE innovating strategy and the corresponding EE level in each subproblem can all be obtained and the original optimization problem is also translated into the form associated with τ_1 and τ_2, and the profit can be maximized by solving the maximizer (τ_1, τ_2).

Comparing the maximized profit of Case 4 to that of Case 5, we can get the following results.

Lemma B.3. *The maximized profit of Case 5 is always lower than that of Case 4.*

Proof of Lemma B.3. Denote the difference between the total profit of Case 3 and Case 4 by $\triangle_{4-5}$. The first-order derivation with respect to τ_1 is calculated as

$$\frac{\partial \triangle_{4-5}}{\partial \tau_1} = \frac{\left(e^{\delta\tau_2} - e^{\delta\tau_1}\right)^2 \left(-\pi\alpha - \pi\beta + \overline{x}k\delta^2\right)^2}{-2k\delta^2 \left(e^{\delta\tau_2} + e^{\delta\tau_1}\right)^2} \le 0, \quad \text{(B.16)}$$

which indicates that $\triangle_{4-5}$ decreases with τ_1 and reaches the minimum when $\tau_1 = \tau_2$. Due to $\triangle_{4-5}|_{\tau_1=\tau_2} = 0$, we have $\triangle_{4-5} \ge 0$. □

According to Lemmas B.2 and B.3, the maximized profit of Case 5 is always lower than that of Case 1; thus Case 5 is also excluded in the optimal reaction of the producer for a given EE standard.

Case 6. Two intersections of $x(t)$ and $\overline{x}$ at time τ_1 and τ_2, respectively, with $x(t) > \overline{x}$ for any $t \in (\tau_1, \tau_2)$ and $x(t) = \overline{x}$ for any $t \in [\tau_2, T]$.

Case 6 is similar to Case 4 except the scenario in the interval $(\tau_2, T]$. The producer chooses to stay at the minimum EE level $\overline{x}$ which can meet the standard of the green market. In other words, the state $x(t)$ stays at the level $\overline{x}$ over $(\tau_2, T]$. Similarly, we divide the optimization problem into three subproblems, whose optimal objectives are, respectively, J_{f1}, J_{f2}, and J_{f3}. Apparently, the first and second subproblems associated with J_{f1} and J_{f2}, respectively, remain the same with that in Case 4, and the third subproblem associated with J_{f3} is the same with the second subproblem in Case 2. Finally, similar to Case 4, the original optimization problem is translated into the form associated with τ_1 and τ_2, and the profit can be maximized by solving the maximizer (τ_1, τ_2).

The following lemma characterizes the relationship between the total profit J_f and the second intersection time τ_2.

Lemma B.4. *The total profit J_f always increases with τ_2 in Case 6.*

Proof of Lemma B.4. In Case 6, the derivation of the producer's total profit J_f with respect to the second intersection time τ_2 is calculated as

$$\frac{\partial J_f}{\partial \tau_2} = \frac{\left(e^{\delta\tau_1} - e^{\delta\tau_2}\right)^2 \left(\pi\alpha + \pi\beta - k\delta^2\overline{x}\right)^2}{2k\delta^2 \left(e^{\delta\tau_1} + e^{\delta\tau_2}\right)^2} \ge 0, \quad \text{(B.17)}$$

which means that J_f increases with τ_2. □

According to Lemma B.4, the maximum J_f can be achieved only when $\tau_2 = T$, which turns to Case 1. Thus, Case 6 is also excluded in the optimal reaction of the producer for a given EE standard.

Case 7. Two intersections of $x(t)$ and $\overline{x}$ at time τ_1 and τ_2, respectively, with $x(t) = \overline{x}$ for any $t \in [\tau_1, \tau_2]$ and $x(t) > \overline{x}$ for any $t \in (\tau_2, T]$.

Case 6 is similar to Case 4 except the scenario in the interval $(\tau_2, T]$. At the beginning, the producer fuels EE innovation to enter the green market at time τ_1 so that the first period refers to profit J_{f1} and then decides to stay at the green market with the minimum cost with the EE level $x(t) = \overline{x}$ in the second period $[\tau_1, \tau_2]$, which leads to profit J_{f2}. Different from Case 4, in the third period $(\tau_2, T]$, the producer chooses to enjoy the green market with the EE level $x(t) > \overline{x}$, resulting in profit J_{f3}. Obviously, the first and second subproblems associated with J_{f1} and J_{f2}, respectively, remain the same with that in Case 4, and the third subproblem associated with J_{f3} is similar to the second subproblem in Case 1 except that the initial time in Case 6 is τ_2 which in Case 1 is τ. Finally, the optimal EE innovating strategy and the corresponding EE level in each subproblem can all be obtained and the original optimization problem is also translated into the form associated with τ_1 and τ_2. The profit can be maximized by solving the maximizer (τ_1, τ_2).

The following lemma characterizes the relationship between the total profit J_f and the second intersection time τ_2.

Lemma B.5. *The total profit J_f always decreases with τ_2 in Case 6.*

Proof of Lemma B.5. In Case 6, the derivation of the producer's total profit J_f with respect to the second intersection time τ_2 can be given by

$$\frac{\partial J_f}{\partial \tau_2} = -\frac{\left(\pi\beta e^{\delta T} + \pi\alpha e^{\delta T} - k\delta^2\overline{x}e^{\delta T} - \pi\beta e^{\delta\tau_2} - \pi\alpha e^{\delta\tau_2}\right)^2}{2k\delta^2 e^{2\delta T}} \le 0, \quad \text{(B.18)}$$

which means that J_f decreases with τ_2. □

According to Lemma B.5, the maximum J_f can be achieved only when $\tau_2 = \tau_1$, which turns to Case 2. Thus, Case 6 is also excluded in the optimal reaction of the producer for a given EE standard.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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