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A game-theoretic analysis of the impact of government subsidy on optimal product greening and pricing decisions in a duopolistic market

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ABSTRACT

In compliance with environmental and emerging international imperatives, promoting sustainable consumption and production is far due and pivotal for greening supply chains. Rampant demand for environmentally-friendly products and regulatory changes have pressured manufacturing companies to reassess their products and processes. Yet, the cost of greening and its allocation remain challenging tasks. This study investigates government subsidy strategies to encourage firms to transition to green production strategies and improve environmental quality when heterogeneous consumers are sensitive to sustainability. We consider a leader-follower Stackelberg game between two profit-maximizing firms with different green technologies (the followers) and a government (the leader). Those two competing firms sell two differentiated products to a price- and pollution-sensitive market. We first discuss the target level of greenness that can improve the environmental quality and then design the appropriate subsidy rate. We show that the government subsidy can decrease the selling price, increase the market share and the profit from greener products, and positively affect EQ. Contrary to some findings in the literature, we find that a higher subsidy rate may not always simultaneously benefit the environment, social welfare, and social surplus. Finally, we validate our structural results with various numerical examples and sensitivity analyses.

1. Introduction

Under rampant sustainability pressures from climate change, international regulations, and consumers, it has increasingly become a policy that governments are subsidizing in various ways industrial firms in their sustainability efforts (e.g., Chen et al., 2019a). Motivated by this fact, we consider how a government might design an appropriate policy to subsidize firms to improve overall environmental quality. Fig. 1 shows the schematization of the problem. To elevate the impact of market competition, we consider a "leader-follower" Stackelberg game between two profit-maximizing firms (the followers) and a government to which they disclose their financial statements (the leader). We treat consumers as heterogeneous individuals. Hence, the Willingness-to-Pay (WTP) is a random variable, and it follows some probabilistic distribution. These two competing firms produce homogeneous products that only differ in their level of greenness. Given the consumers' WTP and the government's subsidy, firms simultaneously decide on the optimal competitive prices and the level of greenness. The government acts as a Stackelberg leader and focuses on designing a subsidy policy (subsidy rate) to improve environmental quality.

The research questions we pose include:

1. What is the impact of the government subsidy policies on duopoly firms' decision-making, the environment, and society?
2. What is the impact of consumer premium payment on duopoly firms' decision-making and the optimal subsidy rates?
3. How to design the optimal subsidy rate to improve the environmental quality and to maximize social welfare and surplus?

In answering these questions, we first investigate the threshold subsidy rate to incentivize duopoly firms to try their best to improve their greenness. Then, we take social welfare and social surplus as the target to optimize the subsidy rate and investigate the impact of different subside policies on the environment and society. Finally, we study how consumers' WTP affects subsidy rate, environmental quality, social welfare, and social surplus.

Our study has several theoretical and practical contributions. First, this study contributes to analytical modelling by linking heterogeneous

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consumer WTP to the demand for green products and investigating WTP's impact on the decision-making between duopoly firms and subsidy policies. Due to green consumption behaviour takes time to develop in the early days of advocating green consumption, there is a gap between willingness and action for green products (Zabkar and Hosta, 2013). Therefore, consumer premium payment has not been paid enough attention to, as pointed out by some studies such as Ghosh and Shah (2015) and Zhang et al. (2015). However, in recent years, with increasing levels of education, concern for the environment, and advertising campaigns, consumers are increasingly willing to pay more for green products (Goldstein et al., 2008; Sheehan and Atkinson, 2012; Zhang and Wu, 2012). By recognizing these shifts in the marketplace, firms have redesigned products to include environmental features that appeal to green consumers (Gu et al., 2015). Especially with the increasing demand for green products, taking consumer premium payment into account in firms' decision-making is necessary and more realistic in formulating their optimal decisions. The second theoretical contribution raised in this study is linking the government, duopoly firms, and heterogeneous consumers and exploring different subsidy policies to improve environmental quality, maximize both social welfare and surplus. Finally, the third theoretical contribution of this study is in unveiling the action mechanism of subsidy policies by considering consumer premium payment. We show that, in some cases, an increase in consumer WTP or governmental subsidy does not necessarily improve the environmental quality. This finding may explain why the government spends too much effort on improving premium payment, but the results have not been as good as expected.

In terms of practical contributions, our study can guide the government to design subsidy policies for different purposes. Second, this study is helpful for the government to find possible shortcomings and solutions in the subsidy process.

The layout of this paper follows. In Section 2, we describe related research and our contribution. In Section 3, we present the market demand for the two types of products based on their utility to the customers, and we formulate the profit functions for the firms. In Section 4, we present the government strategy analyses. In Section 5, we present numerical analyses (sensitivity results) and their discussions related to the overall impact of subsidy policies and parameters on the economy, environment, and society. We conclude and provide suggestions for future research in Section 6. Note that we defer to Appendix all the mathematical proofs of our structural results.

2. Literature review

Concern for unsustainable development is rising: At the heart of this lie increased economic activities at a global level along with the climate crisis, energy and food insecurity, especially in underdeveloped countries, and the scarcity of non-renewable natural resources. Curtailing the impact of unsustainable development requires a concerted effort by all the parties: governments, producers, and consumers. To that end, sustainable production requires that producers take responsibility for their activities' environmental, social, economic, and even cultural implications (e.g., Veleva and Ellenbecker, 2001; Ülkü and Engau, 2021). Because greenhouse gas emissions exacerbate climate change, it is imperative to supply chain partners (suppliers, manufacturers, distributors, retailers) account for carbon footprinting in designing and manufacturing goods and services (e.g., He et al., 2019). However, industries that address pollution concerns at product disposal are often ineffective and incur high costs. Therefore, what is needed is a collaborative focus on greener product design and manufacturing, rather than managing costly and undesirable landfills. On that point, Chen (2001, p.250) states that "Green product development, which addresses environmental issues through product design and innovation as opposed to the traditional end-of-pipe-control approach, is receiving significant attention from customers, industries, and governments around the world." Accordingly, many countries have imposed policies, laws, and regulations to promote a "green economy." For example, in 2008, the UK passed the Climate Change Act law (UK, 2008). China, since the 1990s,

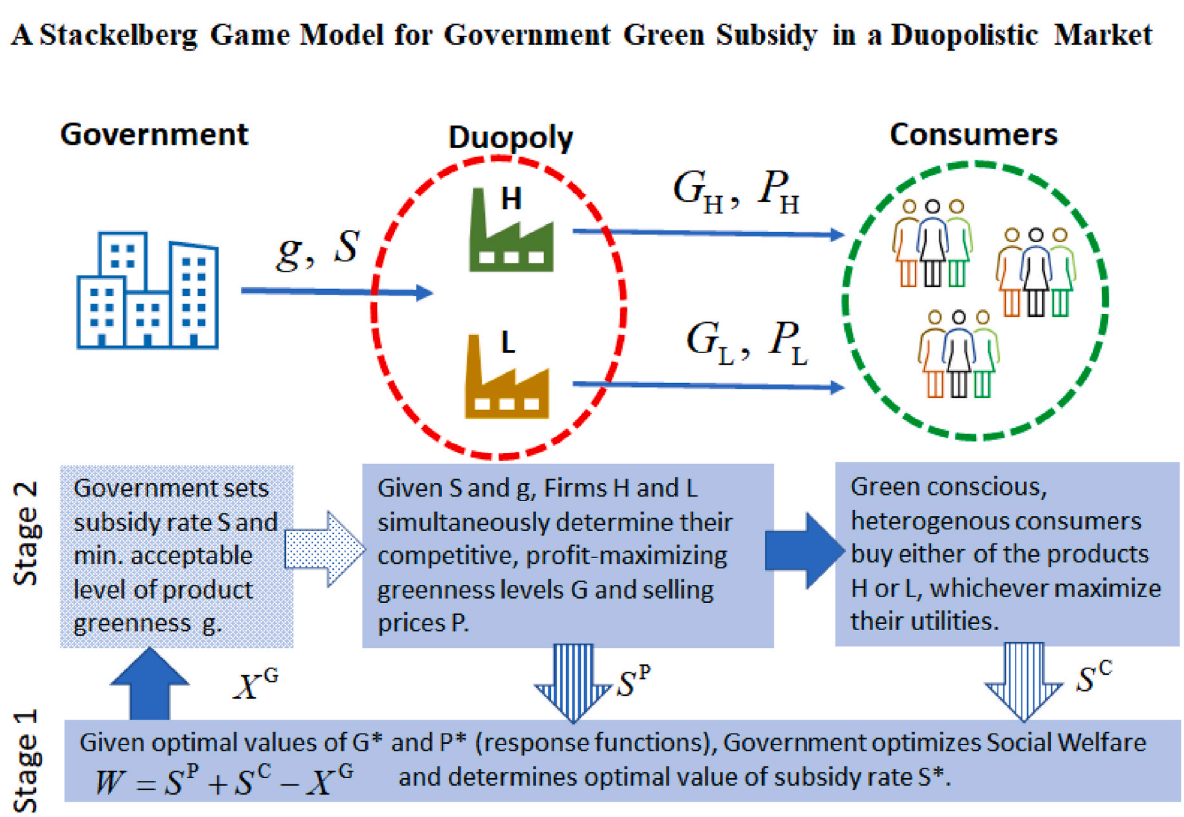

Fig. 1. The schematization of the problem at hand.

has been applying aggressive environmental policies (Zhang et al., 2020). The European Union announced the Strategic Energy Technology Plan, and Germany launched a pilot project on product carbon footprinting. Yet, many challenges have emerged in the adaptation of agreements by the participating countries since the 2012 United Nations Framework Convention on Climate Change (Berrang-Ford et al., 2019).

Consumers are becoming more environmentally aware and striving to adopt sustainable lifestyles that ask for sustainable products. In Germany, for example, it is found that consumer groups are more willing to pay a premium for food production when environmentally friendly technology is employed (Moon and Schonhof, 2011). Most consumers support the development of environmentally friendly products, but not all are willing to or afford to pay the premium. Zhang et al. (2015) report that 67% of the consumers in the US support the purchase of green products due to environmental considerations, and yet 51% of them are willing to pay a higher price for them. In Europe, the proportion of customers willing to pay a higher price for green products increased to 67% in 2008, a substantial rise from 31% in 2005 (Yu et al., 2016). Studies have also shown that customers are willing to pay a premium for green energy (Clark et al., 2003; Hartmann and Apaolaza-Ibáñez, 2012). Besides the greenness of the products, consumers have also begun to question and factor into their purchasing decisions the social impact of the products (e.g., Bhavsar et al., 2021).

Instilling sustainability in economic activities enables sustainable consumption, which emerges from consumers' awareness of green products and their environmental impacts. A critical factor in consumers' purchasing decisions, Willingness to Pay (WTP), is closely related to consumer awareness towards sustainability (Chitra, 2007). Due to their increased awareness and sensitivity to environmental protection, green consumers may be willing to pay a premium for green products. Segmenting and catering to green consumers create both opportunities and challenges for firms; they should restrategize their product lines and consider the competitive operational challenges in acquiring and utilizing green manufacturing technologies and processes. Firms adopting green technology may attract green consumers and other responsible stakeholders by reporting better Corporate Social Responsibility performance metrics. However, because generally transitioning to green manufacturing technologies requires substantial up-front capital investments and increased variable costs, firms exercise caution in such decisions (Krass et al., 2013). On average, green products are more expensive for providing environmental benefits because they usually cost more to produce than those obtained using conventional methods (Conrad, 2005).

Whether firms employ green production methods or not largely depends on the consumers' WTP. According to previous studies in this area, many factors can influence the WTP, such as educational experience (Kaman, 2008; Sheehan and Atkinson, 2012; Zhang and Wu, 2012), the power of egoism (Bickart and Ruth, 2012), and advertising campaigns (Goldstein et al., 2008). However, promoting green consumption by improving WTP has some disadvantages because many factors complicate it. Also, there is a difference between willingness and action; therefore, risk-averse firms may adopt a "wait-and-see" policy in greening their products. Consequently, green manufacturing may necessitate governmental intervention to cover the additional costs. Governments have implemented relevant public policies on subsidizing green transition, such as those in China, the UK (Stern, 2011), and the European Union (Kosenius and Ollikainen, 2013). Some non-governmental and intergovernmental organizations (e.g., Business Council for Sustainable Development and Institute for Sustainable Development) have implemented various measures to help firms adopt environmental management and cleaner technology practices (Hoffman, 2001).

Most of the recent studies have focused on the effects of consumers' environmental awareness (CEA) about the production quantity (see, for example, Conrad, 2005; Su et al., 2012; Zhang et al., 2015), the effects of government subsidy policies on green production (Xu et al., 2017; Sheu and Chen, 2012; Zhang and Wu, 2012), or the impacts of government subsidy policies on green markets (Gil-Moltó and Varvarigos, 2013; Bi et al., 2017; Yu et al., 2016; Heydari et al., 2022). With this study, we contribute to this body of research by investigating how government subsidy policies might influence the choice of green technology. In particular, we investigate the *design of an appropriate subsidy rate to stimulate duopoly firms to adopt green technology* by considering consumer heterogeneity. Indeed, improving the greenness of products is a very urgent problem that developing countries must address. Government strategies should incentivize firms to improve their environmental quality as much as possible, but how?—a curious question we aim to put a light on. Unlike in extant literature on subsidy policies based on a certain level of consumer environmental awareness and cost structures, the subsidy rate investigated in our study has broader applications. For instance, setting an appropriate subsidy threshold will play an essential role in budgeting whereby a government aims to control expenditure while possibly incentivizing the transition to greener products and production processes.

Our study closely aligns with greening supply chains from a collaborative perspective of the supply market, the consumers, and the government. Table 1 below categorizes and compares the salient features of our paper compared to the scholarly articles published in the last two decades that significantly relate to our study. Extant literature related to our study revolves around three main research areas: consumers' environmental awareness and market dynamics, governmental environmental policies, and leader-follower game-theoretic (Stackelberg) models with governmental interventions.

The first area focuses on how consumers' environmental awareness affects market share and product greenness. The widely used methods to treat CEA or WTP are to assume that they obey a particular probability distribution and use this to characterize consumers' heterogeneity. Based on this, enterprises choose product quality (greenness of product) to maximize profit. For example, Zhang et al. (2015) investigate the impact of environmental awareness among consumers on order quantities and revenues for companies manufacturing both environmentally friendly and traditional products. Liu et al. (2012) focus on the effects of competition and CEA on eco-friendly improvement and prices in two-stage supply chains. Except for this, some papers have paid attention to rigid demand products, where each firm's demand is equivalent to its market share, and the aggregate demand is unit one. For example, Rhee (1996) studied the effects of consumer heterogeneity regarding unobservable attributes on quality differentiation and price equilibrium. Amacher et al. (2004) modelled a three-stage game of investment, environmental quality provision, and price competition to study the impact of green technology investment when consumers exhibit eco-friendly preferences. Conrad (2005) explored the market implications of product differentiation when customers value the environmental aspect of products. This study investigated how environmental awareness affects the market share of green products, product quantity, and prices. These previous studies investigated the effects of CEA on green production decisions, but they did not consider the limitations of green technologies that restrict the choice of greenness.

The second main research area focuses on how the environmental policies implemented by governments might affect the environmental quality of green products determined by manufacturers. The research on this topic in the green supply chain is relatively mature. Chen (2001) studied the strategic decisions of producers by jointly considering the interactions between customer preferences and the environmental standards imposed by governments. Sheu and Chen (2012) focused on the effects of governmental financial interventions on competition in the green supply chain based on a three-stage game-theoretic model. Hafezalkotob (2015) developed a price competition model of two green and regular supply chains and analyzed the effects of government tariffs on the players' optimal strategies and environmental impacts of products. Tsireme et al. (2012) explored how policy instruments such as environmental legislation might affect decisions in adopting green

Table 1
Positioning our paper.

Research Papers	Market Segmentation		Heterogeneity		Competition Type		Decision Variables			Sustainability Objectives	
	Mixed	Green	No	Yes	Cournot	Stackelberg	Subsidy Rate	Price	Greenness	Social Welfare	Environ. Quality
Chen (2001)	●		●		●			●	●		●
Krass et al. (2013)	●		●		●		●	●		●	●
Bi et al. (2017)	●			●	●		●	●			●
Ülkü and Hsuan (2017)		●		●	●			●			●
Zhu and He (2017)		●	●			●		●	●		
Sinayi and Rasti-Barzoki (2018)		●	●			●	●	●	●		
Zhou (2018)	●			●		●		●			●
Yenipazarli (2019)		●		●	●		●	●			
Ghosh et al. (2020)		●	●		●			●	●	●	●
Ling and Xu (2021)	●			●		●		●	●		●
Zhang et al. (2020)		●	●			●	●	●	●	●	
This paper		●		●		●	●	●	●	●	●

supply chain management practices. Related studies have obtained a range of different results (Zhu and Sarkis, 2002; Zhang et al., 2008; Seuring and Müller, 2008). Yu et al. (2016) studied the optimal production design for profit-maximizing manufacturers under oligopolistic competition while also considering green preferences and subsidies. Previous pertinent studies have explored the effects of government subsidies on green technical development from different perspectives, such as increasing the rate of green innovation (Aalbers et al., 2013), increasing social welfare (Sinayi and Rasti-Barzoki, 2018), and improving the intensity of green products (Zhu, 2011).

With increasing awareness of environmental protection and sustainable development, many researchers have paid attention to duopoly green competition with vertical product differentiation under government subsidies, the design of subsidy policies and its impact on the environment and social welfare. Bansal and Gangopadhyay (2003) studied how various tax–subsidy policies, such as uniform policies for the firms and policies that discriminate between the two competitors based on their environmental quality, impact environmental quality and social welfare. Bi et al. (2017) applied a Stackelberg game model to study two competitive firms' green emission-reducing technology choices. They determined the optimal selling prices and the emissions per unit product: The green emission-reducing technology subsidy consists of two cases; subsidize only one or both firms. Moreover, they also assessed the government's strategy of minimizing pollutant emissions under two different subsidies. Huang et al. (2019) study the optimal design of an energy-saving government subsidy scheme while also showing their impact on the firms' optimal decisions of product prices and product energy efficiencies. They derived the government's endogenous optimal subsidy scheme under three different objectives, i.e., minimizing the total energy consumption, the average energy consumption per product, and the average energy consumption per unit of gross domestic product (GDP). Li et al. (2020) discussed the effects of three government subsidy schemes on the competition between two manufacturers in green innovation efforts and pricing decisions. In the problem setting of this study, the government subsidy schemes included a green non-subsidy, a green product subsidy, and a green innovation subsidy. Regarding environmental regulation, Yenipazarli (2019) examined competitive firms' research and development (R&D) effort and product pricing under emissions taxation. Drake et al. (2018) studied how regionally asymmetric emissions regulation affects technology adoption decisions of competitive enterprises.

Most previous studies have focused on the effects of environmental awareness among consumers on the production quantity (see, for example, Conrad, 2005; Su et al., 2012; Zhang et al., 2015), the effects of government subsidy policies on green production (Zhang and Wu, 2012; Xu et al., 2017; Zhang and Wu, 2012; Sheu and Chen, 2012) or consumer environmental awareness, and the effects of government subsidy policies on green products (Gil-Moltó and Varvarigos, 2013; Bi et al., 2017; Yu et al., 2016). However, few theoretical studies have adequately analyzed the effects of subsidies on green technology choices from the perspective of enterprises. In particular, these studies have not studied the impact of consumer heterogeneity on product performance (or design) and have neglected the differences in cost structures between firms.

The third stream of research related to our paper is on the use of game theory in supply chain research. To that end, we provide some real-life examples and literature on applications whereby the government is involved in decision-making or imposes compliance regulations in transitioning to green markets. In view of the challenges posed by climate change, more than 70 percent of the world economy, such as the European Union, United Kingdom, Japan and the United States, have committed to achieving net-zero emissions by the middle of the 21st century. China, the world's largest emitter of carbon dioxide, has set a bold target and promised to become carbon neutral before 2060 and to begin cutting its emissions within the next ten years (Mallapaty, 2020). Although benefits of the technology investment in pollution reduction are evident, firms are still cautious (Krass et al., 2013) because green innovation is characterized by positive externalities. Enterprises have invested substantial up-front capital investments as well as increased variable costs in the process of innovation activities while bearing paramount risks and pressures. However, they do not enjoy all the innovation benefits. As a result, a firm would choose a wait-and-see policy rather than actively committing itself to the development of green technology. At this time, innovation subsidies are particularly important for bridging the gap between private benefits and social benefits and promote enterprise innovation from the aspects of alleviating enterprise financial constraints and sharing enterprise innovation risks. Hence, in light of the long-term nature of policy goals on mitigation of pollution and environmental protection, it becomes necessary and important for a government or a regulator to implement some incentive schemes to motivate environmentally beneficial technology (Bi et al., 2017; Wan and Hong, 2019). Meng et al. (2021) also hold that designing effective environmental policy instruments to motivate firms' adoption of green emission-reducing technology, promote a carbon-neutral and sustainable economic system is gaining in importance.

Many countries are also adopting or preparing to adopt incentives to encourage enterprises to invest more in green technologies and produce green products. For example, Canada and Japan have assigned the recycling fee on electrical products (Wang et al., 2014). The United States has provided \$2.4 billion for electric vehicle corporations to support the manufacturing of green products (Gong et al., 2013). The Chinese government has provided 55,000 CNY per unit electric vehicle (driving distance is greater than 250 km) to consumers for promoting the development of new energy vehicles since 2015 in 2016–2020 new energy vehicles applied financial support policy (Yang and Xiao, 2017). In February 2021, the State Council of China issued the "Guiding Opinions on Accelerating the Establishment and Improvement of a

Green and Low-carbon Circular Development Economic System," strengthening the dominant position of enterprises in innovation and speeding up the introduction of policy designs that encourage enterprises to actively invest in green technology innovation. It is clear that government subsidy is an important driving force to support a carbon-neutral and sustainable economic system.

However, due to the scarcity of financial funds, setting an appropriate subsidy plays an important role in budget control. Usually, the government will need to estimate the reaction of enterprises in advance and then design corresponding subsidy policies to achieve the policy objectives. Although the actual effect of the policy designed in this way may deviate from the expectation to some extent, it has guiding significance and is widely adopted by various countries. In general, the government aims to control expenditure while also achieving the goal of maximizing the greenness of products and their processes. In this context, how to design appropriate subsidy policies considering budget constraints and what is the impact of subsidy policies on enterprises, consumers and society are still unexplored.

As the interactions between stakeholders and agents in global business got more complex, game-theoretic modelling has been of wide use in supply chain research (e.g., Leng and Parlar, 2005; Cachon and Netessine, 2014; Agi et al., 2021). Therefore, one of the challenges to be redressed in this work is to reflect the decision-making process of policy determination of the government and the reactions of firms. A dynamic, sequential-move game-theoretic (equilibrium) economic model, the celebrated Stackelberg model (i.e., leader-follower model), plausibly fits well to analyze the decision-making and response interactions for our model setting in this paper (recall Fig. 1). Motivated by the preceding practices and increasing studies utilizing game theory as a methodology, scholars have begun to pay attention to the design of government green subsidy policies and their impact. Bi et al. (2017) performed a study on how a government may use subsidy policy to incentivize firms' adoption of green emission-reducing technology, where the government acts as a Stackelberg leader and the two profit-maximizing firms acts as Stackelberg followers. Hattori and Tanaka (2016) applied a three-stage Stackelberg game model to study government subsidization policy and firms' adoption of new technology: In the first stage, the government determines the subsidy for each firm, and in the second stage, the firms decide whether to adopt the new technology and then determine their output levels. Zhao and You (2019) developed a single-leader-multiple-follower Stackelberg game model, where the government is the leader, and the dairy farms are independent followers. To address the optimal design of waste-to-energy incentive policy for the dairy sector. In the context of sustainable development, Rahimi et al. (2021) the environmental policy-making approach between a green and a non-green supply chain under information ambiguity and competition. The government acts as the leader and sets the policy parameters to enhance the supply chain performance in reducing the environmental pollution, while the supply chain members act as followers to determine the market price of the products and production quantity.

In our study, we link the government, duopoly firms, and heterogeneous consumers and explore different subsidy policies aimed to improve threefold objectives: environmental quality, maximize social welfare, and social surplus. Such a model setting can serve as a valuable stepping stone for more future research in the government-firm-consumer trilogy. Moreover, we also unveil the action mechanism of subsidy policies by considering consumer premium payment. This study provides theoretical significance for China as a developing country and others that target carbon neutrality through subsidy policies, among others.

Our paper adds to the emerging body of scholarly research by investigating how government subsidy policies might influence the choice of green technology. In particular, we investigate the design of an appropriate subsidy rate to stimulate duopoly firms to adopt green technology (performing at a high greenness) by considering consumer heterogeneity. Indeed, greening products is a very urgent problem that developing countries must address. Government strategies should encourage firms to improve their greenness as much as possible: Our study's premise and motivation. Unlike previous studies on subsidy policies based on a certain level of consumer environmental awareness and cost structures, the subsidy rate investigated in the present study has broader applications. Due to the scarcity of financial funds, setting an appropriate subsidy threshold will play an essential role in budgeting. Usually, governmental imperatives enforce controls on expenditure while also maximizing the greenness of products and the processes that manufacture them. In short, our study contributes to the emerging literature about green product design and subsidies whereby we adopt a follower-leader model in a duopolistic market for green consumers.

3. The duopoly Stackelberg model and structural results

Consider, in a price- and environmentally-sensitive duopolistic market, two manufacturing firms (Firm-L and Firm-H) competing with products, Products L and H (recall Fig. 1). These products are substitutable and horizontally differentiated in their level of greenness as perceived by the consumers. Unlike Firm-L, which exerts *low* or no investment in greening its Product-L, Firm-H deliberately invests in R&D for green products and strives to use low-carbon materials in the production process of its Product-H. Therefore, compared to its counterpart, Product-H is *high* in its level of greenness. Thus, compared to its rival, Firm-H incurs a higher unit production cost $c_H > c_L$ and higher R&D cost per unit of an increased level of greenness in the product$\beta_H \geq \beta_L$. Due to increased societal and global pressures, the government incentivizes greener production by offering firms a subsidy to improve environmental quality. Taking subsidies as exogenous variables, those firms decide and compete on price and greenness. Naturally, the additional cost of and the subsidizing green technology result in varied prices of these products. Consumers react to those differences in their purchasing decision processes accordingly. Table 2 exhibits the notations and their definitions used for the succeeding mathematical models.

We start with the development of the profit function, which comprises four parts: gross profit from sales products in the market $(P_i - m_i)Q_i$, plus the subsidy reward provided by the government $S(G_i - g)Q_i$, plus the cost-savings achieved by increased product greenness $\varepsilon(G_i - g)Q_i$, less the R&D investment cost $\beta(G_i - g)^2$. The cost-savings and the R&D investment cost

Table 2
Nomenclature.

Indices	
Subscript $i \in \{H, L\}$	H: High greenness, L: Low greenness
Subscript $j \in \{0, 1\}$	0: No subsidy, 1: Subsidy granted
Superscript $k \in \{C, G, P\}$	C: Consumer, G: Government, P: Producer
Parameters	
β_i	Cost coefficient for R&D for greening
m_i	Unit manufacturing cost (in monetary units, i.e., m.u.)
ε	Reputation effect (in m.u./unit greenness)
g	Minimum acceptable level of greenness (a constant)
$\gamma = m\beta/\varepsilon^2$	Comprehensive technical parameter
θ	Consumers' premium payment, a random var. (in m.u.)
Decision variables	
G_i	The level of greenness for Product-i, measureless
P_i	Unit selling price of Product-i (in, m.u.)
S	The green subsidy rate (in m.u. per unit of greenness)
Surrogate variables	
Q_i	Market share of Firm-i, i.e., Q_L and Q_H
π_i	Total profit for Firm-i
E	Environmental quality
S^C	Consumer surplus
S^P	Producer surplus
X^G	Government expenditure
W	Social welfare
R	Social surplus

follow the model setting of D'Aspremont and Jacquemin (1991), Bi et al. (2017), Chen et al. (2019b), and Osório and Pinto (2020). This convex R&D cost function describes the increasing marginal cost of transforming innovation to greenness; that quadratic functional form has been widely used in the literature on R&D investment, such as Savaskan and Van Wassenhove (2006), Sengupta (2012), Amacher et al. (2004), Zhang et al. (2018) and Chen et al. (2019b). In the price sensitivity and environmental sensitivity market, green consumers can contribute to the environment and obtain psychological satisfaction by repeatedly purchasing green products (Romani et al., 2016). Moreover, consumers who have bought green products would recommend them to acquaintances, thus increasing the word of mouth (WOM) and reputation of green products (Frey and Stutzer, 2006). For example, one of five American consumers claims that WOM is critical in green purchase decisions (Brécard, 2016). These reputation effects can bring social network effects (social network externalities) and thus increase the competitiveness and profitability of firms (Leibenstein, 1950; Romani et al., 2016). Drawing on Chen et al. (2019b) and Xu et al. (2017), we use the expression $\varepsilon(G_i - g)Q_i$ to capture this aspect whereby g denotes the lowest greenness accepted by the market, m_i is the unit production cost, ε is the spillover coefficient, and S is a subsidy rate by the government. Then, the profit-maximization problem of Firm-i can be cast as:

$$\begin{aligned} \max_{P_i, G_i} \pi_i &= \underbrace{(P_i - m_i)Q_i}_{\text{Revenue}} - \underbrace{\beta_i(G_i - g)^2}_{\text{R\&D cost}} + \underbrace{\varepsilon(G_i - g)Q_i}_{\text{Network effect}} + \underbrace{S(G_i - g)Q_i}_{\text{Subsidy}} \\ s.t. \quad & m_i \geq \varepsilon(G_i - g). \end{aligned} \tag{1}$$

where Q_i is the market share of, and G_i is the level of greenness designed by, Firm-i, i $\in \{L, H\}$. Note that both the reputation effect and the R&D investment rates are assumed to be the same for both firms. In this study, we are interested in investigating to what extent the provision of R&D subsidies to promote the duopoly competitors would devote to green technology.

The consumers know the price of products offered by both firms, and they also are aware that the product greenness of Firm-H is higher than that of Firm-L. Consumers would be willing or able to pay a different price premium for green products. To reflect in our model that consumer heterogeneity, similar to Conrad (2005), θ denotes the random variable representing consumers' price premiums and is uniformly distributed over $[0, \Phi]$.

Many empirical studies support that consumers would pay a price premium for greener products. However, how the consumers' WTP reacts to the greenness of the products is still a problem. Shao et al. (2018) use the ordered logit model and ordinary least-square method to estimate the factors affecting the WTP in China. They find the environmental attitude, education, and GDP per capita have a positive effect on WTP. Surprisingly though, in that study, the impact of pollution on WTP is found insignificant. Grösche and Schröder (2011) and Mozumder et al. (2011) study how green electricity used in manufacturing influences WTP; both studies show a weak positive correlation. Two ways can explain this weak influence. One is that it is not easily accessible for individuals to know the precise greenness or abatement of the products. Secondly, WTP is affected by many factors: the two most significant ones being income level and conscience. It means that consumers pay more for green products due to personal characteristics and their self-assessment of the pollution rate from those products (Shao et al., 2018; Franzen and Vogl, 2013).

Most consumers do not know accurate information about product greenness; they can only distinguish the difference between green products via product labels. Consumers know that environmentally superior products have a higher level of greenness than the inferior ones, but they do not know to what extent. And higher greenness products are usually more expensive. For example, most foods adopt a green label policy. China's green food has two grades: Grade A and Grade AA. The greenness of each grade is a range value. Products that meet specific standards in the production process can obtain corresponding grade certification. Consumers usually judge whether to buy green products according to the price.

We exclusively focus on consumers who buy either of the products, those with a non-negative utility from the purchase. By purchasing the product, the consumer derives a utility $U = WTP - P$. Consumers who buy Product-L derive a utility of U_L, and their WTP satisfies $WTP_L = WTP$. Consumers purchasing greener product Product-H are willing to pay a higher premium and obtain a utility of U_H, where $WTP_H = WTP + \theta$ (c.f., Ülkü and Hsuan, 2017; Ling and Xu, 2021). Then, we can explicitly write consumer utility functions for each segment as:

$$U_L = WTP - P_L, \text{ and } U_H = WTP + \theta - P_H, \tag{2}$$

where P_L and P_H are the prices set by the two firms L and H, respectively.

Let $\tilde{\theta}$ represent the location of the boundary consumer who is indifferent between choosing the product L or H. Via Eq. (2), setting $U_L = U_H$ and solving for when $\theta \leftarrow \tilde{\theta}$ we find $\tilde{\theta} = P_H - P_L$. If consumers' premium payments are lower than $\tilde{\theta}$, then they will buy Product-L; otherwise, they will buy the greener product, Product-H. Then we can find a critical point $\tilde{\theta}$, which acts as a boundary point in segmenting the market.

The percentage of "budget consumers" represents the market share of Firm-L, and the percentage of environmentally-conscious "green consumers" represents the market share of Firm-H. Those two firms share the market whose size is 1. Then, we can cast the market shares for each firm as follows:

$$Q_L = \int_0^{\tilde{\theta}} \Phi^{-1} d\theta = (P_H - P_L)/\Phi \text{ and,} \tag{3}$$

$$Q_H = 1 - Q_L = (\Phi - P_H + P_L)/\Phi. \tag{4}$$

Proposition 1. *Under decentralized decision making, the optimal equilibrium greenness levels, demand shares, and prices for both Firms L and H are:*

$$G_L^* = g + \min\left\{ m_L/_\varepsilon, Q_L(\varepsilon + S)/_{2\beta_L} \right\} \tag{5}$$

$$G_H^* = g + \min\left\{ \frac{m_H}{\varepsilon}, \frac{Q_H(\varepsilon + S)}{2\beta_H} \right\} \tag{6}$$

$$P_L^* = \frac{2}{3}[m_L - (\varepsilon + S)(G_L^* - g)] + \frac{1}{3}[m_H - (\varepsilon + S)(G_H^* - g)] + \frac{\Phi}{3} \tag{7}$$

$$P_H^* = \frac{1}{3}[m_L - (\varepsilon + S)(G_L^* - g)] + \frac{2}{3}[m_H - (\varepsilon + S)(G_H^* - g)] + \frac{2\Phi}{3} \tag{8}$$

Proof: All proofs are in the Appendix.

From Eqs. (5) and (6), we know that the optimal market shares are restricted by the constraint conditions, and they may have four different equilibrium values. Substituting the optimal prices P_L^* and P_H^* into (3) and (4) implies that.

(1) When $G_L^* - g = \frac{(\varepsilon+S)}{2\beta_L} Q_L^*$ and $G_H^* - g = \frac{m_H}{\varepsilon}$,

$$Q_L^{(L^-, H^+)} = \frac{2(\Phi - m_L - m_H S/\varepsilon)}{6\Phi - (1 + S/\varepsilon)^2 \frac{m_L}{r_L}} \tag{9}$$

(2) When $G_L^* - g = \frac{m_L}{\varepsilon}$ and $G_H^* - g = \frac{\varepsilon+S}{2\beta_L} Q_H^*$,

$$\begin{cases} if\ \frac{m_H}{m_L} \le 3r_H, & Q_L^{(L^+,H^-)} = \dfrac{2(2\Phi + m_H + m_L S/\varepsilon) - (1+S/\varepsilon)^2 \frac{m_H}{r_H}}{6\Phi - (1+S/\varepsilon)^2 \frac{m_H}{r_H}} \\ if\ \frac{m_H}{m_L} > 3r_H, & Q_L^{(L^+,H^-)} = \dfrac{2(\Phi + m_H + m_L S/\varepsilon) - (1+S/\varepsilon)^2 \frac{m_H}{r_H}}{6\Phi - (1+S/\varepsilon)^2 \frac{m_H}{r_H}} \end{cases} \tag{10}$$

(3) When $G_L^* - g = \frac{\varepsilon+S}{2\beta_L} Q_L^*$ and $G_H^* - g = \frac{\varepsilon+S}{2\beta_L} Q_H^*$,

$$Q_L^{(L^-,H^-)} = \frac{2(2\Phi + \Delta m) - (1+S/\varepsilon)^2 \frac{m_H}{r_H}}{6\Phi - (1+S/\varepsilon)^2 \frac{m_L}{r_L} - (1+S/\varepsilon)^2 \frac{m_H}{r_H}} \tag{11}$$

(4) When $G_L^* - g = \frac{m_L}{\varepsilon}$ and $G_H^* - g = \frac{m_H}{\varepsilon}$,

$$Q_L^{(L^+,H^+)} = \frac{1}{3} - \frac{\Delta m S/\varepsilon}{3\Phi} \tag{12}$$

where , $\Delta m = m_H - m_L$ and $r_i = \frac{m_i \beta_i}{\varepsilon^2}$, $i \in \{L, H\}$.

4. Analysis of the government subsidy policy

This section analyzes the government subsidy policies based on different objectives and the competitive firms' decision-making using the Stackelberg game model. The government is the leader, and the firms are the followers. The government has two goals in setting the subsidy rate. The first goal is to make competitive firms thrive to maximize the greenness of their products. The second goal is to improve social welfare or social surplus. In setting the second goal, the government has two options: considering only the economic benefit to maximize social welfare or taking the environmental impact into account in economic development. Then, maximizing social welfare could be replaced with maximizing social surplus. In the first stage, the government first determines the feasible subsidy rates that can incentivize both firms to improve their products' greenness as high as possible. Based on the feasible region of subsidy rate, the government then sets an optimal subsidy rate to maximize the social welfare or social surplus. In the second stage, the two competitive firms, as the followers, determine the optimal prices and greenness levels for their products. Our Stackelberg game is solved backwards; first, firms' decisions and, then, the government's (leader) decision on the subsidy rate.

4.1. The optimal greenness based on environmental quality

This section mainly explores the optimal greenness level, which can improve the EQ from the government's perspective. Firstly, we analyze the case where no subsidy is offered by the government, i.e., when $S = 0$. In the absence of governmental intervention, we assess different equilibria, among which we find the ones with the highest EQ. Building on Proposition 1, there are four possible equilibrium states without a subsidy, as shown in Fig. 2. Moreover, in Table 3, we display the required conditions for each equilibrium state (see Appendix for derivations).

Next, we analyze the total EQ obtained in the equilibrium state. We denote this quantity by E. The function for EQ is borrowed from Nicola

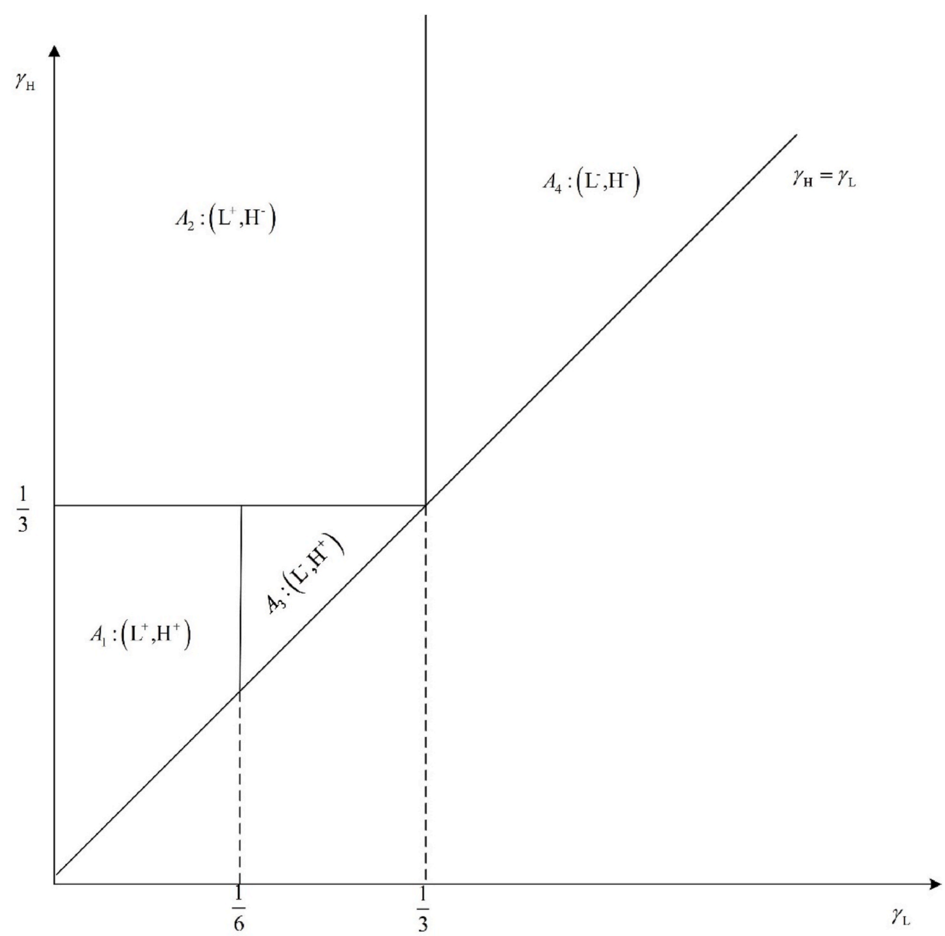

Fig. 2. Equilibrium areas and states.

Table 3
Equilibrium conditions and states *without* subsidy.

Area	γ_L	γ_H	WTP	Equilibrium state
A_1	$0<\gamma_L<\frac{1}{6}$	$\gamma_L<\gamma_H<\frac{1}{3}$	$\Phi\geq\Lambda_1$	(L^+, H^+)
	$\gamma_L=\frac{1}{6}$	$\gamma_H=\frac{1}{3}$	$\Phi\geq\max\left\{\frac{3}{2}m_L,\frac{3}{4}m_H\right\}$	
A_2	$0<\gamma_L\leq\frac{1}{3}$	$\gamma_H\geq\frac{1}{3}$	$\Phi\geq\Lambda_2$	(L^+, H^-)
A_3	$\frac{1}{6}\leq\gamma_L<\frac{1}{3}$	$\gamma_L<\gamma_H\leq\frac{1}{3}$	$\Phi\geq\Lambda_3$	(L^-, H^+)
A_4	$\frac{1}{3}<\gamma_L<\gamma_H$	$\gamma_H>\frac{1}{3}$	$\Phi\geq\Lambda_4$	(L^-, H^-)

where $\gamma_i=\frac{m_i\beta_i}{\varepsilon^2}$, $\Lambda_1=\max\left\{\frac{\gamma_L+\gamma_H-0.5}{6\gamma_L-1}\frac{m_H}{\gamma_H},\frac{\gamma_L+\gamma_H-0.5}{6\gamma_H-2}\frac{m_L}{\gamma_L},9m_L\gamma_L,\frac{9}{4}m_H\gamma_H\right\}$ $\Lambda_2=\frac{1}{4}\frac{m_L}{\gamma_L}+\frac{\Delta m}{2}$, $\Lambda_3=\frac{1}{2}\frac{m_H}{\gamma_H}-\Delta m$, and $\Lambda_4=\max\left\{\frac{\gamma_L+\gamma_H-0.5}{6\gamma_L-1}\frac{m_H}{\gamma_H},\frac{\gamma_L+\gamma_H-0.5}{6\gamma_H-2}\frac{m_L}{\gamma_L},m_L,0.5m_H-2\Delta m\right\}$.

and Giorgio (2013) and Ghosh et al. (2020) and formulated as:

$$E_j=Q_{L,j}(G_{L,j}-g)+Q_{H,j}(G_{H,j}-g) \tag{13}$$

where $j=\{0,1\}$. Here, $j=0$ implies that no subsidy is granted to either of the two firms and $j=1$ denotes that both firms get subsidized. We present the comparison of these cases as Proposition 2.

Proposition 2. *The equilibrium state* (L^+, H^+) *exhibits a greater EQ than the other equilibrium states without a subsidy, under the following conditions*:

1. *When* $0<\gamma_L\leq\frac{1}{3}$, $\gamma_H\geq\frac{1}{3}$ *and consumer's WTP satisfies* $\Phi\geq\Lambda_2$,

   $E_0^{(L^+,H^+)}>E_0^{(L^+,H^-)}$.

2. *When* $\frac{1}{6}\leq\gamma_L<\frac{1}{3}$, $\gamma_L<\gamma_H\leq\frac{1}{3}$, *and consumer's WTP satisfies* $\Phi\geq\Lambda_3$,

   $E_0^{(L^+,H^+)}>E_0^{(L^-,H^+)}$.

3. *When* $\frac{1}{3}<\gamma_L<\gamma_H$, $\gamma_H>\frac{1}{3}$ *and consumer's WTP satisfies* $\Phi\geq\Lambda_4$,

   $E_0^{(L^+,H^+)}>E_0^{(L^-,H^-)}$.

Proposition 2 indicates that EQ will be highest when both firms adopt the highest greenness in each equilibrium area. However, firms may be unwilling to produce at the highest degree of greenness to maximize profits; therefore, appropriate government subsidies may encourage firms to transition to greener production. Therefore, this study will further analyze whether government subsidies can promote firms to improve product greenness and ensure the highest possible EQ. We show this by Corollary 1.

Corollary 1. *The environmental quality will enhance through the subsidy policy when both firms still perform at their peak greenness, that is* $E_1^{(L^+,H^+)}>E_0^{(L^+,H^+)}$.

4.1.1. *The feasible region for subsidy rate*

What is an appropriate subsidy rate to ensure that both of these competing firms perform at their peak greenness? We construct the term "peak greenness" as the firm's highest achievable equilibrium product greenness under the given constraints. Firm-L chooses its peak greenness as the dominant strategy implies that whatever strategy Firm-H chooses, Firm-L chooses its peak greenness is always optimal, which means that $\frac{\varepsilon+S}{2\beta_L}Q_{L^-}^*>\frac{m_L}{\varepsilon_L}$, and which can be recast as $\frac{2\gamma_L}{1+S/\varepsilon}<Q_L^{(L^-,H^-)}, Q_L^{(L^-,H^+)}<1$. Similarly, Firm-H adopts peak greenness as the dominant strategy when $\frac{\varepsilon+S}{2\beta_H}Q_{H^-}^*>\frac{m_H}{\varepsilon_H}$ which translates to $0<Q_L^{(L^-,H^-)}, Q_L^{(L^+,H^-)}<1-\frac{2\gamma_H}{1+S/\varepsilon}$. Then, we find the necessary conditions under which both firms *simultaneously* reach their peak levels of greenness as $\frac{2\gamma_L}{1+S/\varepsilon}<Q_L^{(L^-,H^-)}, Q_L^{(L^-,H^+)}<1\cap 0<Q_L^{(L^-,H^-)}, Q_L^{(L^+,H^-)}<1-\frac{2\gamma_H}{1+S/\varepsilon}$..

By solving this system of inequalities, we obtain the government's (8) subsidy policy as in Proposition 3.

Proposition 3. *Both firms with different manufacturing costs will strive for their peak greenness for production if*

$$\Phi>\max\left\{\frac{1}{2}\frac{m_H}{\gamma_H}(1+S/\varepsilon)^2-m_H-m_LS/\varepsilon,\frac{1}{4}\frac{m_L}{\gamma_L}(1+S/\varepsilon)^2-\frac{m_L}{2},\varphi_1\right\}\quad \textit{and}$$

$$S\geq(6r_H-1)\varepsilon,\ \textit{where}\ \varphi_1=\frac{m_HS/\varepsilon+(1+S/\varepsilon)\frac{\beta_H}{\beta_L}m_H+m_L-\frac{(1+S/\varepsilon)^2}{2}\frac{m_L}{r_L}}{\frac{6}{1+S/\varepsilon}r_H-1}.$$

Proposition 3 implies that the government adopting a subsidy policy incentivizes the duopoly to increase greenness in their production, and thereby, the total environmental quality. We note that the subsidy rate is simply a function of the unit production cost *m*, the cost-saving rate for every unit greenness ε, and the R&D cost coefficient β. The subsidy policy needs to be supported by the premium payment paid by consumers. Moreover, when the duopoly firms adopt their peak greenness, a higher subsidy rate and premium payment cannot further improve the greenness of products.

4.1.2. *Competitive equilibrium*

In this section, we give the corresponding optimal strategies of firms when the government adopts the subsidy rate in Section 4.2. Via Eqs. (3)–(8), the optimal strategies for the two firms follow.

The optimal competitive decisions for Firm-L are:

$$G_L^*-g=\frac{m_L}{\varepsilon},\ P_L^*=\frac{1}{3}\left[\Phi-\frac{(\Delta m+3m_L)S}{\varepsilon}\right]. \tag{14}$$

The optimal competitive decisions for Firm-H are:

$$G_H^*-g=\frac{m_H}{\varepsilon},\ P_H^*=\frac{1}{3}\left[2\Phi-\frac{(2\Delta m+3m_L)S}{\varepsilon}\right]. \tag{15}$$

By due substitution into the demand functions, we obtain

$$Q_L^*=\frac{\Phi-\Delta mS/\varepsilon}{3\Phi},\ Q_H^*=\frac{2\Phi+\Delta mS/\varepsilon}{3\Phi}. \tag{16}$$

Therefore, the optimal profits for the two firms can be obtained as:

$$\pi_L^*=\frac{1}{9\Phi}[\Phi-\Delta mS/\varepsilon]^2-m_L^2\frac{\beta_L}{\varepsilon^2}, \tag{17}$$

$$\pi_H^*=\frac{1}{9\Phi}[2\Phi+\Delta mS/\varepsilon]^2-m_H^2\frac{\beta_H}{\varepsilon^2}. \tag{18}$$

Stimulated by the subsidy, both firms reach their peak green levels and compete mutually in the market to obtain positive profits by adopting different strategies, where Firm-H offers superior green products and charges a higher price. Accordingly, Firm-H captures a larger market share.

Proposition 4. *The manufacturing cost difference between the two firms* Δm *and change in the range of WTP both influence firms' optimal decisions and environmental quality* E_1. *The higher the cost difference and with government subsidies allowed, the higher the deviation from optimal prices for both firms,* P_L^* *and* P_H^*. *However, the optimal market share of Firm-L (Firm-H) decreases (increases) as* Δm *increases. The impacts of* Δm *on profits are uncertain, and they depend on* Φ *and S. Higher* Δm *increases total EQ, i.e.* $\frac{\partial P_L^*}{\partial\Delta m}<0$, $\frac{\partial P_H^*}{\partial\Delta m}<0$, $\frac{\partial Q_L^*}{\partial\Delta m}<0$, $\frac{\partial Q_H^*}{\partial\Delta m}>0$, $\frac{\partial E_1}{\partial\Delta m}>0$. *Secondly, higher WTP, i.e., an increase in the upper bound* Φ, *decreases (increases) the market share of Firm-H (Firm-L). Meanwhile, both firms raise their prices, but Firm-H has a* *higher increase in price than that of Firm-L. The profits of both firms increase, but more so for Firm-H. Moreover, E_1 decreases in Φ, i.e.* $\frac{\partial Q_{\mathrm{L}}^*}{\partial \Phi} > 0,\ \frac{\partial Q_{\mathrm{H}}^*}{\partial \Phi} < 0,\ \frac{\partial P_{\mathrm{H}}^*}{\partial \Phi} > \frac{\partial P_{\mathrm{L}}^*}{\partial \Phi} > 0,\ \frac{\partial \pi_{\mathrm{H}}^*}{\partial \Phi} > \frac{\partial \pi_{\mathrm{L}}^*}{\partial \Phi} > 0,\ \frac{\partial E_1}{\partial \Phi} < 0.$

4.2. Optimal subsidy for welfare maximization

In this section, we derive the optimal subsidy that maximizes the social welfare (W), and we investigate the effect of a subsidy on consumer surplus (S^{C}), producer surplus (S^{P}), and government expenditure (X^{G}). Then, we analyze the firms' optimal decisions. Using the equilibrium profits in Eqs. (17) and (18), the producer surplus can be obtained as follows:

$$S^{\mathrm{P}} = \pi_{\mathrm{L}} + \pi_{\mathrm{H}} = \frac{1}{9\Phi}[\Phi - \Delta m S/\varepsilon]^2 - m_{\mathrm{L}}^2\frac{\beta_L}{\varepsilon^2} + \frac{1}{9\Phi}[2\Phi + \Delta m S/\varepsilon]^2 - m_{\mathrm{H}}^2\frac{\beta_{\mathrm{H}}}{\varepsilon^2} \tag{19}$$

And, the consumer surplus obtained by purchasing green products is

$$\begin{aligned} S^{\mathrm{C}} &= \int_0^{\theta^*} U_{\mathrm{L}}\frac{1}{\Phi}d\theta + \int_{\theta^*}^{\Phi} U_{\mathrm{H}}\frac{1}{\Phi}d\theta \\ &= (WTP - P_{\mathrm{L}}^*)Q_{\mathrm{L}}^* + (WTP + \frac{\theta + \Phi}{2} - P_{\mathrm{H}}^*)Q_{\mathrm{H}}^* \end{aligned} \tag{20}$$

where P_{L}^* Q_{L}^*, P_{H}^* and P_{H}^* refer to equation 21–23.

The total government expenditure is:

$$X^{\mathrm{G}} = S\left(Q_{\mathrm{L}}^* G_{\mathrm{L}}^* + Q_{\mathrm{H}}^* G_{\mathrm{H}}^*\right) = \frac{\Delta m^2}{3\Phi}\left(\frac{S}{\varepsilon}\right)^2 + \left(m_{\mathrm{H}} - \frac{\Delta m}{3}\right)\frac{S}{\varepsilon} \tag{21}$$

Combining (19), (20), and (21), social welfare is obtained as:

$$\begin{aligned} W &= S^{\mathrm{C}} + S^{\mathrm{P}} - X^{\mathrm{G}} \\ &= -\frac{\Delta m^2}{6\Phi}(\frac{S}{\varepsilon})^2 + \frac{\Delta m}{9}\frac{S}{\varepsilon} + \frac{4\Phi}{9} + WTP - m_{\mathrm{H}}\gamma_{\mathrm{H}} - m_{\mathrm{L}}\gamma_{\mathrm{L}} \end{aligned} \tag{22}$$

Proposition 5. *The government subsidy S decreases the sale prices of products, increases the market share, and the profit derived from Product-H. The comparative statics regarding S follow:*

$$\frac{\partial P_{\mathrm{L}}^*}{\partial S} < 0,\ \frac{\partial P_{\mathrm{H}}^*}{\partial S} < 0,\ \frac{\partial Q_{\mathrm{L}}^*}{\partial S} < 0,\ \frac{\partial Q_{\mathrm{H}}^*}{\partial S} > 0,$$
$$\frac{\partial \pi_{\mathrm{L}}^*}{\partial S} < 0,\ \frac{\partial \pi_{\mathrm{H}}^*}{\partial S} > 0,\ \frac{\partial S^{\mathrm{C}}}{\partial S} > 0,\ \frac{\partial S^{\mathrm{P}}}{\partial S} < 0,\ \frac{\partial X^{\mathrm{G}}}{\partial S} > 0.$$

Proposition 5 demonstrates that the government subsidy decreases the selling prices for both firms. Also, Firm-H enjoys a larger market share compared to that of Firm-L. The lower selling price and smaller market share jointly yield a reduction in the profit of Firm-L, and that loss is greater than the gain provided by the government subsidy. On the other hand, Product-H captures a larger market share and enables a larger profit for Firm-H. However, the government subsidy increases expenditure.

Proposition 6. *If both firms choose the peak greenness, the subsidy rate maximizing the social welfare displayed in* Eq. (22) *is*

$$S^{W^*} = \frac{\Phi\varepsilon}{3\Delta m}. \tag{23}$$

We note that W is concave in subsidy rate under the condition that both firms manufacture their products at peak greenness. This implies that more subsidies are not always better. And social welfare-maximizing subsidy rate S^{W^*} is proportional to consumer premium payment Φ and inversely proportional to the cost difference between the two firms Δm. Substituting S in equation 14–18 with S^{W^*}, we can obtain the following results:

The optimal strategies for the Firm-L are:

$$P_{\mathrm{L}}^{W^*} = \frac{1}{3}\left[\Phi - \frac{(\Delta m + 3m_{\mathrm{L}})S^{W^*}}{\varepsilon}\right], \text{ and } Q_{\mathrm{L}}^{W^*} = \frac{\Phi - S^{W^*}\Delta m/\varepsilon}{3\Phi}.$$

The optimal strategies for Firm-H are:

$$P_{\mathrm{H}}^{W^*} = \frac{1}{3}\left[2\Phi - S^{W^*}(2\Delta m + 3m_{\mathrm{L}})/\varepsilon\right], \text{ and } Q_{\mathrm{H}}^* = \frac{2\Phi + \Delta m S^{W^*}/\varepsilon}{3\Phi}.$$

Therefore, the optimal profits for the two firms can be obtained as:

$$\pi_{\mathrm{L}}^{W^*} = \frac{1}{9\Phi}[\Phi - S^{W,^*}\Delta m/\varepsilon]^2 - m_{\mathrm{L}}^2\frac{\beta_{\mathrm{L}}}{\varepsilon^2}, \text{ and}$$

$$\pi_{\mathrm{H}}^{W^*} = \frac{1}{9\Phi}[2\Phi + S^{W^*}\Delta m/\varepsilon]^2 - m_{\mathrm{H}}^2\frac{\beta_{\mathrm{H}}}{\varepsilon^2}.$$

4.3. Optimal subsidy for social surplus optimization

With the growing concern on depleted natural resources and polluted environments, sustainable production and consumption have received significant attention from governments, industries, and consumers worldwide. These concerns are gradually being taken into consideration when measuring the economic and social welfare of a country. In environmental economics, environmental impact and environmental cost of a production process have drawn much attention. One of the research streams focuses on the carbon footprint of a production process and the life-cycle assessment (LCA) in its industry (Yenipazarli, 2019). Another branch focuses on designing regulations such as environmental taxes to motivate the choice of innovative and "green," emissions-reducing technologies (Krass et al., 2013). Because the taxation approach directly measures the price of emissions to the firm, it received significant traction attention from the regulators. In this study, we gauge the EQ with the social welfare decisions, and the government can marry production activity and environmental concerns. This section aims to investigate the optimal subsidy to maximize the social surplus (*SS*). Drawing on Barnett (1980) and Ghosh et al. (2020), the *SS* include both social welfare and environment quality (E) and is derived as follows:

$$R = S^{\mathrm{C}} + S^{\mathrm{P}} - X^{\mathrm{G}} + E = -\frac{\Delta m^2}{6\Phi}\left(\frac{S}{\varepsilon}\right)^2 + \left(\frac{\Delta m}{9} + \frac{\Delta m^2}{3\Phi\varepsilon}\right)\frac{S}{\varepsilon} + \frac{4\Phi}{9} - \frac{\Delta m}{3\varepsilon} + WTP - m_{\mathrm{H}}\gamma_{\mathrm{H}} - m_{\mathrm{L}}\gamma_{\mathrm{L}} \tag{24}$$

Proposition 7. *Given that both firms choose the peak greenness, S^{R^*} is higher than S^{W^*} where subsidy rate maximizing R given in* Eq. (24) *follows as in* Eq. (25).

$$S^{R^*} = \frac{\Phi\varepsilon}{3\Delta m} + 1. \tag{25}$$

Proposition 7 implies that the S^{R^*} is related not only to consumer premium payment Φ and the cost difference between the two firms Δm, but also to the cost-saving rate ε. Moreover, from Eqs. (23) and (25), we note that $S^{R^*} > S^{W^*}$. It is not difficult to understand that when the government incorporates environmental problems into social welfare, it calls for more resources to achieve that goal. The lower the R&D spillover effect of firms, the more financial support the government needs to make up for the deficiency of firms in reducing their environmental impact.

The optimal strategies for Firm-L are:

$$P_{\mathrm{L}}^{R^*} = \frac{1}{3}\left[\Phi - S^{R^*}(\Delta m + 3m_{\mathrm{L}})/\varepsilon\right], \text{ and } Q_{\mathrm{L}}^{R^*} = \frac{\Phi - S^{R^*}\Delta m/\varepsilon}{3\Phi}.$$

The optimal strategies for Firm-H are:

$$P_{\mathrm{H}}^{R^*} = \frac{1}{3}\left[2\Phi - S^{R^*}(2\Delta m + 3m_{\mathrm{L}})/\varepsilon\right], \text{ and } Q_{\mathrm{H}}^{R^*} = \frac{2\Phi + \Delta m S^{R^*}/\varepsilon}{3\Phi}.$$

Therefore, the optimal profits for the two firms can be found as:

$$\pi_{\mathrm{L}}^{R^*} = \frac{1}{9\Phi}\left[\Phi - S^{R^*}\Delta m/\varepsilon\right]^2 - m_{\mathrm{L}}^2\frac{\beta_{\mathrm{L}}}{\varepsilon^2}, \text{ and}$$
$$\pi_{\mathrm{H}}^{R^*} = \frac{1}{9\Phi}\left[2\Phi + S^{R^*}\Delta m/\varepsilon\right]^2 - m_{\mathrm{H}}^2\frac{\beta_{\mathrm{H}}}{\varepsilon^2}.$$

Proposition 8. $Q_{\mathrm{L}}^{R^*} > Q_{\mathrm{L}}^{W^*}$, $\pi_{\mathrm{H}}^{R^*} > \pi_{\mathrm{H}}^{W^*}$, $\pi_{\mathrm{L}}^{R^*} < \pi_{\mathrm{L}}^{W^*}$, $G_{\mathrm{S}}^{R^*} > G_{\mathrm{S}}^{W^*}$.

When maximizing social surplus, Firm-H can obtain a higher market share and profit than social welfare maximization. The EQ can also be improved when the government gauges environmental issues with social welfare considerations.

5. Numerical analyses

This section offers numerical experiments and sensitivity analyses to support the preceding structural results we derived. We first explore the impact of the subsidy on firms' decisions and then on social welfare and EQ. Based on the assumptions of the model and the conditions of equilibrium existence, and drawing partly on the numerical values used in Basiri and Heydari (2017), Liu and Yi (2017), and Ling and Xu (2021), we employ the following base-case parameters: $m_{\mathrm{L}} = 2$, $m_{\mathrm{H}} = 3$, $\varepsilon = 0.1$, $\beta_{\mathrm{L}} = 0.0015$, $\beta_{\mathrm{H}} = 0.002$, $g = 1$, $\Phi = 29.4$. In addition to the general results obtained in Section 4, the insights from the following sensitivity analyses on key parameters confine to this base-case data. Nevertheless, it enables us to showcase the mechanics and the utility of the optimal, closed-form models we have developed thus far.

How does the subsidy rate affect firms' equilibrium performances in duopolistic competition? We first explore this fundamental question from the perspectives of market share and profit. Figs. 3 and 4 show that Firm-H's market share and profit increase in the subsidy rate. A higher subsidy rate lowers the price and market share of Firm-L, resulting in lower profit. These imply that the government should be cautious about subsidies when consumers' WTP is low. Firm-L should be strategic in receiving subsidies, as it may negatively impact its position in the market.

Secondly, we analyze the impact of consumers' premium payments on firms under the optimal subsidy rate. The results are displayed in Fig. 5 and Fig. 6. Fig. 5 shows that when the premium payment increases, the market share of Firm-H decreases, while it increases for Firm-L. And by Fig. 6, it is reaffirmed that an increase in premium payment will enhance the profits of both firms. With the rise of premium payment, the optimal prices of both firms increase, while the price rise for Product-H is greater than its counterpart. Because the greenness of their respective products does not change, a higher price will reduce the market share of Firm-H; the profit gained by increasing the price is greater than the profit loss caused by the shrinking of its market share. These results concur with the works of Chitra (2007) and Liu et al. (2012), as they claimed that higher WTP for more eco-friendly products would benefit more eco-friendly manufacturers.

The preceding sensitivity analyses focus on the profitability of Firm-L and Firm-H (Figs. 3–6), whereas the succeeding sensitivity analyses (Figs. 7–12) focus on the aggregate impact on the environment and society (social welfare and consumer surplus) so that we have complete and extensive numerical analyses supporting our structural results through Propositions 1 to 8.

Fig. 7 highlights that the social welfare and social surplus are concave with the subsidy rate, implying that the subsidy rate has a unique optimizer. Increasing the subsidy rate will increase social welfare first and then decrease. The reason is that subsidies will lower the selling price of green products, which will increase the utility of consumers and reduce the profits of firms. When the subsidy rate is low, the increase of

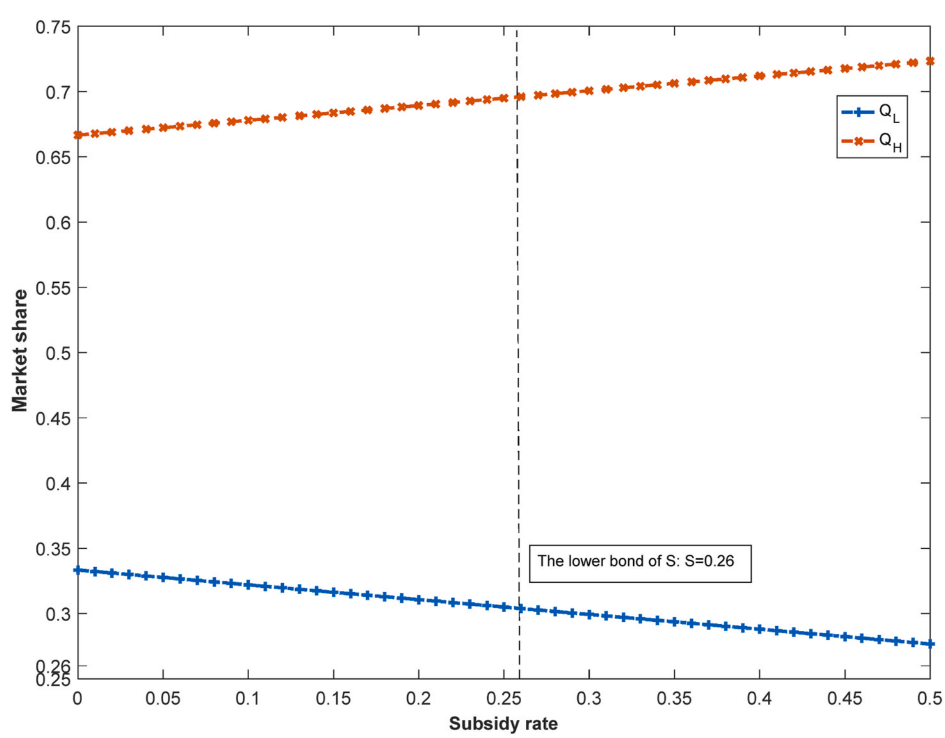

Fig. 3. The market shares of the two firms under different subsidy rates.

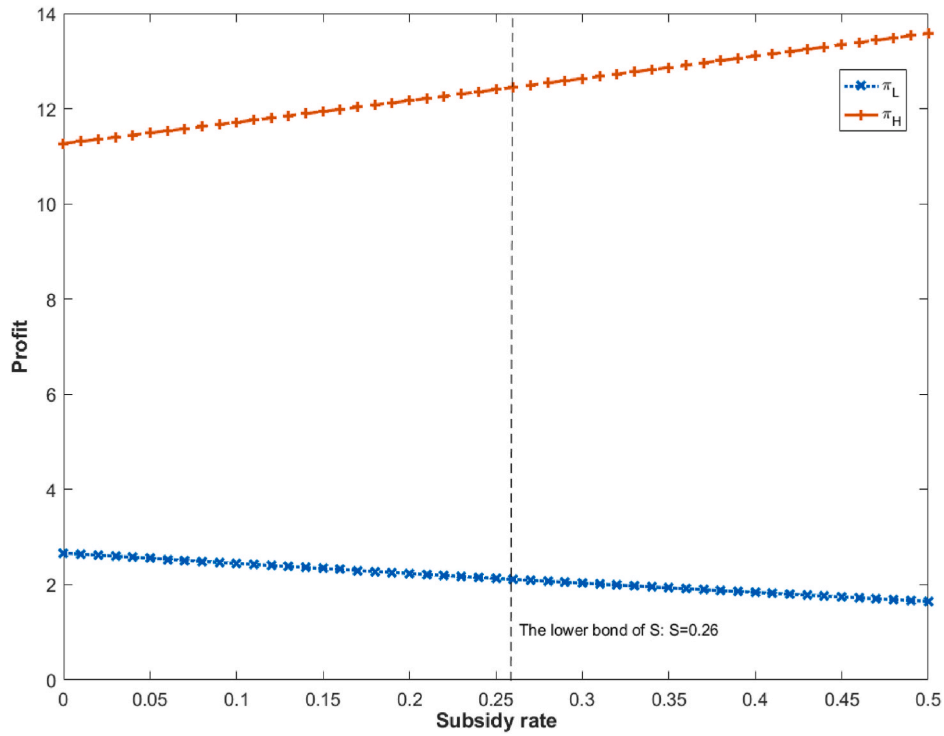

Fig. 4. The profits of the two firms under different levels of subsidy rate.

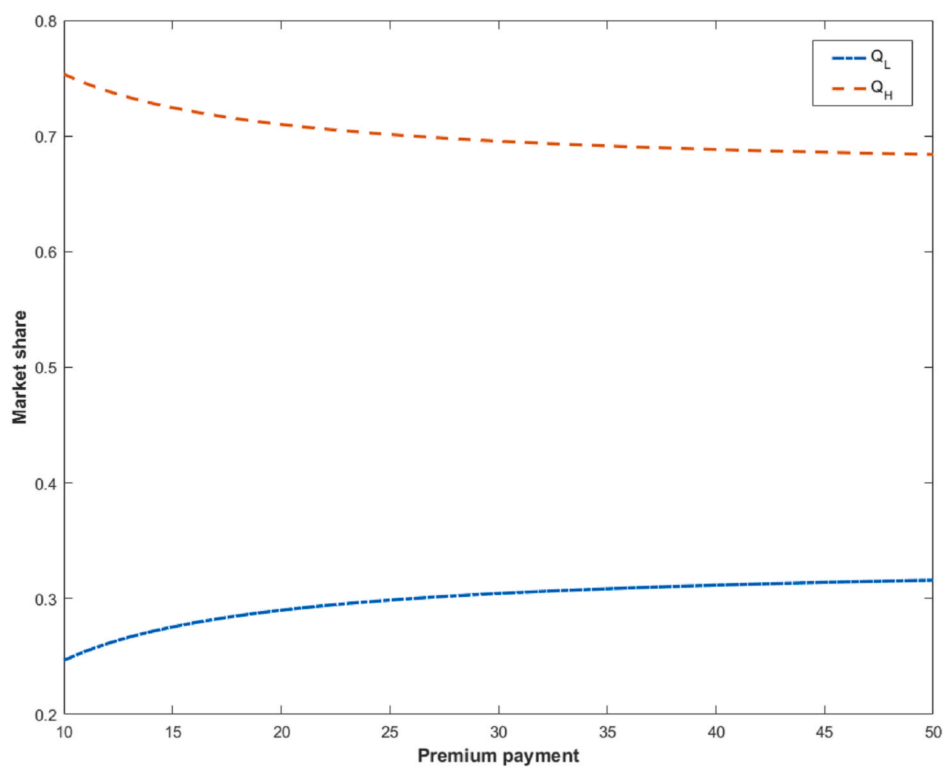

Fig. 5. The market shares of the two firms under different premium payments.

utility brought by increasing subsidies to consumers is greater than the decrease of producers' profits, so the total social welfare is improved; On the contrary, when the subsidy rate is high, the increase of utility brought by increasing subsidies to consumers is less than the decrease of producers' profits, so the total social welfare decreases. At the same time, increasing the subsidy rate declines the market share of Firm-L, which in turn implies more Product-H in a "greener" market. To that end, as seen in Fig. 7, the higher the subsidy rate, the higher the overall environmental quality. However, suppose the environmental quality is a variable in the social welfare function. In that case, the impact of the subsidy rate increase on the total social surplus depends on the changes in environmental quality and social welfare. We observe from Fig. 7 that

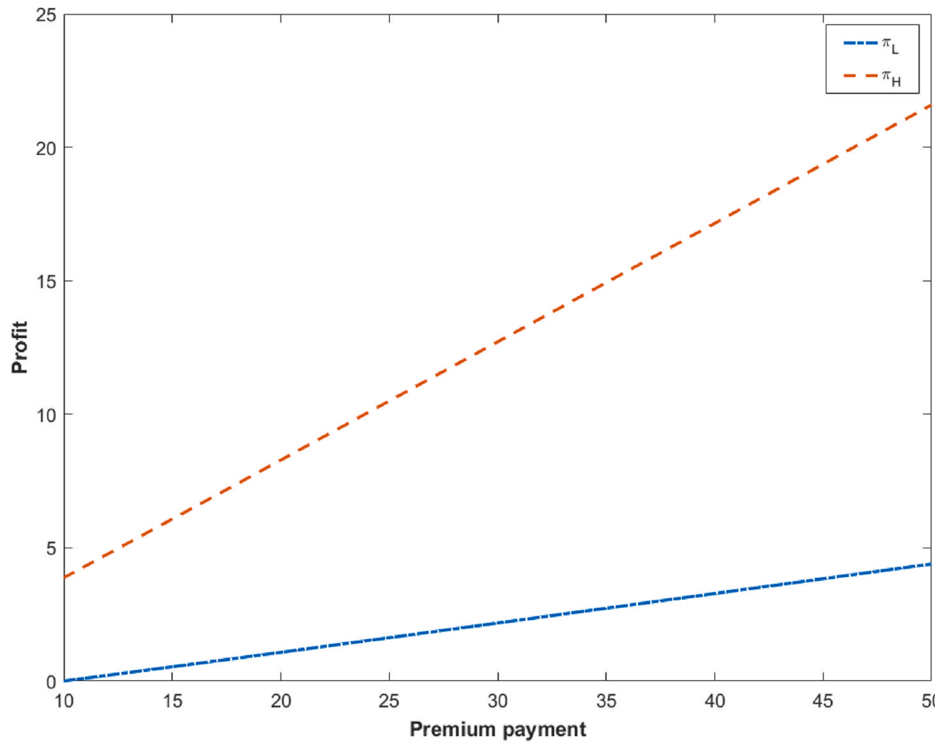

Fig. 6. The profits of the two firms under different premium payments.

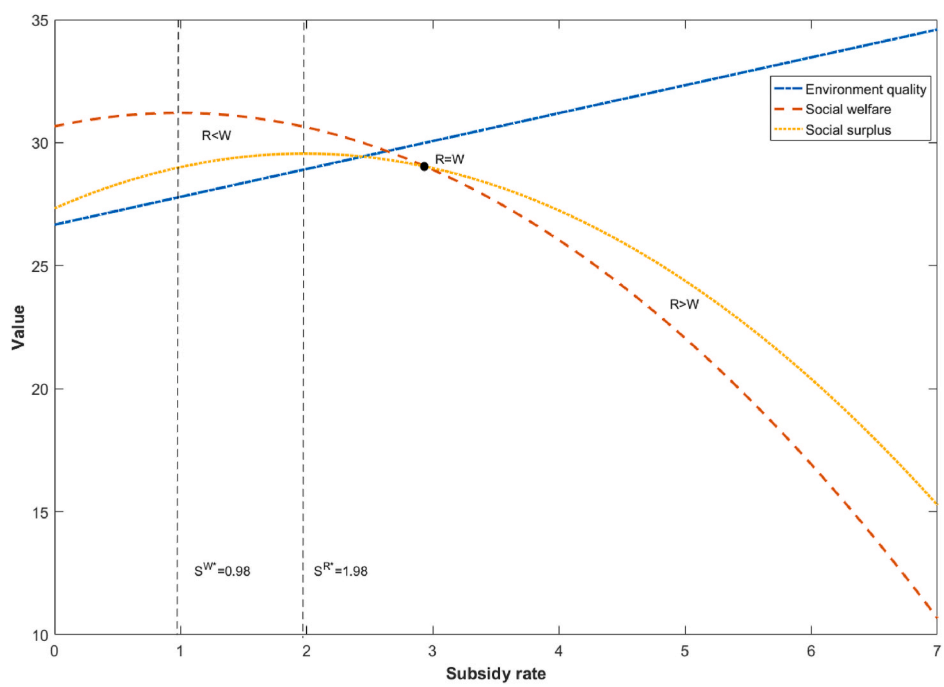

Fig. 7. The impact of the subsidy rate on environment and society.

the total social surplus function is concave in the subsidy rate. Because the social surplus includes not only the economic effects of green products but also the environmental impact, the subsidy rate needed to maximize the social surplus is higher than the optimal subsidy rate for maximizing social welfare, that is $S^{R^*} > S^{W^*}$. We also find an important phenomenon in Fig. 7: When the subsidy rate S is much higher than S^{R^*}, the apparent improvement of environmental quality will make the social surplus higher than social welfare. This phenomenon implies that setting a higher green subsidy rate by the government can significantly improve the environmental quality and make the total social surplus higher than social welfare, albeit the total social surplus may not be the highest.

We analyze the impact of consumers' premium payments on society. With the rise of premium payment, the price rise of Firm-H is greater than that of Firm-L. Since the greenness of their respective products does not change, a higher price will reduce the market share of the active firm. So the environmental quality will decrease with the increase in

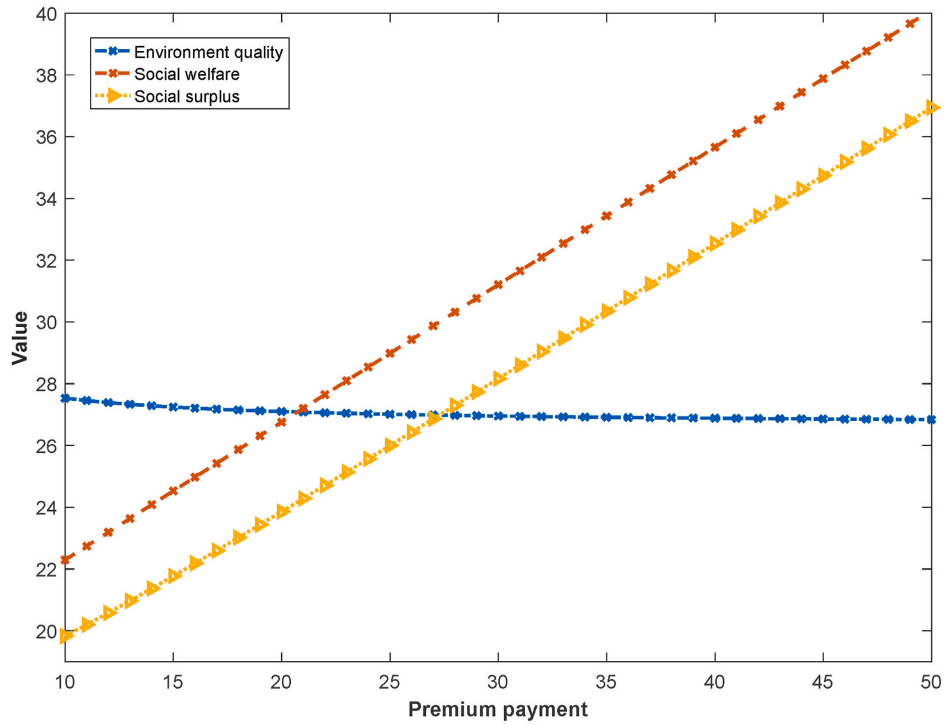

Fig. 8. The impact of premium payment on environment and society.

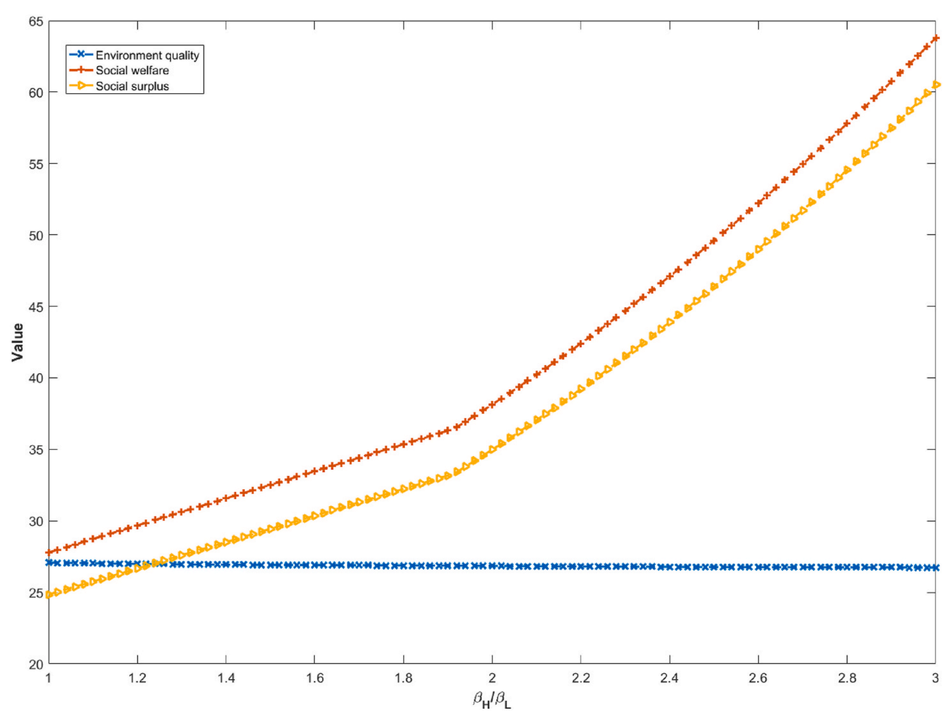

Fig. 9. The impact of cost coefficient for R&D on environment and society.

premium payment. But the social welfare and social surplus will improve with premium payment increasing as firms obtain more profit, as shown in Fig. 8.

Then, we analyze the impact of R&D cost and production cost on society. Fig. 9 shows that with the increase of cost coefficient ratio for R&D, Firm-H has a higher cost and thus, the price of Firm-H is greater than that of Firm-L. A higher price will reduce the market share of the active firm, but the greenness of their respective products stays unchanged. So the environmental quality will decrease with the increase in cost coefficient ratio for R&D, which is similar to Fig. 8. Due to the rising in R&D cost, the price increase behaviour of Firm-H will induce its competitor to follow and increase its price increase. The profit increment of these two firms is higher than the decrement of consumers' surplus, which, in turn, is reflected in the increase of social welfare and social surplus. These results imply that the increase in R&D costs is not appropriate for environmental improvement and consumers. Fig. 10

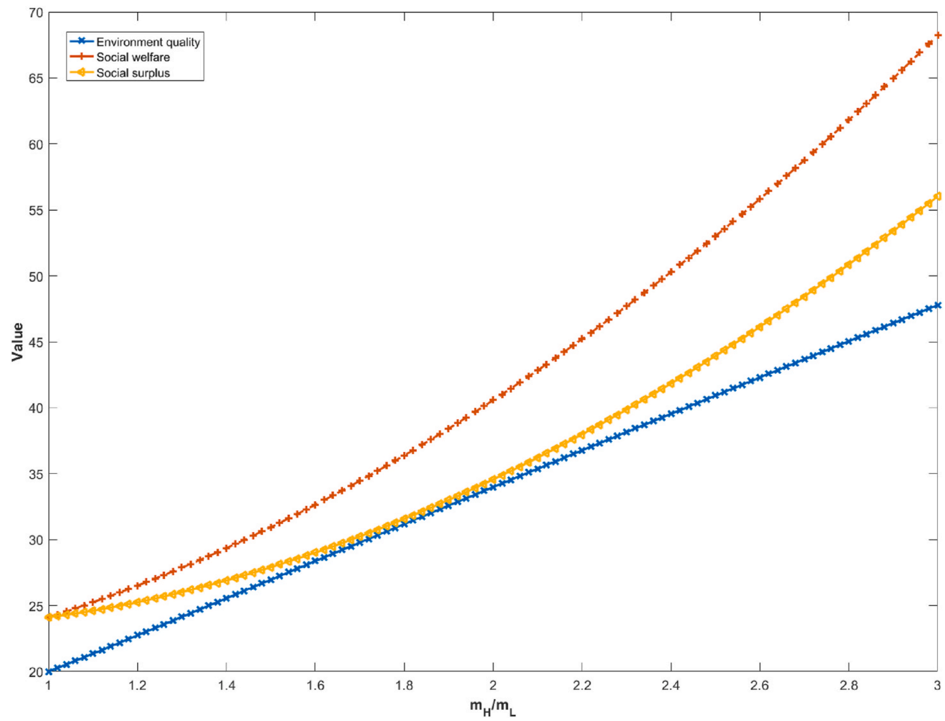

Fig. 10. The impact of production cost on environment and society.

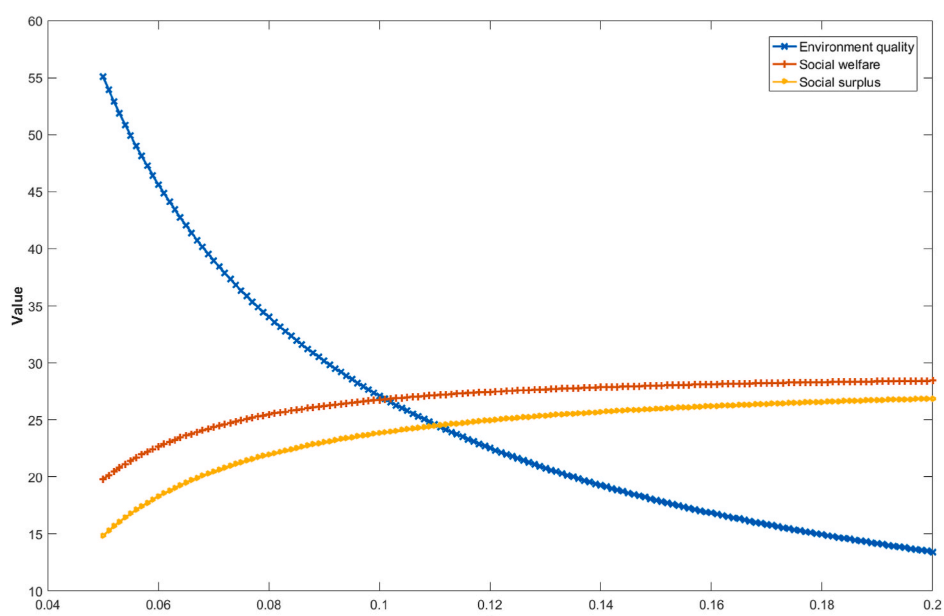

Fig. 11. The impact of reputation effect on environment and society.

presents the impact of production cost on society. Using more environmentally friendly low-carbon materials incurs higher production costs to Firm-H, but this will help improve product greenness. Higher greenness will increase market share and enhance environmental quality. The social welfare and surplus will improve with production cost increasing as firms obtain more profit (see Fig. 10).

Fig. 11 validates that the promotion of Firm-H's reputation effect is not conducive to environmental quality but beneficial to social welfare and social surplus. The reason is that the reputation effect will make firms raise their product prices. Because the product of Firm-H is greener, the price increase range is correspondingly larger than that of Firm-L. A higher price will damage the market share of Firm-H, so the environmental quality will decrease with the increase in reputation effect. The profit increment of the two firms is higher than the decrement of consumers' surplus, so the social welfare and social surplus show an upward trend. These results imply that the reputation effect can increase

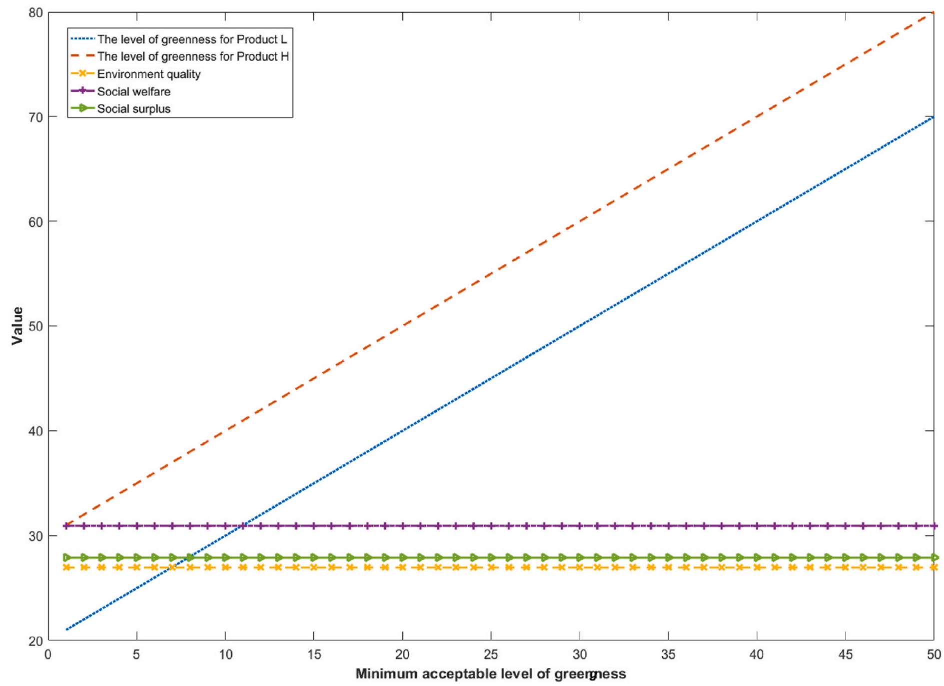

Fig. 12. The impact of minimum acceptable of greenness on environment and society.

profits for green firms, but it damages consumer surplus to a certain extent.

Finally, we analyze the impact of the minimum acceptable level of greenness ξ on society. As shown in Fig. 12, the government setting a higher ξ policy may encourage both firms to improve the greenness of their products. Under the condition of optimal subsidy, both firms produce with their firm-specific peak greenness set at a fixed level because the technological upper limit of each firm cannot be raised in a short time. Therefore, the policy parameter ξ does not affect the optimal decision of the two firms in equilibrium, thereby, the environmental quality, social welfare and social surplus.

6. Conclusions

For a duopolistic market with consumers sensitive to the product price and its environmental quality, this study explored how and under which technological constraints government subsidy strategies might improve the environmental quality by using a leader-follower Stackelberg game model between two profit-maximizing firms (the followers) and a government (the leader). We proxied the environmental quality by the weighted average greenness of these competing firms. We formulated the determination of the optimal subsidy rate in a three-step procedure: Firstly, we showed that environmental quality could be improved when both firms performed at their peak greenness. Secondly, via the backward induction method, we investigated the subsidy rate at which both firms perform at their peak greenness. Thirdly, we further studied two different subsidy strategies considering societal benefits (i.e., maximizing social welfare or social surplus) based on the two firms performing at their peak greenness. We compared the difference in environmental quality, social welfare, and social surplus based on those two strategies. This model allowed us to analyze the mutual influence between two competing firms and their interactions with the government. Moreover, our model can inform the government about designing an appropriate green subsidy policy and supporting firms in determining to what extent they should invest in greening products.

In general, we showed that the government subsidy could improve environmental quality: There is a specific matching relationship between the optimal subsidy rate and production cost, R&D cost coefficient and consumers' willingness to pay. Firstly, the competitive equilibrium results obtained for the firms showed that the provision of the government subsidy could decrease the selling prices, increase the market share for the "greener" product, and effectively improve the environmental quality. By subsidizing, the government can stimulate both types of firms to perform at their peak greenness and help improve environmental wellbeing. We showed that properly designed government subsidies could enhance the market shares and profit for greener products. Unlike Yu et al. (2016), this study factored in the consumer heterogeneity in premium payment for greener products, a more comprehensive and realistic modelling framework. Green technology innovation of firms involves three subjects: consumers, firms and government. Therefore, when the government formulates the subsidy policy, it should consider both firm-level parameters and patterns of green consumption. Simply subsidizing firms' green technology innovation without considering consumers' premium for green products may lead to the subsidy effect dampening than expected. Influencing consumers to pay higher for green products through publicity and other means may not stipulate green consumption, nor can it help reduce the environmental impacts as expected by the government. Therefore, we emphasize that encouraging firms through subsidies to invest in green technology innovation requires the government to consider consumer purchasing behaviour and sustainability attitudes.

Contrary to Hafezalkotob (2015), which demonstrated that a higher subsidy rate would increase the environmental quality, we find that a higher subsidy rate may not always simultaneously benefit the environment quality, social welfare, and the social surplus. A higher subsidy rate may result in improved environmental quality but under the condition of a higher WTP. For effective environmental policies, both WTP and subsidizing are instrumental and have to be concerted: providing a subsidy alone does not create real impact. If consumers' premium is low, it may be beneficial for the government and firms to enhance consumers' attitudes towards environmental sustainability by educating them on the immediacy and necessity of sustainable lifestyles in which awareness turns into action.

Our structural results indicate that increasing social surplus, compared to social welfare, calls for a higher subsidy, a result also demonstrated by our numerical analysis. Social surplus depends on both the economic efficiency and the environmental impact of the firms. Suppose the government only pays attention to the economic benefits of green products. In that case, it can achieve welfare improvement through a lower subsidy rate, but it is not conducive to improving the social surplus and environmental quality. However, we assert that the government should set a relatively high subsidy rate to encourage firms to increase investment in green technology and improve the greenness of products to improve the long-term environmental quality and social surplus.

We also find that a higher production cost and R&D coefficient and a lower cost-saving rate would require a higher subsidy rate. It is reasonable that a higher cost needs to be covered by a higher subsidy, which can help support firms producing with a high level of greenness. We suggest that the government should subsidize green-innovating firms timely, more so to cover the significant upfront costs. Finally, a consumer's higher WTP indicates a preference for high-grade green products over inferior or low-grade green alternatives. Higher premiums do not necessarily translate into increased environmental quality, as shown in Fig. 8. This may explain why governments spend a great deal of effort in improving WTP, but the results have not been as good as expected. Because greening products and processes require greening technology that is relatively costlier than substandard technology, firms usually stay cautious in adopting new technology. At that stage, a government subsidy for green technology may yield firms producing more greener products to meet consumers' demand and also comply with environmental imperatives. When consumers are willing to pay more for green products, the government can encourage firms to increase investment in green innovation and produce high-grade green products by subsidizing firms, which will help promote the development of the green market.

In summary, this study contributes to green supply chain management research by demonstrating how governments can design a subsidy policy to encourage firms with different green technology levels to increase the greenness of their products and manufacturing processes. Our results also add insights into the mutual influences between competing firms and their interactions with the government. This research framework can be extended to a pure competition (from duopolistic to polypolistic) with many competing firms, each of which manufactures a substitutable product yet with a distinct level of greenness to satisfy consumer demands with varying WTP. In that case, the level of greenness may be treated as a continuous decision variable. However, such an approach would impose further modelling challenges probing analytical tractability: Discretization into more than two categories (e.g., low, medium, and high levels of product greenness) could be required but with obvious added technical challenges. Nevertheless, our model in this paper based on two classifications (H and L) can serve as a stepping stone to that next level of modelling we plan to work.

In addition to extending our duopolistic model to a purely competitive one, there remains numerous further research in this burgeoning field of inquiry in government-incentivized sustainable supply chain models. With increased environmental imperatives and pressures on cost efficiency, further research could investigate the impact of cooperation between the competing firms. How would our model insights change if the government also subsidizes consumers for their green purchases? With urgency in concrete actions towards the climate crisis, how would governmental subsidy programs differ in a developing country versus a highly developed one? What would be the impact of inter-governmental subsidy programs towards sustainable development goals? These current and pressing questions warrant further research.

CRediT authorship contribution statement

Yantao Ling: Conceptualization, Investigation, Methodology, Validation, Visualization, Formal analysis, Writing – original draft, Writing – review & editing. **Jing Xu:** Conceptualization, Funding acquisition, Investigation, Methodology, Validation, Writing – original draft. **M. Ali Ülkü:** Supervision, Conceptualization, Funding acquisition, 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.

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Appendix. for Proofs

Proof of Proposition 1

The optimization problems for the two firms are defined as:

$$\max_{P_i,G_i}\pi_i = \underbrace{(P_i - m_i)Q_i}_{\text{Net sales revenue}} - \underbrace{\beta_i(G_i - g)^2}_{\text{R\&D cost}} + \underbrace{\varepsilon(G_i - g)Q_i}_{\text{Social network effect}} + \underbrace{S(G_i - g)Q_i}_{\text{Government subsidy}},\ i \in \{L, H\}, Q_L = \frac{P_H - P_L}{\overline{\theta}}, Q_H = 1 - Q_L$$
$$s.t. \quad m_i \geq \varepsilon(G_i - g).$$

To check the second-order conditions (SOC), we first find the Hessian matrix H as, $H = \begin{vmatrix} \frac{\partial^2\pi_i}{\partial P_i^2} & \frac{\partial^2\pi_i}{\partial P_i\partial G_i} \\ \frac{\partial^2\pi_i}{\partial G_i\partial P_i} & \frac{\partial^2\pi_i}{\partial G_i^2} \end{vmatrix}$. Note that H is negative definite for

$\Phi > \max\left\{\frac{m_L}{\gamma_L}, \frac{m_H}{\gamma_H}\right\}$, therefore the objective functions are concave. Then, according to (1), (3), (4), and solving for the first-order conditions (FOC) optimality condition $\frac{\partial \pi_i}{\partial G_i} = 0$, we obtain, for both firms, the optimal greenness levels as $G_L^* = \min\left\{\frac{m_L}{\varepsilon}, \frac{\varepsilon+S}{2\beta_L}Q_L\right\} + g$, and $G_H^* = \min\left\{\frac{m_H}{\varepsilon}, \frac{\varepsilon+S}{2\beta_H}Q_H\right\} + g$. Similarly, from the FOC optimality condition $\frac{\partial \pi_i}{\partial P_i} = 0$, and embedding the optimal values of the greenness levels, we determine the optimal prices as $P_L^* = \frac{2}{3}[m_L - (\varepsilon + S)(G_L^* - g)] + \frac{1}{3}[m_H - (\varepsilon + S)(G_H^* - g)] + \frac{\Phi}{3}$, and $P_H^* = \frac{1}{3}[m_L - (\varepsilon + S)(G_L^* - g)] + \frac{2}{3}[m_H - (\varepsilon + S)(G_H^* - g)] + \frac{2\Phi}{3}$. Finally, by substituting the optimal prices p_L^* and p_H^* into (3) and (4), we have $Q_L^* = \frac{1}{3} + \frac{[m_H - \varepsilon(G_H^* - g)] - [m_L - \varepsilon(G_L^* - g)]}{3\Phi}$, and $Q_H^* = \frac{2}{3} - \frac{[m_H - \varepsilon(G_H^* - g)] - [m_L - \varepsilon(G_L^* - g)]}{3\Phi}$. Note that each$G_i^*$ value can take on two different values, therefore, we need to consider all of the four possible combinations in determining optimal market shares. In order to simplify the expression, we let L^+ denote the case where Firm-L attains its highest greenness, which means $G_L^* - g = \frac{m_L}{\varepsilon}$. Similarly, L^- indicates that $G_L^* - g = \frac{(\varepsilon+S)}{2\beta_L}Q_L^*$. H^+ denotes $G_H^* - g = \frac{m_H}{\varepsilon}$, and H^- presents $G_H^* - g = \frac{\varepsilon+S}{2\beta_L}Q_H^*$. In the following analysis, we solve the four optimal market shares for passive firm, which are presented as follows:

The four different optimal market shares for Firm-H are:

When $G_L^* - g = \dfrac{(\varepsilon + S)}{2\beta_L}Q_L^*$, and $G_H^* - g = \dfrac{m_H}{\varepsilon}$, then $Q_L^{(L^-,H^+)} = \dfrac{2(\Phi - m_L - m_H S/\varepsilon)}{6\Phi - (1 + S/\varepsilon)^2\frac{m_L}{r_L}}$. (A1)

When $G_L^* - g = \dfrac{m_L}{\varepsilon}$, and $G_H^* - g = \dfrac{\varepsilon + S}{2\beta_L}Q_H^*$, then (A2)

$$\begin{cases} \text{if } \dfrac{m_H}{m_L} \le 3r_H, Q_L^{(L^+,H^-)} = \dfrac{2(2\Phi + m_H + m_L S/\varepsilon) - (1 + S/\varepsilon)^2\dfrac{m_H}{r_H}}{6\Phi - (1 + S/\varepsilon)^2\dfrac{m_H}{r_H}} \\ \text{if } \dfrac{m_H}{m_L} > 3r_H, Q_L^{(L^+,H^-)} = \dfrac{2(\Phi + m_H + m_L S/\varepsilon) - (1 + S/\varepsilon)^2\dfrac{m_H}{r_H}}{6\Phi - (1 + S/\varepsilon)^2\dfrac{m_H}{r_H}} \end{cases}$$

When $G_L^* - g = \dfrac{\varepsilon + S}{2\beta_L}Q_L^*$ and $G_H^* - g = \dfrac{\varepsilon + S}{2\beta_L}Q_H^*$, then we get $Q_L^{(L^-,H^-)} = \dfrac{2(2\Phi + \Delta m) - (1 + S/\varepsilon)^2\frac{m_H}{r_H}}{6\Phi - (1 + S/\varepsilon)^2\frac{m_L}{r_L} - (1 + S/\varepsilon)^2\frac{m_H}{r_H}}$. (A3)

When $G_L^* - g = \dfrac{m_L}{\varepsilon}$ and $G_H^* - g = \dfrac{m_H}{\varepsilon}$ we get $Q_L^{(L^+,H^+)} = \dfrac{1}{3} - \dfrac{\Delta m S/\varepsilon}{3\Phi}$ where $\Delta m = m_H - m_L$ and $r_i = \dfrac{m_i\beta_i}{\varepsilon^2}, i \in \{L, H\}$ (A4)

Proof for Analyses in Fig. 2 and Table 3

The above four optimal market shares also denote four types of equilibrium states. Now, we will discuss when the two competitive firms will choose one of the four equilibrium states. We first explore the dominant strategies for the two firms. Then, we further study the possible Nash equilibrium and its conditions that need to be met. Specifically, there are four types of dominant strategies for the two firms with no subsidy follow:

1. L^+ means that $\frac{\varepsilon}{2\beta_L}Q_{L^-}^* > \frac{m_L}{\varepsilon}$, which can be converted into

   $2\gamma_L < Q_L^{(L^-,H^-)}, Q_L^{(L^-,H^+)} < 1.$ (A5)

   Substituting (A1) and (A3) into (A5), the reasonable scope of Φ and γ are given in Table 1.

Table 1A
The reasonable scope of Φ and γ based on L^+

γ_L	γ_H	WTP
$0 < \gamma_L < 1/6$	$0 < \gamma_H < 0.5 - \gamma_L$	$\Phi_3 - 0.5m_H < \Phi < \min\{\Phi_3, \Phi_4\} \cup \Phi > \max\{\Phi_3, \Phi_4\}$
$0 < \gamma_L < 1/6$	$\gamma_H > 0.5 - \gamma_L$	$\Phi > \Phi_3$
$1/6 < \gamma_L < 1/2$	$\gamma_H > 0$	$\max\{0, \Phi_4\} < \Phi < \min\{\Phi_3 - 0.5m_H, \Phi_2\}$

2. L^- means that $\frac{\varepsilon}{2\beta_L}Q_{L^-}^* > \frac{m_L}{\varepsilon}$, which can be converted into:

   $0 < Q_L^{(L^-,H^-)}, Q_L^{(L^-,H^+)} < \min\{2\gamma_L, 1\}.$ (A6)

Substituting (A1) and (A3) into (A6), the reasonable scope of Φ and γ are given in Table 2.

Table 2A
The reasonable scope of Φ and γ based on L^-

γ_L	γ_H	WTP
$0 < \gamma_L < 1/6$	$\gamma_H > 0$	$\max\{0, \Phi_4\} < \Phi < \min\{\Phi_2, m_L\}$
$1/6 < \gamma_L < 1/2$	$\gamma_H < 0.5 - \gamma_L$	$\Phi > \Phi_4$
$1/6 < \gamma_L < 1/2$	$\gamma_H > 0.5 - \gamma_L$	$m_L < \Phi < \min\{\Phi_1, \Phi_4\} \cup \Phi > \max\{\Phi_1, \Phi_4, m_L\}$
$\gamma_L > 1/2$	$\gamma_H > 0$	$\Phi > \max\{\Phi_1, \Phi_3, m_L\}$

3. H^+ means that $\frac{\varepsilon}{2\beta_H}Q^*_{H^-} > \frac{m_H}{\varepsilon_H}$. Since $Q_L + Q_H = 1$, then the conditions can be rewritten as follows.

$$0 < Q_L^{(L^-,H^-)}, Q_L^{(L^+,H^-)} < 1 - 2\gamma_H \tag{A7}$$

Substituting (A2) and (A4) into (A7), the reasonable scope of Φ and γ are given in Table 3.

Table 3A
The reasonable scope of Φ and γ based on H^+

γ_L	γ_H	WTP
$0 < \gamma_L < 0.5 - \gamma_H$	$0 < \gamma_H < 1/3$	$\Phi_2 - m_L < \Phi < \min\{\Phi_2, \Phi_5\} \cup \Phi > \max\{\Phi_2, \Phi_5\}$
$\gamma_L > 0.5 - \gamma_H$	$0 < \gamma_H < 1/3$	$\Phi > \Phi_2$
$\gamma_L > 0$	$1/3 < \gamma_H < 1/2$	$\max\{0, \Phi_5\} < \Phi < \Phi_2 - m_L$

4. H^- means that $\frac{\varepsilon}{2\beta_H}Q^*_{H^-} < \frac{m_H}{\varepsilon_H}$, the conditions can be rewritten as follows:

$$\max\{0, 1 - 2\gamma_H\} < Q_L^{(L^-,H^-)}, Q_L^{(L^+,H^-)} < 1 \tag{A8}$$

Substituting (A2) and (A4) into (A8), the reasonable scope of Φ and γ are given in Table 4.

Table 4A
The reasonable scope of Φ and γ based on.H^-

γ_L	γ_H	WTP
$\gamma_L > 0$	$0 < \gamma_H < 1/3$	$\max\{0, \Phi_5\} < \Phi < 0.5m_H$
$\gamma_L < 0.5 - \gamma_H$	$1/3 < \gamma_H < 1/2$	$\Phi > \Phi_3$
$\gamma_L > 0.5 - \gamma_H$	$1/3 < \gamma_H < 1/2$	$0.5m_H < \Phi < \min\{\Phi_3, \Phi_5\} \cup \Phi > \max\{\Phi_3, \Phi_5\}$
$\gamma_L > 0$	$\gamma_H > 1/2$	$0.5m_H < \Phi < \min\{\Phi_2, \Phi_3\} \cup \Phi > \max\{\Phi_2, \Phi_3, 0.5m_H\}$

where $\Phi_1 = \frac{1}{6}\left(\frac{m_L}{\gamma_L} + \frac{m_H}{\gamma_H}\right)$, $\Phi_2 = \frac{1}{2}\frac{m_H}{\gamma_H} - m_H + m_L$, $\Phi_3 = \frac{1}{4}\frac{m_L}{\gamma_L} + \frac{m_H - m_L}{2}$, $\Phi_4 = \frac{\gamma_L+\gamma_H-0.5}{6\gamma_L-1}\frac{m_H}{\gamma_H}$, $\Phi_5 = \frac{\gamma_L+\gamma_H-0.5}{6\gamma_H-2}\frac{m_L}{\gamma_L}$.

Combining L^+ and L^- with H^+ and H^- respectively, we can obtain four types of equilibrium states and their conditions that need to be satisfied. The results are as follows:

i. (L^+, H^+) exists in area A_1 ($0 < \gamma_L < \frac{1}{6}$, $\gamma_L < \gamma_H < \frac{1}{3}$ and $\gamma_L = \frac{1}{6}$, $\gamma_H = \frac{1}{3}$), firm H produces the greener product $G_L^* < G_H^*$ and Φ satisfies $\Phi \geq \frac{m_L}{\gamma_L}$.

The optimal strategies are:

$$G_L^* = \frac{m_L}{\varepsilon} + g, P_L^* = \frac{\Phi}{3}, G_H^* = \frac{m_H}{\varepsilon} + g, P_H^* = \frac{2\Phi}{3}, Q_L^* = \frac{1}{3}, Q_H^* = \frac{2}{3}, \pi_H^* = \frac{4}{9}\Phi - m_H\gamma_H, \pi_L^* = \frac{\Phi}{9} - m_L\gamma_L.$$

ii. (L^+, H^-) exists in area A_2 ($0 < \gamma_L \leq \frac{1}{3}$ and $\gamma_H \geq \frac{1}{3}$) and there are two possible equilibrium results:
(a) If $\frac{m_H}{m_L} \leq 3\gamma_H$, Firm-L produces greener product, that is $G_L^* > G_H^*$. The optimal strategies are:

$$G_L^* = \frac{m_L}{\varepsilon_L} + g, \ P_L^* = \frac{\Phi}{3}\left[2 + \frac{(6\gamma_H - 1)m_H}{6\gamma_H\overline{\theta} - m_H}\right], \ G_H^* = \frac{\Phi - m_H}{6\gamma_H\Phi - m_H}\frac{m_H}{\varepsilon_H} + g, \ P_H^* = \frac{\Phi}{3}\left[1 + \frac{(6\gamma_H - 1)m_H}{6\gamma_H\Phi - m_H}\right].$$

$$Q_L^* = \frac{2\gamma_H(2\Phi + m_H) - m_H}{6\gamma_H\Phi - m_H}, \text{ and } Q_H^* = \frac{2\gamma_H(\Phi - m_H)}{6\gamma_H\Phi - m_H}, \pi_H^* = Q_H^{*2}\left(\overline{\theta} - \frac{1}{4}\frac{m_H}{\gamma_H}\right), \text{ and } \pi_L^* = Q_L^{*2}\overline{\theta} - m_L\gamma_L,$$

where $\Phi \geq \max\left\{9m_L\gamma_L, \frac{m_L}{\gamma_L}, \frac{m_H}{\gamma_H}\right\}$.

(b) If $\frac{m_H}{m_L} > 3\gamma_H$, firm *H* produce greener product $G_L^* < G_H^*$. The optimal strategies are:

$$G_L^* = \frac{m_L}{\varepsilon_L} + g, \ P_L^* = \frac{\Phi}{3}\left[1 + \frac{(6\gamma_H - 2)m_H}{6\gamma_H\Phi - m_H}\right]; \ G_H^* = \frac{2\Phi - m_H}{6\gamma_H\Phi - m_H}\frac{m_H}{\varepsilon_H} + g, \ P_H^* = \frac{2\Phi}{3}\left[1 + \frac{(6\gamma_H - 2)m_H}{6\gamma_H\Phi - m_H}\right].$$

$$Q_{\mathrm{L}}^{*}=\frac{2\gamma_{\mathrm{H}}(\Phi+m_{\mathrm{H}})-m_{\mathrm{H}}}{6\gamma_{\mathrm{H}}\Phi-m_{\mathrm{H}}},\ Q_{\mathrm{H}}^{*}=\frac{2\gamma_{\mathrm{H}}(2\Phi-m_{\mathrm{H}})}{6\gamma_{\mathrm{H}}\Phi-m_{\mathrm{H}}},\ \pi_{\mathrm{H}}^{*}=Q_{\mathrm{H}}^{*2}\left(\Phi-\frac{1}{4}\frac{m_{\mathrm{H}}}{\gamma_{\mathrm{H}}}\right),\ \pi_{\mathrm{L}}^{*}=Q_{\mathrm{L}}^{*2}\Phi-m_{\mathrm{L}}\gamma_{\mathrm{L}},$$

where $\Phi\geq\max\left\{9m_{\mathrm{L}}\gamma_{\mathrm{L}},\frac{m_{\mathrm{L}}}{\gamma_{\mathrm{L}}},\frac{m_{\mathrm{H}}}{\gamma_{\mathrm{H}}}\right\}$.

iii. $(\mathrm{L}^-,\mathrm{H}^+)$ exists in area A_3 ($\frac{1}{6}\leq\gamma_{\mathrm{L}}<\frac{1}{3}$ and $\gamma_{\mathrm{L}}<\gamma_{\mathrm{H}}\leq\frac{1}{3}$), firm H produce greener product $G_{\mathrm{L}}^{*}<G_{\mathrm{H}}^{*}$ and Φ satisfies $\Phi\geq\frac{m_{\mathrm{L}}}{\gamma_{\mathrm{L}}}$. The optimal strategies are:

$$G_{\mathrm{L}}^{*}=\frac{\Phi-m_{\mathrm{L}}}{6\gamma_{\mathrm{L}}\Phi-m_{\mathrm{L}}}\frac{m_{\mathrm{L}}}{\varepsilon_{\mathrm{L}}}+g,\ P_{\mathrm{L}}^{*}=\frac{\Phi}{3}\left[1+\frac{2(6\gamma_{\mathrm{L}}-1)m_{\mathrm{L}}}{6\gamma_{\mathrm{L}}\Phi-m_{\mathrm{L}}}\right],\ G_{\mathrm{H}}^{*}=\frac{m_{\mathrm{H}}}{\varepsilon_{\mathrm{H}}}+g,\ P_{\mathrm{H}}^{*}=\frac{\Phi}{3}\left[2+\frac{(6\gamma_{\mathrm{L}}-1)m_{\mathrm{L}}}{6\gamma_{\mathrm{L}}\Phi-m_{\mathrm{L}}}\right].$$

$$Q_{\mathrm{L}}^{*}=\frac{2\gamma_{\mathrm{L}}(\Phi-m_{\mathrm{L}})}{6\gamma_{\mathrm{L}}\Phi-m_{\mathrm{L}}},\ Q_{\mathrm{H}}^{*}=\frac{2\gamma_{\mathrm{L}}(2\Phi+m_{\mathrm{L}})-m_{\mathrm{L}}}{6\gamma_{\mathrm{L}}\Phi-m_{\mathrm{L}}},\ \pi_{\mathrm{H}}^{*}=Q_{\mathrm{H}}^{*2}\Phi-m_{\mathrm{H}}\gamma_{\mathrm{H}},\pi_{\mathrm{L}}^{*}=Q_{\mathrm{L}}^{*2}\left(\Phi-\frac{1}{4}\frac{m_{\mathrm{L}}}{\gamma_{\mathrm{L}}}\right).$$

iv. $(\mathrm{L}^-,\mathrm{H}^-)$ exist in area A_4 ($\frac{1}{3}<\gamma_{\mathrm{L}}<\gamma_{\mathrm{H}}$ and $\gamma_{\mathrm{H}}>\frac{1}{3}$) and firm L produce greener product. The optimal strategies are:

$$G_{\mathrm{L}}^{*}=\frac{\Phi-\Phi_7}{3(\Phi-\Phi_1)}\frac{\varepsilon_{\mathrm{L}}}{\beta_{\mathrm{L}}}+g,\ G_{\mathrm{H}}^{*}=\frac{\Phi-\Phi_6}{6(\Phi-\Phi_1)}\frac{\varepsilon_{\mathrm{H}}}{\beta_{\mathrm{H}}}+g,\ P_{\mathrm{H}}^{*}=\frac{\Phi}{3}+\frac{[2\gamma_{\mathrm{L}}(6\gamma_{\mathrm{H}}-1)m_{\mathrm{H}}+2\gamma_{\mathrm{H}}(3\gamma_{\mathrm{L}}-1)m_{\mathrm{L}}]\Phi-3(\gamma_{\mathrm{L}}+\gamma_{\mathrm{H}}-0.5)m_{\mathrm{L}}m_{\mathrm{H}}}{18\gamma_{\mathrm{L}}\gamma_{\mathrm{H}}(\Phi-\Phi_1)},$$

$$P_{\mathrm{L}}^{*}=\frac{2\Phi}{3}+\frac{[\gamma_{\mathrm{L}}(6\gamma_{\mathrm{H}}-1)m_{\mathrm{H}}+4\gamma_{\mathrm{H}}(3\gamma_{\mathrm{L}}-1)m_{\mathrm{L}}]\Phi-3(\gamma_{\mathrm{L}}+\gamma_{\mathrm{H}}-0.5)m_{\mathrm{L}}m_{\mathrm{H}}}{18\gamma_{\mathrm{L}}\gamma_{\mathrm{H}}(\Phi-\Phi_1)},\ Q_{\mathrm{L}}^{*}=\frac{2(\Phi-\Phi_7)}{3(\Phi-\Phi_1)},\ Q_{\mathrm{H}}^{*}=\frac{\Phi-\Phi_6}{3(\Phi-\Phi_1)}.$$

$$\pi_{\mathrm{H}}^{*}=Q_{\mathrm{H}}^{*2}\left(\Phi-\frac{1}{4}\frac{m_{\mathrm{H}}}{\gamma_{\mathrm{H}}}\right),\ \pi_{\mathrm{L}}^{*}=Q_{\mathrm{L}}^{*2}\left(\Phi-\frac{1}{4}\frac{m_{\mathrm{L}}}{\gamma_{\mathrm{L}}}\right),\ \text{where } \Phi\geq\max\left\{\frac{m_{\mathrm{L}}}{\gamma_{\mathrm{L}}},\frac{m_{\mathrm{H}}}{\gamma_{\mathrm{H}}}\right\},\ \text{and } \Phi_6=\frac{1}{2}\frac{m_{\mathrm{L}}}{\gamma_{\mathrm{L}}}-m_{\mathrm{L}}+m_{\mathrm{H}},\ \Phi_7=\frac{1}{4}\frac{m_{\mathrm{H}}}{\gamma_{\mathrm{H}}}+\frac{m_{\mathrm{L}}-m_{\mathrm{H}}}{2}.$$

Proof of Proposition 2

1. $E_0^{(\mathrm{L}^+,\mathrm{H}^+)}-E_0^{(\mathrm{L}^-,\mathrm{H}^+)}=\frac{(6r_{\mathrm{L}}-1)m_L}{3[6r_{\mathrm{L}}\Phi-m_L]^2\varepsilon}[6r_{\mathrm{L}}\Phi^2-6r_{\mathrm{L}}m_{\mathrm{H}}\Phi+\Delta mm_{\mathrm{L}}]\rangle 0.$

2. $$E_0^{(\mathrm{L}^+,\mathrm{H}^+)}-E_0^{(\mathrm{L}^+,\mathrm{H}^-)}=\begin{cases}\dfrac{2r_{\mathrm{H}}^2}{[6r_{\mathrm{H}}\Phi-m_{\mathrm{H}}]^2}\left[\Omega_1\Phi^2+\Omega_2\Phi+\Omega_3\right].>0,\ if\dfrac{m_{\mathrm{H}}}{m_{\mathrm{L}}}\leq 3r_{\mathrm{H}},\\ \dfrac{(3r_{\mathrm{H}}-1)m_{\mathrm{H}}}{3[6r_{\mathrm{L}}\Phi-m_{\mathrm{L}}]^2\varepsilon}\left[24r_{\mathrm{H}}\Phi^2-12r_{\mathrm{H}}m_{\mathrm{L}}\Phi+2m_{\mathrm{H}}\Delta m\right].>0,\ if\dfrac{m_{\mathrm{H}}}{m_{\mathrm{L}}}>3r_{\mathrm{H}}.\end{cases}$$

3. $E_0^{(\mathrm{L}^+,\mathrm{H}^+)}-E_0^{(\mathrm{L}^-,\mathrm{H}^-)}=\frac{2\varepsilon}{\Phi_1}\left[\Omega_4\Phi^2+\Omega_5\Phi+\Omega_6\right]>0$ where

$$\Omega_1=6\frac{m_{\mathrm{L}}}{\varepsilon}+\frac{\varepsilon}{\beta_{\mathrm{H}}}-12\frac{m_{\mathrm{H}}}{\varepsilon}<0,\Omega_2=2\frac{m_{\mathrm{H}}\varepsilon}{\beta_{\mathrm{H}}}+6\frac{m_{\mathrm{H}}m_{\mathrm{L}}}{\varepsilon}-3\frac{m_{\mathrm{L}}\varepsilon}{\beta_{\mathrm{H}}},\quad \Omega_3=\frac{m_{\mathrm{H}}^2\varepsilon}{\beta_{\mathrm{H}}}-\frac{m_{\mathrm{H}}\varepsilon^3}{3\beta_{\mathrm{H}}^2}-\frac{m_{\mathrm{L}}\varepsilon}{\beta_{\mathrm{H}}}\left(m_{\mathrm{H}}-\frac{1}{3}\frac{m_{\mathrm{L}}}{\gamma_{\mathrm{H}}}\right),\Omega_4=\frac{1}{2\beta_{\mathrm{H}}}+\frac{1}{\beta_{\mathrm{L}}}-\frac{3\gamma_{\mathrm{L}}}{\beta_{\mathrm{L}}}-\frac{6\gamma_{\mathrm{H}}}{\beta_{\mathrm{H}}}<0,$$

$$\Omega_5=\frac{3}{2\beta_{\mathrm{H}}}\frac{m_{\mathrm{L}}}{\gamma_{\mathrm{L}}}-\frac{m_{\mathrm{H}}-m_{\mathrm{L}}}{\beta_{\mathrm{H}}}-2\frac{m_{\mathrm{H}}}{\beta_{\mathrm{L}}}-\frac{m_{\mathrm{L}}}{\beta_{\mathrm{H}}}-\frac{2m_{\mathrm{H}}-m_{\mathrm{L}}}{\beta_{\mathrm{L}}},\ \text{and}\ \Omega_6=\frac{m_{\mathrm{H}}}{\gamma_{\mathrm{H}}}\left(\frac{\Delta m}{2\beta_{\mathrm{L}}}-\frac{m_{\mathrm{H}}}{6}-\frac{1}{3}\frac{m_{\mathrm{H}}}{\beta_{\mathrm{L}}}\right)+\frac{m_{\mathrm{L}}}{\gamma_{\mathrm{L}}}\left(\frac{1}{8\beta_{\mathrm{H}}}\frac{m_{\mathrm{L}}}{\gamma_{\mathrm{L}}}-\frac{m_{\mathrm{H}}}{6}\right).$$

Proof of Corollary 1

$$E_1^{(\mathrm{L}^+,\mathrm{H}^+)}=Q_{\mathrm{L},1}^{(\mathrm{L}^+,\mathrm{H}^+)}.\frac{m_{\mathrm{L}}}{\varepsilon}+Q_{\mathrm{H},1}^{(\mathrm{L}^+,\mathrm{H}^+)}.\frac{m_{\mathrm{H}}}{\varepsilon}=\left(\frac{1}{3}-\frac{\Delta mS}{3\Phi\varepsilon}\right)\frac{m_{\mathrm{L}}}{\varepsilon}+\left(\frac{2}{3}+\frac{\Delta mS}{3\Phi\varepsilon}\right)\frac{m_{\mathrm{H}}}{\varepsilon}$$

$$E_0^{(\mathrm{L}^+,\mathrm{H}^+)}=Q_{\mathrm{L},0}^{(\mathrm{L}^+,\mathrm{H}^+)}.\frac{m_{\mathrm{L}}}{\varepsilon}+Q_{H,0}^{(L^+,H^+)}.\frac{m_{\mathrm{H}}}{\varepsilon}=\frac{1}{3}\frac{m_{\mathrm{L}}}{\varepsilon}+\frac{2}{3}\frac{m_{\mathrm{H}}}{\varepsilon}$$

$$E_1^{(\mathrm{L}^+,\mathrm{H}^+)}-E_0^{(\mathrm{L}^+,\mathrm{H}^+)}=\frac{S\Delta m^2}{3\Phi\varepsilon^2}>0$$

Proof of Proposition 3

$\frac{2\gamma_L}{1+S/\varepsilon} < Q_L^{(L^-,H^-)}, Q_L^{(L^-,H^+)} < 1 \cap 0 < Q_L^{(L^-,H^-)}, Q_L^{(L^+,H^-)} < 1 - \frac{2\gamma_H}{1+S/\varepsilon}$ can be rewritten as the following system of inequalities:

$$\begin{cases} \dfrac{2\gamma_L}{1+S/\varepsilon} < Q_L^{(L^-,H^-)} < 1 - \dfrac{2\gamma_H}{1+S/\varepsilon} \\ \dfrac{2\gamma_L}{1+S/\varepsilon} < Q_L^{(L^-,H^+)} < 1 \\ 0 < Q_L^{(L^+,H^-)} < 1 - \dfrac{2\gamma_H}{1+S/\varepsilon} \end{cases}$$

Plugging Equations 9–11 into the above inequalities, we can obtain that

$$\begin{cases} \dfrac{2\gamma_L}{1+S/\varepsilon} < \dfrac{2(2\Phi+\Delta m)-(1+S/\varepsilon)^2\dfrac{m_H}{r_H}}{6\Phi-(1+S/\varepsilon)^2\dfrac{m_L}{r_L}-(1+S/\varepsilon)^2\dfrac{m_H}{r_H}} < 1 - \dfrac{2\gamma_H}{1+S/\varepsilon} \\ \dfrac{2\gamma_L}{1+S/\varepsilon} < \dfrac{2(\Phi - m_L - m_H S/\varepsilon)}{6\Phi-(1+S/\varepsilon)^2\dfrac{m_L}{r_L}} < 1 \quad \text{and} \end{cases}$$

$$\begin{cases} \dfrac{2(\Phi+m_H+m_L S/\varepsilon)-(1+S/\varepsilon)^2\dfrac{m_H}{r_H}}{6\Phi-(1+S/\varepsilon)^2\dfrac{m_H}{r_H}} > 0 \\ \dfrac{2(2\Phi+m_H+m_L S/\varepsilon)-(1+S/\varepsilon)^2\dfrac{m_H}{r_H}}{6\Phi-(1+S/\varepsilon)^2\dfrac{m_H}{r_H}} < 1 - \dfrac{2\gamma_H}{1+S/\varepsilon} \end{cases}$$

For the inequalities $\frac{2\gamma_L}{1+S/\varepsilon} < \frac{2(2\Phi+\Delta m)-(1+S/\varepsilon)^2\frac{m_H}{r_H}}{6\Phi-(1+S/\varepsilon)^2\frac{m_L}{r_L}-(1+S/\varepsilon)^2\frac{m_H}{r_H}} < 1 - \frac{2\gamma_H}{1+S/\varepsilon}$, the left side

$$\frac{2\gamma_L}{1+S/\varepsilon} < \frac{2(2\Phi+\Delta m)-(1+S/\varepsilon)^2\frac{m_H}{r_H}}{6\Phi-(1+S/\varepsilon)^2\frac{m_L}{r_L}-(1+S/\varepsilon)^2\frac{m_H}{r_H}} \Rightarrow S/\varepsilon > \max\{3r_L-1, 6r_H-1\}, \overset{r_H>r_L}{\Rightarrow} S/\varepsilon > \max\{3r_L-1, 6r_H-1\}$$

and the right side

$$\frac{2(2\Phi+\Delta m)-(1+S/\varepsilon)^2\frac{m_H}{r_H}}{6\Phi-(1+S/\varepsilon)^2\frac{m_L}{r_L}-(1+S/\varepsilon)^2\frac{m_H}{r_H}} < 1 - \frac{2\gamma_H}{1+S/\varepsilon} \Rightarrow \left(\frac{6}{1+S/\varepsilon}r_H - 1\right)\Phi < m_H S/\varepsilon + (1+S/\varepsilon)\frac{\beta_H}{\beta_L}m_H + m_L - \frac{(1+S/\varepsilon)^2}{2}\frac{m_L}{r_L}.$$

For the inequalities $\frac{2\gamma_L}{1+S/\varepsilon} < \frac{2(\Phi-m_L-m_H S/\varepsilon)}{6\Phi-(1+S/\varepsilon)^2\frac{m_L}{r_L}} < 1 \Rightarrow 4\Phi > (1+S/\varepsilon)^2\frac{m_L}{r_L} - 2m_L$.

For the system of inequalities, we have

$$\begin{cases} \dfrac{2(\Phi+m_H+m_L S/\varepsilon)-(1+S/\varepsilon)^2\dfrac{m_H}{r_H}}{6\Phi-(1+S/\varepsilon)^2\dfrac{m_H}{r_H}} > 0 \Rightarrow 2\Phi > \dfrac{m_H}{\gamma_H}(1+S/\varepsilon)^2 - 2m_H - 2m_L S/\varepsilon \\ \dfrac{2(2\Phi+m_H+m_L S/\varepsilon)-(1+S/\varepsilon)^2\dfrac{m_H}{r_H}}{6\Phi-(1+S/\varepsilon)^2\dfrac{m_H}{r_H}} < 1 - \dfrac{2\gamma_H}{1+S/\varepsilon} \Rightarrow \left(\dfrac{6r_H}{1+S/\varepsilon} - 2\right)\Phi < \dfrac{S}{\varepsilon}m_H \end{cases}$$

By combining the results above, Proposition 3 is proved. □

Proof of Proposition 4

Using first-order derivatives, we can show the impact of Δm on firms' decision-making and environmental quality are as follows:

$$\frac{\partial P_{\mathrm{L}}^{*}}{\partial \Delta m} = -\frac{S}{3\varepsilon} < 0,\ \frac{\partial P_{\mathrm{H}}^{*}}{\partial \Delta m} = -\frac{2S}{3\varepsilon} < 0,\ \frac{\partial Q_{\mathrm{L}}^{*}}{\partial \Delta m} = -\frac{S}{3\Phi\varepsilon} < 0,\ \frac{\partial Q_{\mathrm{H}}^{*}}{\partial \Delta m} = \frac{S}{3\Phi\varepsilon} > 0,\ \frac{\partial E_1}{\partial \Delta m} = \frac{(m_{\mathrm{H}} - m_{\mathrm{L}})S}{3\Phi\varepsilon^2} > 0.$$

Again, with first-order derivatives, we can show the impact of Φ on equilibrium results and environmental quality as follows:

$$\frac{\partial Q_{\mathrm{L}}^{*}}{\partial \Phi} = \frac{\Delta m S}{3\varepsilon\Phi^2} > 0,\ \frac{\partial Q_{\mathrm{H}}^{*}}{\partial \Phi} = -\frac{\Delta m S}{3\varepsilon\Phi^2} < 0,\ \frac{\partial P_{\mathrm{H}}^{*}}{\partial \Phi} = \frac{2}{3} > 0,\ \frac{\partial P_{\mathrm{L}}^{*}}{\partial \Phi} = \frac{1}{3} > 0,\ \frac{\partial \pi_{\mathrm{H}}^{*}}{\partial \Phi} = \frac{(2\Phi - \Delta m S/\varepsilon)Q_H^{*}}{3\Phi} = \frac{Q_L^{*}Q_H^{*} + \Phi Q_H^{*}}{3\Phi} > 0,$$
$$\frac{\partial \pi_{\mathrm{L}}^{*}}{\partial \Phi} = \frac{(\Phi + \Delta m S/\varepsilon)Q_L^{*}}{3\Phi} = \frac{Q_L^{*}Q_H^{*} - \Phi Q_L^{*}}{3\Phi} > 0,\ \mathit{and}\ \frac{\partial E_1}{\partial \Phi} = -\frac{\Delta m S(m_{\mathrm{H}} - m_{\mathrm{L}})}{3\varepsilon^2\Phi^2} < 0.$$

Proof of Proposition 5

$\frac{\partial S^{\mathrm{C}}}{\partial S} = \frac{3\Delta m(1+Q_{\mathrm{L}})\varepsilon + \Delta m\varepsilon + 9m_{\mathrm{L}}\varepsilon}{9} > 0,\ \frac{\partial X^{\mathrm{G}}}{\partial S} = \frac{(m_{\mathrm{L}}+2m_{\mathrm{H}})\varepsilon}{3} + \frac{2\Delta m^2 S}{3\Phi} > 0.$ □

Proof of Proposition 6

From Eq. (22), $W = S^{\mathrm{C}} + S^{\mathrm{P}} - X^{\mathrm{G}} = -\frac{\Delta m^2}{6\Phi}\left(\frac{S}{\varepsilon}\right)^2 + \frac{\Delta m}{9}\frac{S}{\varepsilon} + \frac{4\Phi}{9} + WTP - m_{\mathrm{H}}\gamma_{\mathrm{H}} - m_{\mathrm{L}}\gamma_{\mathrm{L}}$. The FOC implies $\frac{\partial W}{\partial S} = 0 \Rightarrow S = \frac{\Phi\varepsilon}{3\Delta m}$, and from the SOC, $\frac{\partial^2 W}{\partial S^2} = -\frac{\Delta m^2}{3\Phi\varepsilon^2} < 0$. Hence, the social welfare function W is concave with respect to S, and the subsidy rate that maximizing the social welfare is $S^{W^*} = \frac{\Phi\varepsilon}{3\Delta m}$. □

Proof of Proposition 7

Recall $R = S^{\mathrm{C}} + S^{\mathrm{P}} - X^{\mathrm{G}} + E = -\frac{\Delta m^2}{6\Phi}\left(\frac{S}{\varepsilon}\right)^2 + \left(\frac{\Delta m}{9} + \frac{\Delta m^2}{3\Phi\varepsilon}\right)\frac{S}{\varepsilon} + \frac{4\Phi}{9} - \frac{\Delta m}{3\varepsilon} + WTP - m_{\mathrm{H}}\gamma_{\mathrm{H}} - m_{\mathrm{L}}\gamma_{\mathrm{L}}$. The FOC implies $\frac{\partial R}{\partial S} = 0 \Rightarrow S = \frac{\Phi\varepsilon}{3\Delta m} + 1$, and the SOC implies $\frac{\partial^2 R}{\partial S^2} = -\frac{\Delta m^2}{3\Phi\varepsilon^2} < 0$. Therefore, the social welfare function R is concave with respect to α, and the subsidy rate that maximizing the social welfare is $S^{R,*} = \frac{\Phi\varepsilon}{3\Delta m} + 1$.

Proof of Proposition 8

(Sketch) It is straightforward but somewhat laborious. Working through the closed-form terms by some algebra leads to those comparisons.

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