Green technology upgrading choice in a competitive setting: the effect of environmental tax

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Abstract

Environmental pollution and energy crisis have exerted pressures on firms' green production technology and regulators have enacted many policies to motivate firms to shift toward green production. However, fierce competition and huge financial burdens associated with green technology upgrading have caused inertia. This research considers a supply chain consisting of a regulator and two symmetric firms where the regulator influences the market by imposing a tax on firms' environmental pollutant emissions and the two firms compete by selling substitutable products to the market. A price competition model is proposed to examine the equilibrium solutions that the two firms can reach in their technology upgrading process, and the effect of the environmental tax is evaluated. The two firms' Nash equilibrium solutions regarding their technology improvement decision show that there is no asymmetric equilibrium. The decision to upgrade or not upgrade may arise in equilibrium, depending on the technology's fixed cost. Besides, a prisoner's dilemma may arise when the two firms do not upgrade their technology, and multiple equilibria may arise when the fixed cost incurred is at a medium level. Technology improvement decision is the dominant strategy when either prisoner's dilemma arises or multiple equilibria arise for the two firms regardless of whether the environmental tax is exogenous given or not. In addition, firms' reactions to environmental tax may be non-monotone: the two firms may make technology improvement decisions in response to an initial increase in tax. However, the role of the tax on firms' improvement decisions is limited when the regulator further increases the tax. Finally, the optimal tax level for the regulator that can maximize welfare is obtained to illustrate how should the regulator set the tax level according to the equilibrium solutions between the two firms.

Keywords: Technology upgrading; green supply chain management; game theory; environmental tax

1. Introduction

In recent years, energy crises and environmental pollution have become regular topics of discussion in the media. For instance, U.S. Energy Information Administration (EIA) forecasted that global consumption of energy would increase by 50% from 2005 to 2030 (Yang et al., 2021). The accelerated pace of energy consumption has led to an energy shortage crisis and serious environmental pollution. Consequently, many firms are investing in green technologies such that the products can consume less energy and are more environmentally friendly. A number of alternative pollution abatement technologies have been developed by many firms in many industries. For instance, for the automobile industry, using electrical vehicles to gradually replace gasoline and diesel vehicles is the most realistic mid-term solution to reduce carbon emissions and oil dependence, is already becoming a goal for many countries including China, France, and the United States (U.S. Department of Energy., 2011; Avci et al., 2015; Weeda et al., 2012; Zhang, 2012). For the shipping industry, new sulfur requirement forces many ship operators to replace their current high-sulfur fuel oils with low-sulfur fuel oils, such as marine diesel oil, marine gas oil, very low-sulfur fuel oil, and ultra-low sulfur fuel oil (Zhu et al., 2020).

Firms' production technology improvement choice is a strategic decision for many firms and numerous factors must be taken into consideration (Khan et al., 2021b; Khan et al., 2022a). For the benefits of technology improvement, firms that upgrade their green technology can enjoy a larger market share, improve the efficiency of the product so that less pollution will be generated, and reduce the cost of causing environmental pollution. There is growing evidence of green consumerism. For instance, Li et al. (2021) argue that the adoption behavior of electric vehicles would be significantly affected by customers' environmental concerns and thereby, affecting a firm's distribution decision. Hence, firms' basic market demand will increase if they upgrade their production technology to manufacture greener products (Atasu et al., 2008; Khan et al., 2022b; Khan et al., 2022c; Xu and Wang, 2018; Yang et al., 2021). However, most of the developing processes of pollution-abatement technologies require substantial up-front capital investments and consequently, lead to variable production costs change (Krass et al., 2013). Taking the fuel desulfurization process as an example, reducing the sulfur content of fuel oil can reduce sulfur emissions during combustion. However, this requires potential refinery modifications which in turn leads to huge capital investments. For example, hydrodesulfurization is a specific hydrotreatment process that removes the sulfur content of the fuel in the middle distillates of kerosene and gas oil by using hydrogen but it may contribute to high production costs as high temperatures and high hydrogen pressure are needed in the process (Chu Van et al., 2019). The incurred capital investment costs and the consequent change in production cost will become a huge financial burden for the firms who developed those pollution-abatement technologies.

In addition to the financial burden generated by the change in cost structure, market competition also plays a vital role in firms' technology improvement decisions. Usually, there is more than one firm in the market, and the decision of one firm is affected by the decision of the other. Competition between firms not only affects the value of the improved technology but also affects the incentive of the firm which upgrades its technology. On the one hand, the firm which improves its technology may reap the market by enjoying a larger market share by tapping into the green consumer market and achieving high efficiency in removing environmental pollution. On the other hand, any additional cost incurred for the technology improvement may place the firm in a disadvantageous position if the market competition between the two firms is highly competitive. The effect of competition complicates firms' decisions in technology improvement.

In order to motivate firms to improve their technology, the regulator has used many tools to regulate the market, including consumer rebates, fines, environmental taxes, subsidies, and so on (Krass et al., 2013). Among these tools, the taxation approach is the most common because it directly addresses firms' emissions. A classic and successful example of the enaction of taxation method is the adoption of the Montreal Protocol whose aim is to eliminate the manufacture, trade, and use of ozone-destroying substances. With the enaction of the tax, global consumption of ozone-destroying substances had dropped by 70% (Krass et al., 2013). Hence, firms that do not upgrade green technology may face a huge tax burden from the regulator, leading to greater difficulty in maintaining their competitive status (Khan et al., 2021e). This gives rise to a fundamental question: how should the firm make technology improvement decisions when facing a taxation burden from the regulator? Moreover, from the perspective of the regulator, how should the regulator set its policy such that the firms in the market will upgrade to greener technology and the welfare of society be maximized?

This research aims to examine firms' technology improvement decisions in a competitive setting with the consideration of environmental tax from the regulator. We consider a supply chain consisting of a regulator and two symmetric firms where the regulator affects the market by imposing a tax on firms' environmental pollution and the two firms compete with each other by selling substitutable products. There are two kinds of technology available for firms: existing non-green technology and greener technology. We do not specify the details of the technology and in fact, there are many kinds of technology and technology upgrading methods in the market. We assume that new technology is greener than current technology in environmental pollution and that the products produced by the new technology will generate fewer pollutants. The two firms can choose between the two technologies, and we assume that either choice will not shorten the time of the product to the market. If new technology is selected, the firm which upgrades to the new technology will enjoy a large market share and generate less environmental pollutants. However, the firm also needs to incur a one-time initial fixed cost for the improvement and a higher variable cost for production (Krass et al., 2013). The regulator imposes a tax on every unit of environmental pollution generated by the firms and the pollution is measured by the production quantity of the product. The processes can be formulated as a multi-stage game, more details of the game will be introduced later. More specifically, we try to answer the following research questions:

(1) What are the equilibrium outcomes for the two firms in a competitive setting and how should one firm make a technology improvement decision with the consideration of the decision of the other?

(2) What is the impact of the environmental tax on firms' technology improvement decisions?

(3) How should the regulator set the optimal tax level so that the tax can induce more firms to improve their technology and maximize social welfare at the same time?

Our research is closely related to Krass et al. (2013) and Yang et al. (2021). They examined a firm's technology improvement decision while considering policies implemented by the regulator. In this research, we examine the impact of environmental tax imposed on a firm's environmental pollutants on a firm's green technology decision in a competitive setting. Therefore, our model and results extend the current research in several ways. First, we assume that the application of new green technology can not only increase consumers' demand for the product but also help the firm more efficiently in reducing environmental pollutants. This is because more consumers will purchase which will increase the firm's basic market demand when the produced products become greener. The greener the products, the less environmental pollutants they will emit. Second, we examine the impact of market competition on a firm's technology improvement decision. This is because market competition will influence a firm's decision by not only affecting the value of the improved technology but also the incentive of the firm and hence, fierce competition may either induce firms to make technology upgrading decisions or remain inactive towards the decision. Finally, we consider that the regulator affects the market by imposing a tax on pollutants. There are many tools that the regulators can be used to influence the market, and the taxation method is considered in this research. This is because the firms will always face a taxation burden from the regulator whether they upgrade technology or not and hence, the regulator can always affect the whole market by using taxation as a lever.

The rest of this paper is organized as follows. Previous literature that is closely related to this topic is reviewed in Section 2. Model settings and descriptions are presented in Section 3. Section 4 shows the analysis of the firms' problems and equilibrium outcomes between the two firms. How should the regulator set the optimal tax level that can maximize the total welfare is stated in Section 5. Section 6 concludes the paper. The Appendix summarizes all the proofs of the model.

2. Literature review

This research is closely related to three streams of research: (a) green supply chain management; (b) production technology choice; and (c) government intervention. Each of these will be reviewed below.

2.1. Green supply chain management

The stream of research that focuses on green supply chain management is gaining popularity among researchers in recent years, among which Agrawal et al. (2019) can serve as an overview. A number of researchers addressed green supply chain management problems from the remanufacturing perspective (Atasu et al., 2008; Ma et al., 2017; Wu and Zhou, 2019; Zhou et al., 2020; Zhou et al., 2021; Zhou and Yuen, 2021a). The main problem addressed in this stream of research is the attitude and the management of remanufacturing. In the earlier stages, many researchers have examined whether an original equipment manufacturer (OEM) should interfere with the remanufacturing market and how, when the existence of remanufactured products will cannibalize consumers' demand for new products (Ferrer and Swaminathan, 2006; Guide, 2000; Guide et al., 2003; Subramanian et al., 2013). Atasu et al. (2008) find that OEMs can use remanufacturing to defend their market share when competition exists in remanufacturing. Örsdemir et al. (2014) examine the quality design of new products for an OEM which faces competition from an independent remanufacturer, and the design of the new products will consequently affect the design of remanufactured products. Wang et al. (2017) study the impact of the quality of used products on a retailer's remanufacturing in-house or outsourced decision. Zhou et al. (2020) investigate OEM's remanufacturing authorization strategy when competition exists in the secondary market. Zhou and Yuen (2021a) examine OEM's remanufacturing strategy and mode selection when production outsourcing is used for new product production. However, we examine the general green supply chain management problem for a firm from the technology improvement perspective, not just recycling or remanufacturing. Besides, our work is similar to the above because we also consider a firm's attitude towards new green technology and how should the firm make technology improvement decisions when two types of technologies are available. These considerations are similar to a firm's attitude toward remanufacturing and the management of a green supply chain.

2.2. Production technology choice

The stringent environmental regulations motivate many firms to invest in technology so that products can generate fewer pollutants, and this stream of research is closely related to our topic.

Krass et al. (2013) investigate several important aspects of environmental taxes, fixed cost subsidies, and consumer rebates that are used to induce the firm to upgrade to green and emissions-reducing technology. They analyze the optimal policy for the firm whose goal is to maximize total profit and the social welfare maximizing policy for the regulator and find that firm's reaction to the taxes may be non-monotone: the firm may choose to upgrade to green technology with an initial increase in taxes, while with the further increase in the taxes, the firm may not improve its production technology. Alizamir et al. (2016) examine the setting of feed-in tariffs so that the regulator can accelerate the deployment of renewable energy technology with a given specific goal (minimizing total expenditure or maximizing total social welfare). Drake et al. (2016) study how the firm's technology decisions and capacity decisions are affected by emission tax and emissions cap-and-trade regulation. The technology decision in their research is whether the firm should operate in a single technology or multiple technologies. Yenipazarli (2016) states that remanufacturing can deliver many environmental benefits and hence, he examines the conditions under which the OEM should engage in remanufacturing itself when emission taxes are imposed on a firm's production quantity. Yu et al. (2016) concentrate on the decision problem faced by manufacturers who need to determine the greenness of their product, the production quantity for each green level, and the production technology selection. Li et al. (2018) study the impact of cap-and-trade policy on manufacturers' operational decisions regarding low-carbon production and sustainable energy consumption. Shen et al. (2020) apply green technology adoption to the textiles and apparel supply chain and analyze the impact of green technology improvement on the whole supply chain. Yenipazarli et al. (2020) evaluate environmental innovation by using a life-cycle approach that considers cost structure, advertising, and competition. Rahmani and Ramachandran (2021) examine detailed operational issues in technology innovation, and whether committed stopping or flexible stopping is preferable for the innovation when the deadline of the project is presented. Yang et al. (2021) also consider a firm's technology improvement decision in a competitive setting by considering government subsidies. Considering the adoption of blockchain technology, Khan et al. (2021a) show that blockchain technology and green information systems can positively promote the sustainable development of the supply chain. Consistent with this stream of research, we also examine a firm's technology improvement decision where the firm can choose between two kinds of technology, namely, current non-green technology and new greener technology. However, we investigate the firm's decision problem in a competitive setting where the firm's decision is not only affected by the operational factors of the technology improvement itself but also the decision of the other firm in the market. In addition, our model also incorporates the greenness of the technology, that is, the newly adopted technology will produce fewer pollutants.

Concerning a firm's technology decision in a competitive environment, this research is related to Wu et al. (2022) and Li et al. (2022). Wu et al. (2022) conduct a strategic analysis for adopting blockchain technology with considering the competition between two supply chains. Li et al. (2022) combine Economic Production Quantity with Economic Order Quantity models to study the mechanism of multiple carbon policies and find that mixed strategies combining remanufacturing and low-carbon investment can be both economically and environmentally friendly. This research differs from these two studies in the following dimensions. First, instead of focusing on competition between two supply chains, the research focuses on the competition between two firms that sell the same product to the market. These two kinds of competition are different in that competition between two supply chains means that each supply chain is self-organized, while competition between two firms means that these two firms are within the same supply chain, resulting in different competition impacts on the firm's technology decision. Second, this study aims to examine the impact of an environmental tax on a firm's technology improvement decision in a competitive market rather than investigating the details of the mechanism of multiple carbon policies. Finally, the impact of the role of the government on a firm's improvement decision is also considered in this study.

2.3. Government intervention

The government often affects the operations of the market by using many incentive programs to improve supply chain performance and achieve social welfare. Sheu and Chen (2012) discuss how the competition among green supply chains is affected by government financial intervention, i.e., green taxation and subsidization. They find that green taxation and green subsidization play different roles in the green supply chain, and the two policies should be used contingent on specific conditions. Cohen et al. (2016) examine the impact of government subsidies on green technology adoption with the consideration of the manufacturing industry's response where the subsidies are directly offered to consumers to motivate the suppliers to adjust their production and pricing decisions accordingly. Wang et al. (2016) argue that the carbon tariff policy implemented in developing-country firms will create a cost difference for firms in developing and developed countries and hence, they establish a price competition model to examine the impact of such tariff policies on duopoly market entry decisions. Shao et al. (2017) use the adoption of electric vehicles to examine how should the government choose between two kinds of subsidy policies: price discount or subsidy scheme. Yu et al. (2018) discuss the implementation of government subsidy policy when the goal of the policy is to improve consumer welfare, and they examine whether the subsidy should be offered to consumers who consume the product or be offered to manufacturers who produced the product. Yu et al. (2019) examine a subsidy optimization problem for a development supply chain and find that the donor's subsidy policy should consider the entity that accepts subsidy, supply chain structures, retail competition, substitutable products, and demand uncertainty. Tong et al. (2019) investigate the impact of cap-and-trade policy on a supply chain where the retailer can choose whether to promote low-carbon products and the manufacturer can decide whether to take some measures to reduce carbon emissions. Safarzadeh et al. (2020) propose a novel pricing model for new energy-efficient products and examine the policies available for policymakers to coordinate an energy-intensive supply chain. Zhou and Yuen (2021b) examine the regulator's policy in two different market structures, investigate bunker suppliers' optimal pricing strategies with and without government subsidy, and the setting of the subsidy for a government whose goal is to maximize the total social welfare. Hong et al. (2021) consider a scenario where the government offers subsidies to green products, but the subsidies can either be offered to consumers or firms, and they further examine the impact of consumers' behavior on the government's optimal policy selection. In this research, we also consider the impact of government intervention on a green supply chain. However, we assume that the regulator affects firms' decisions by imposing a tax on pollutants as from the perspective of emission, the taxation method is more efficient than other kinds of policies. In addition, taxation imposed on emissions can have a direct effect on firms' technology improvement decisions.

3. Modelling Framework

We consider a supply chain consisting of a regulator and two symmetric firms (firm 1 and firm 2). The regulator sets the environmental emission policy with the goal of maximizing total social welfare, and the two symmetric firms compete with each other in the market by selling substitutable products. Each firm can choose to upgrade its production technology or continue using the existing technology. In the following, we will introduce our key assumptions and notations considering market demand, cost structure, regulatory policy, firms' decisions, and game sequence.

3.1. Market Demand

We consider a linear duopoly market demand model to portray the competition between the two firms. The linear demand model has been widely used to model price competition in the market (Bolandifar et al., 2016; Yenipazarli, 2017). Let p_i and q_i denote the price and demand for the firm i, where $i=1$ and 2. Hence, the demand for firm i's product is given by $q_i = a - p_i + bp_{3-i}$. In the model, parameter a represents the potential market size of the two firms, and parameter b ($0 \le b \le 1$) stands for the competition intensity between the two firms. When b is equal to zero, the products sold by the two firms are completely independent and there is no market competition. As b increases, competition between the two firms becomes intense, and the firm's demand is greatly affected by the other firm's pricing decision. And the products sold by the two firms are perfectly substitutable when b is equal to 1. With the upgrading of green technology, the firms' potential market size would increase from a to $a+m$. The increase in potential market size is because the environmental innovation of the product decreases hazardous emissions and enhances products' environmental performance and thus attracting green customers to purchase. The setting that considers the market expansion effect with the adoption of green technology is consistent with previous works, such as Ghosh and Shah (2015), Yenipazarli (2017), and Yang et al. (2021).

3.2. Cost Structure

Firms need to incur both fixed and variable costs to produce a product and additional fixed and variable costs are needed if firms choose to upgrade their technology. By using the current technology, firms produce q_i units of output at the cost $K_b + c_b q_i$, where K_b and c_b stand for fixed and variable production costs. For upgrading the current technology, firms' fixed production cost will be increased from K_b to $K_b + K$, and firms' variable production cost will be increased from c_b to $c_b + c$, where $K, c \geq 0$ represents the additional costs incurred. Therefore, firms' total production cost is $K_b + K + (c_b + c)q_i$ if green technology is implemented. To focus on changes arising from the technology upgrade, we assume that $K_b, c_b = 0$. The normalization of the production costs of the current technology is consistent with previous work like Krass et al. (2013) and Yang et al. (2021).

In addition, as a natural by-product, undesirable pollutants will be emitted by firms' production process and hence, firms have to bear the environmental cost. For the existing technology (i.e., current non-green technology), we assume that the emission rate is χ. Thus, the total environmental emission pollutants for the firm's current production process are χq_i if the firm produces q_i units of output. Compared with the existing technology, green technology can remove α $(\times 100\%)$ of undesirable pollutants, where $\alpha \in (0,1)$ denotes the effectiveness of the new technology (Krass et al., 2013). Note that, the larger the α, the greener the new technology. Therefore, the total environmental emission pollutants become $(1-\alpha)\chi q_i$ if new technology is implemented in the production process. Without loss of generality, we assume that $\chi = 1$ and the environmental pollution of the product is a linear function with respect to the production output (Yenipazarli, 2016). The results can easily be extended to the case when $\chi > 0$.

3.3. Regulatory Policy

There are many policies that regulators can use to regulate the market and curb the emissions of products. The policies include subsidies and deposit refund schemes for harmful products, tradable emission allowances, taxes on emissions, and so on (Iraldo et al., 2011; Khan et al., 2021c; Yenipazarli, 2019). The taxation approach has been widely used to regulate and curb the undesirable emissions of products (Khan et al., 2021d). It can more effectively motivate firms to invest in sustainable production methods than that of subsidies and emissions trading programs (Yenipazarli, 2016). Moreover, compared with subsidies, taxes are the direct administrative cost levied on firms that can mandate the environmental objectives of firms in addition to other objectives pursued by firms (Lévy et al., 2007). In this context, we assume that the policy used by the regulator is taxation and the regulator imposes a tax $t \geq 0$ per unit of pollutant emitted. Therefore, a firm will face a total tax charge of $t\chi q_i$ for the total pollutants χq_i.

3.4. Firms' Decision and Game Sequence

Given the regulator tax policy t, the two firms compete in the market by setting their sales price p_i respectively and simultaneously to maximize their profits, and the profit function for each firm can be calculated as follow:

$$\max_{p_i} \prod_i = (p_i - \mathrm{I}c)q_i - t(1 - \mathrm{I}\alpha)q_i - \mathrm{I}K$$

where the first term corresponds to the revenue generated from the selling of products whether produced by current or green technology and the variable cost incurred to upgrade the technology. The second term is the environmental cost caused by the firms' undesirable pollutants. The third term is the fixed cost that the firms incur if the firms have decided to upgrade technology. Note that without technology upgrading, on the one hand, the firm will not incur variable and fixed costs. On the other hand, the firm's environmental pollutants will not decrease if the current technology is used in the firm's production process. Hence, I is an indicator function in the formula which is equal to 1 if new technology is implemented and 0 otherwise.

There is a two-stage game in the two firms' production process and the game proceeds as follows: First, the two firms determine whether to incur additional costs to invest in green technology. Second, the two firms simultaneously decide their prices for the product when the production technology decision is determined. We assume that the production lead time is quite short so that the two firms' products can bring to the market at the same time even though one firm implements the new technology while the other firm has not. Let *I* and *N* stand for the case where the firm improves its current technology and does not improve its current technology, respectively. Clearly, depending on the technology improvement decision of the two firms, there are possible structures: {*NN, IN, NI, II*}, where the letters stand for the technology choice of the two firms, respectively. Note that case *IN* and case *NI* are symmetric because the two firms investigated in this paper are symmetric. Therefore, in the following process, we only calculate the case *IN*, and the equilibrium solutions in the case *NI* can be obtained symmetrically. The matrix that incorporates the two firms' technology improvement decisions is illustrated in Table 1.

Table 1. Firms' strategies regarding their technology improvement decision.

		Firm 2	
		To upgrade	Not to upgrade
Firm 1	To upgrade	Case *II* (*SII*)	Case *IN* (*SIN*)
	Not to upgrade	Case *NI* (*SNI*)	Case *NN* (*SNN*)

In addition, we further consider two scenarios concerning the regulator's tax policy. The scenarios reflect whether the tax level t is an exogenously given parameter or is endogenously determined by the regulator where the goal is to maximize the total social welfare. Let *S* represent the scenario where the tax level is endogenously determined by the regulator and hence, the four possible structures between the two firms become to: $\{SNN, SIN, SNI, SII\}$. The four structures in the scenario where the tax level is exogenously given shall remain the same at the form: $\{NN, IN, NI, II\}$. A Stackelberg game exists between the regulator and the two firms where the regulator is the Stackelberg leader, and the two firms are the Stackelberg follower. The problem can be solved by backward induction. In the following, we first solve the two firms' equilibrium solutions which can also be considered with the scenario where the tax level is exogenously given. Then, we consider the regulator's problem from the social welfare perspective, which can also be considered in the scenario where the tax level is endogenously determined by the regulator.

4. Model of the Firms' Technology Choice

In this section, we first examine the equilibrium solutions for the scenarios in which the tax level is an exogenously given parameter in the three structures (i.e., $\{NN, IN, II\}$). Then, we derive the equilibrium strategies for the two firms concerning their technology upgrading decision. Finally, the impact of an environmental tax on the equilibrium outcome is examined. Superscripts *NN*, *IN*, and *II* are used to denote the three structures.

4.1. Equilibrium Outcome

Case NN: In this case, the two firms will not upgrade their technology. Therefore, the two firms' basic market demand will not expand and avoid incurring additional costs for the new green technology. The two firms' equilibrium solutions are summarized in the following Proposition.

Proposition 1. In case NN when neither firm upgrades the current technology, the equilibrium prices for the two firms are: $p_i^{NN} = \frac{a+t}{2-b}$, and the equilibrium production quantities for the two firms are: $q_i^{NN} = \frac{a-(1-b)t}{2-b}$. Correspondingly, the equilibrium profits for the two firms are: $\Pi_i^{NN} = \frac{\left(a-(1-b)t\right)^2}{(2-b)^2}$.

Intuitively, the two firms will increase the sales price of the product when the basic market demand is large and consequently, the two firms will increase their production quantities. In general, the firms will decrease the sales price of the product when the market competition is fierce to induce more consumers to make a purchase. However, we find that the competition intensity has a positive impact on the firms' sales price and the two firms will increase the sales price when the market competition between the two products is fierce. Besides, the tax burden levied on the two firms will also induce the two firms to increase their sales price. The direct impact of the tax is increasing the firms' production cost and the firms will transfer such burden to consumers by increasing the sales price.

Case IN: In this case, firm 1 upgrades its current technology, whereas firm 2 continues using its current technology. Therefore, the basic market demand for firm 1 will increase, and the environmental pollutants for the firm will decrease, but the firm will also need to incur additional variable and fixed costs for the technology improvement. For firm 2, the firm does not need to incur additional costs and the basic market demand for this firm will not expand. The two firms' equilibrium solutions are summarized in the following Proposition.

Proposition 2. In case IN when only one firm improves the technology, the equilibrium prices for the two firms are: $p_1^{IN} = \frac{a(2+b)+2(c+m)+(2+b-2\alpha)t}{4-b^2}$ and $p_2^{IN} = \frac{a(2+b)+b(c+m)+(2+b-b\alpha)t}{4-b^2}$, the equilibrium production quantities for the two firms are: $q_1^{IN} = \frac{a(2+b)-(2-b^2)c+2m-(2-b-b^2-2\alpha+b^2\alpha)t}{4-b^2}$ and $q_2^{IN} = \frac{a(2+b)+b(c+m)-(2-b-b^2+b\alpha)t}{4-b^2}$. Correspondingly, the equilibrium profits for the two firms are: $\Pi_1^{IN} = \frac{\left(a(2+b)-(2-b^2)c+2m-(2-b-b^2-2\alpha+b^2\alpha)t\right)^2}{(4-b^2)^2} - K$ and $\Pi_2^{IN} = \frac{\left(a(2+b)+b(c+m)-(2-b-b^2+b\alpha)t\right)^2}{(4-b^2)^2}$.

Proposition 2 shows the two firms' equilibrium solutions when firm 1 upgrades to green technology while firm 2 continues to use the current technology and the impact of operational parameters on both firms' optimal decisions. Most of the impacts are quite similar to that of Proposition1 and hence, we only focus on three main parameters: market demand, variable cost, and environmental pollutants. It shows that the change of the three parameters not only affects the optimal decisions of the firm that upgrades to green technology but also affects the firm's decision that does not improve the technology. For instance, both will increase the sales price of the product when the basic market demand and variable cost increase, and the two firms will decrease the sales price when the environmental pollutants increase. The three parameters affect the two firms' optimal decisions in one direction except that the increase of the variable cost will induce firm 1 to decrease the production quantity but will motivate firm 2 to increase the production quantity. However, the mechanism behind the impact of the three parameters on the two firms' optimal decisions is different. The impact of the three parameters on firm 1's optimal decisions is direct, whereas firm 2's optimal decisions are only indirectly affected by these three parameters. For instance, the increase of the variable cost will directly increase the production cost of firm 1 and therefore, firm 1 shall increase its sales price to offset the additional cost. However, from firm 2's perspective, its product can become more competitive if the production cost of firm 1 increases, and hence, it can increase the sales price without losing market demand. Besides, the impact of the three parameters on firm 1's optimal decisions is greater than that of on firm 2.

In addition, we also notice that $p_1^{IN} > p_2^{IN}$ and $q_1^{IN} > q_2^{IN}$. This means that the improvement of the technology empowers the firm to set a higher price and embraces a larger market demand at the same time. However, this does not mean that the firm which upgrades the technology can always achieve a higher profit than that of the firm which does not as $\Pi_1^{IN} > \Pi_2^{IN}$ not necessarily holds. This is because firm 1 has to incur additional costs for the technology improvement even though it can set a higher price and embrace larger demand after the upgrade. Therefore, the firm should upgrade to green technology only when the profit gained from the improvement outweighs the cost incurred.

Case II: In this case, both firms choose to upgrade their technology, incurring an additional variable and fixed cost. Therefore, the basic market demand for the two firms will increase correspondingly. The following Proposition summarizes the equilibrium solutions for the two firms.

Proposition 3. In case II when both firms upgrade to green technology, the equilibrium prices for the two firms are: $p_i^{II} = \frac{a+c+m+t-\alpha t}{2-b}$, and the equilibrium production quantities for the two firms are: $q_i^{II} = \frac{a-(1-b)c+m-(1-b)(1-\alpha)t}{2-b}$. Correspondingly, the equilibrium profits for the two firms are: $\Pi_1^{II} = \frac{\left(a-(1-b)c+m-(1-b)(1-\alpha)t\right)^2}{(2-b)^2} - K$.

Proposition 3 shows the two firms' optimal decisions. The two firms have the same optimal prices, production quantities and equilibrium profits since both the two firms implement new green technology. Consistent with Proposition 2, Proposition 3 also shows that the two firms will increase their sales price of the product when the basic market demand and variable cost increase, and when the environmental pollutant decrease. Consequently, the increase in market demand will have a positive impact on the firms' production quantity, whereas the production quantity of the firms will be negatively affected by the increase in the variable cost.

4.2. Equilibrium Analysis

In the former subsection, we examined the two firms' optimal solutions in three different cases: *NN* (neither firm upgrade technology), *IN* (one firm upgrades the technology while the other firm does not), and *II* (both firms upgrade technology). In this subsection, we determine whether any of the three strategies lead to equilibrium. From the former subsection, we see that the fixed cost plays an important role in the relative profitability of the two firms' technology upgrading decisions. In the following, we detail the specific conditions under which each type of equilibrium arises.

Proposition 4. When the fixed cost incurred, K, is above a threshold, i.e., $K > K_2$, the unique equilibrium is one in which both firms do not upgrade to green technology (i.e., *NN*). When the fixed cost incurred is within an intermediate range, i.e., $K_1 < K < K_2$, the scenarios (i.e., *II* and *NN*) can both arise in equilibria. When the fixed cost incurred is sufficiently low, i.e., $K < K_1$, the unique equilibrium is both firms to upgrade to green technology (i.e., *II*), where $K_1 = \frac{(a-(1-b)t)^2}{(2-b)^2} - \frac{\left(a(2+b)-(2-b^2)c+2m-(2-b-b^2-2\alpha+b^2\alpha)t\right)^2}{(4-b^2)^2}$ and

$$K_2 = \frac{\left(a-(1-b)c+m-(1-b)(1-\alpha)t\right)^2}{(2-b)^2} - \frac{\left(a(2+b)+b(c+m)-(2-b-b^2+b\alpha)t\right)^2}{(4-b^2)^2}.$$

Proposition 4 presents the equilibrium outcomes for the two firms regarding their respective technology upgrading decisions, and how they are affected by the incurred fixed cost. We focus on the analysis of the equilibrium that both firms upgrade to green technology (i.e., *II*). Consider the case when firm 1 decides to improve to green technology while firm 2 continues using the current technology. On the positive side, with the improvement of the technology, more consumers will purchase the product of firm 1 though the sales price of product 1 is higher than that of product 2, and unit environmental pollutants of firm 1 will decrease which may consequently decrease firm 1's environmental cost. On the negative side, additional variable and fixed costs are needed for the innovation of green technology, and firm 1's total environmental cost may increase as more consumers will purchase the product. Clearly, holding all other parameters constant, the positive effects of upgrading technology outweigh the negative effects when the fixed cost incurred is sufficiently low. Therefore, firm 2's loss from market demand due to the deviation of improvement is greater when the fixed cost is smaller. Hence, both firms upgrading to green technology is more likely to exist when the fixed cost incurred for the improvement is below a threshold. The analysis for the equilibrium that both firms do not upgrade to green technology (i.e., *NN*) is similar to that of equilibrium *II* and is not repeated here.

There are two equilibria involving *NN* and *II* under the condition $K_1 < K < K_2$. However, for all parameters under the region, the equilibrium that both firms upgrade to green technology (i.e., *II*) is always more profitable than that of the equilibrium *NN*. As such, the problem for the firms is to coordinate.

Both firms' profits in these three cases are further compared to check whether the equilibrium outcomes that arose in the Proposition 4 are in line with the goal of profit maximization. We find that although the two firms can reach an equilibrium in which both firms should not improve on green technology when the fixed cost incurred is sufficiently high, it may not always beneficial to them. The prisoner's dilemma for the two firms is examined in the following Proposition.

Proposition 5. There exists a threshold K_3 with $K_3 > K_2$, such that a prisoner's dilemma arises when $K_2 < K < K_3$, in which both firms do not upgrade to green technology (i.e., *NN*), where $K_3 = \frac{\left(a-(1-b)c+m-(1-b)(1-\alpha)t\right)^2}{(2-b)^2} - \frac{\left(a-(1-b)t\right)^2}{(2-b)^2}$.

Proposition 5 is a subset of equilibria examined in Proposition 4. It shows that both firms do not upgrade to green technology may arise a prisoner's dilemma when the fixed cost incurred is sufficiently large though upgrading to green technology can give both firms a larger profit. As explained earlier, the positive effects of upgrading technology cannot outweigh the negative effects when the fixed cost incurred to upgrade that technology is sufficiently high. Hence, both firms' decision to not upgrade to green technology will arise in equilibrium. Therefore, the equilibrium *NN* dominates that of *II* when $K_3 > K_2$ and as such, the prisoner's dilemma will not arise. When the incurred fixed cost is large but at a moderate level (i.e., $K_2 < K < K_3$), the firm which upgrades its technology will become less competitive as it shall incur high fixed costs though it can gain a large market share and increase the sales price of its product after the technology improvement. However, the other firm which does not upgrade can remain competitive by not incurring additional costs for the innovation though it can only gain a small market share. This implies that the equilibrium will stabilize at *NN*. However, under this scenario, the whole market will not expand and both firms can never benefit from the expansion of the market. Finally, both firms will achieve less profit. Therefore, although the two firms have to incur additional costs to upgrade to green technology, they can benefit from the increase in the total market demand, causing profits under equilibrium *II* to be larger than that in equilibrium *NN*.

An important implication of the above result is that both firms upgrade to green technology (i.e., *II*) has the potential to resolve the prisoner's dilemma situation where the fixed cost incurred for the upgrading is at a moderate level and results in neither firm improving their technology. This result is completely different from Yang et al. (2021). They examined the role of government subsidy on firms' technology improvement decisions and found that both firms upgrading to new technology will be trapped in a prisoner's dilemma as the advantage of market expansion would be weakened by the competition between the two firms when the government does not play a role in the upgrading process. However, we show that the impact of the tax policy can make the case where both firms upgrade to green technology, bringing the two firms out of a prisoner's dilemma even when the level of the tax is an exogenously given parameter. This is because the tax is a direct cost levied on firms which will directly increase the firms' burden on production costs. The unit environmental cost of the firm will decrease if it improves its technology since the firm will emit less undesirable environmental pollutants with such improvement and hence, equilibrium *II* may bring the two firms out of a prisoner's dilemma. Figure 1 summarizes the equilibrium outcomes of the two firms.

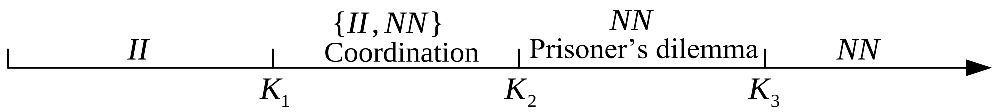

Figure 1. Equilibrium outcomes between the two firms.

From Figure 1, it is clear that when the fixed cost incurred for the technology improvement is high, then the two firms should not upgrade their technology. The two firms should improve their technologies when the fixed cost incurred decreases. However, when the fixed cost is at a medium level, the two firms may fall into a prisoner's dilemma. Furthermore, the strategy that both firms improve their technology is more profitable even when there are multiple equilibria, thus implying that the *II* strategy not only has the potential to bring the two firms out of prisoner's dilemma but also motivates the two firms to coordinate.

4.3. Impact of Environmental Tax

The equilibrium outcomes for the two firms are examined in the former subsection. In this subsection, the impact of an environmental tax on the two firms' equilibrium outcomes is investigated. From the former subsection, we know that the equilibrium outcomes between the two firms highly depend on the fixed cost incurred for the technology improvement. Hence, in this subsection, we mainly examine the impact of an environmental tax on the fixed cost incurred for technology improvement.

Corollary 1. When the environmental tax is exogenously given, the impacts of an environmental tax on the threshold that determines the two firms' equilibrium outcomes are summarized as follows:

(1) For threshold function K_1, for any $t_1 \in (0,1)$, there are two sub-conditions: (i) if $0<\alpha<2-\frac{2b}{2-b^2}$, then $\frac{\partial K_1}{\partial t}>0$ for any $t \in (0,t_1)$, and $\frac{\partial K_1}{\partial t}<0$ for any $t \in (t_1,1)$; (ii) if $2-\frac{2b}{2-b^2}<\alpha<1$ and $\sqrt{3}-1<b<1$, then $\frac{\partial K_1}{\partial t}<0$, and $\frac{\partial K_1}{\partial t}>0$ for any $t \in (t_1,1)$, where $t_1=\frac{(2-b-b^2)((2-b^2)c-2m)+(2-b^2)(a(2+b)-(2-b^2)c+2m)\alpha}{(2-b^2)(4+b(-2+b(-2+\alpha))-2\alpha)\alpha}$.

(2) For threshold function K_2, for any $t_2 \in (0,1)$, then $\frac{\partial K_2}{\partial t}>0$ if $t \in (0,t_2)$, and $\frac{\partial K_2}{\partial t}<0$ if $t \in (t_2,1)$, where $t_2=\frac{(2-b-b^2)((2-b^2)c-2m)+((2-b^2)((2+b)(a+bc)-2c)+(4-b^2(2+b))m)\alpha}{(2-b^2)\alpha(4-2b(1+b)-2\alpha+b(2+b)\alpha)}$.

(3) For threshold function K_3, for any $t_3 \in (0,1)$, then $\frac{\partial K_3}{\partial t}>0$ if $t \in (0,t_3)$, and $\frac{\partial K_3}{\partial t}<0$ if $t \in (t_3,1)$, where $t_3=\frac{(1-b)c(1-\alpha)-m(1-\alpha)+a\alpha}{(1-b)(2-\alpha)\alpha}$.

(4) For the prisoner's dilemma region K_3-K_2, for any $t_4 \in (0,1)$, then $\frac{\partial (K_3-K_2)}{\partial t}<0$ if $t \in (0,t_4)$, and $\frac{\partial (K_3-K_2)}{\partial t}>0$ if $t \in (t_4,1)$, where $t_4=\frac{(2-b-b^2)(c+m)+a(2+b)\alpha+b(c+m)\alpha}{\alpha(4-b(2+2b-\alpha))}$.

Corollary 1 shows how the equilibrium outcomes and the prisoner's dilemma when the environmental tax is exogenous given are affected by the environmental tax. Recall that both firms upgrade to green technology (i.e., *II*) will arise in equilibrium if $K<K_1$, and the value of K_1 is affected by many parameters. If the efficiency of the new technology in removing

pollutants is at a low level (i.e., $0<\alpha<2-\frac{2b}{2-b^2}$), K_1 first increases then decreases with t. However, as the new technology becomes more efficient (i.e., $2-\frac{2b}{2-b^2}<\alpha<1$) and the product competition between the two firms becomes fierce (i.e., $\sqrt{3}-1<b<1$), the value of K_1 first decreases then increases with t. These indicate several important implications for this research. Firstly, the environmental tax policy can encourage the two firms to upgrade their current technology if the environmental tax and the efficiency of the new technology are both at a relatively low level, i.e., $t\in(0,t_1)$ and $0<\alpha<2-\frac{2b}{2-b^2}$. However, as the environmental tax increases, the tax policy cannot motivate the two firms to upgrade their current technology. Secondly, when the market competition between the two firms becomes fierce (i.e., $\sqrt{3}-1<b<1$) and the new technology becomes efficient in removing pollutants (i.e., $2-\frac{2b}{2-b^2}<\alpha<1$), a low environmental tax cannot motivate the two firms to make technology improvement decisions. Conversely, a high environmental tax policy must be enacted if the regulator wants the two firms to upgrade their current technology. There will be fewer environmental pollutants if new technology is adopted as the new technology becomes greener if α increases. However, the fierce competition between the two firms prevents the two firms from making technology upgrading decisions. Hence, the regulator should enact a high environmental tax policy to force the two firms to make a change in technology as the new technology is much more environmentally friendly than that of the current technology. The result comes as follows. The two firms will face a heavier cost burden if a heavy environmental tax policy is enacted. Therefore, the two firms should make technology improvement decisions as the implementation of new technology can remove most of the pollutants caused by the production even if the competition between the two firms is fierce and any technology improvement decision may place the firms at a disadvantageous position.

The values of K_2 and K_3 first increase then decrease with the environmental tax. Recall that neither firm will upgrade to green technology (i.e., *NN*) will arise in equilibrium if $K>K_2$. The result shows that the environmental tax can first induce the two firms to make technology improvement decisions if the environmental tax is relatively low (i.e., $t\in(0,t_2)$). However, the two firms will not upgrade their technology if the regulator further increases the tax. This implies that environmental tax can motivate firms to upgrade, but the setting of the tax must be at an appropriate level. Otherwise, a high tax level may harm firms' technology improvement decisions. The combined effect of an environmental tax on the values of K_1, K_2, and K_3 is that the environmental tax can first pull the firms out of the prisoner's dilemma. However, the prisoner's dilemma is more likely to arise when the environmental tax further increases.

5. Regulator's Problem: Model of Social Welfare

The preceding analysis suggests that the environmental tax can motivate the two firms to upgrade their technology if it is at an appropriate level. However, the environmental tax may have an adverse effect on the two firms' technology upgrading decision if the regulator sets the environmental tax at a relatively high level. In this section, we examine how should the regulator set the tax level in equilibrium so that the setting of the tax can maximize the total social welfare. We begin with formulating the social welfare function Π_r for each case, and then proceed to the regulator's problem and examine how should the regulator set the optimal environmental tax aiming at maximizing the total social welfare.

Suppose that the regulator's welfare function consists of three components: the firm's profit, tax revenue spent by the regulator on public services, and environmental cost caused by products' pollution. Hence, the welfare function can be formulated as follows:

$$\Pi_r = \sum_{i=1}^{2} \Pi_i + t(1 - \mathrm{I}\alpha)\sum_{i=1}^{2} q_i - \beta(1 - \mathrm{I}\alpha)\sum_{i=1}^{2} q_i$$

where β with $\beta \geq 0$ represents the monetary payout that each emission brings to society, I is the indicator function, and is equal to 1 if new technology is adopted and 0 otherwise. We assume that all pollutants have the same environmental cost whether emitted by current technology or new technology (Cachon, 2014; Yenipazarli, 2016).

From the above analysis, it is clear that there are no asymmetric equilibria, and both unique equilibrium and multiple equilibria will arise in symmetric form. The setting of the tax level in the multiple equilibria scenario is quite similar to that of the unique equilibrium scenario since multiple equilibria also appear in the symmetric form. Hence, in this section, we only examine the two symmetric equilibria where both firms upgrade and neither firm upgrade. In addition, in the following analysis, we only investigate the setting of the optimal tax fee. The two firms' optimal responses can be obtained accordingly by substituting the optimal tax fee and are hence omitted.

5.1. Case SII: Both Firms Upgrade to New Technology

5.1.1. Equilibrium Analysis

In case SII, both firms will upgrade to new technology and hence, both the two firms will incur variable and fixed costs for the technology upgrading, and the indicator function in the welfare function is equal to 1. Therefore, the regulator's problem is formulated as follows:

$$\max_t \Pi_r^{SII} = \Pi_1^{II} + \Pi_2^{II} + t(1-\alpha)(q_1^{II} + q_2^{II}) - \beta(1-\alpha)(q_1^{II} + q_2^{II})$$

$$s.t. K \leq K_1$$

Before moving to the optimal setting of the environmental tax level that can maximize the total social welfare, we first investigate the structural properties of the welfare function Π_r^{SII}.

Theorem 1. The welfare function of the regulator (i.e., Π_r^{SII}) is continuous and strictly concave in $t \in (0,1)$ which leads to an inverted-U-shape curve with respect to the environmental tax. Hence, there exists a unique maximum at t^{SII} for the welfare function of the regulator, where $t^{SII} = \frac{1}{2}\left(\frac{b\left(a-(1-b)c+m\right)}{(1-b)(1-\alpha)} + (2-b)\beta\right)$.

According to Theorem 1, a higher environmental tax does not always mean higher social welfare for the regulator. When the environmental tax increases, it appears that the regulator's welfare would first go up. However, the two firms' profits will drop significantly which will consequently decrease the regulator's welfare if the environmental tax is increased too much. The outcome is that the two firms will decrease their production quantity if the tax burden posed by the regulator is heavy and this will further decrease the firms' profit and the total welfare of the regulator.

For the regulator, it is clear that the optimal tax level is t^{SII} as it is where the regulator's welfare function can be maximized. t^{SII} increases with m, α, and β. This indicates that the regulator is more likely to set a high environmental tax when more customers purchase when (1) the product that is produced by new technology, (2) the new technology is highly efficient in reducing emission, and (3) the environmental cost of the products' pollutants is high. However, the impacts of three parameters (i.e., m, α, and β) on the regulator's tax policy are completely different even though they move t^{SII} toward the same direction. The two firms can earn more profit from the technology improvement decision if their basic market demand is increased to a large extent and the newly adopted technology is highly efficient. Hence, the regulator can reap many benefits from the firms by imposing a higher tax level. However, there will be a serious environmental burden if β is at a relatively high level and therefore, the regulator has to impose a high tax level on the firms to force them to improve their technology.

However, the equilibrium that both firms upgrade to new technology will only arise in equilibrium on the condition that $K \le K_1$. Thus, the regulator maximizes Π_r^{SII} over $t \in (0,1)$ subject to the constraint $K \le K_1$ to obtain its optimal tax fee. The constraint condition may make the regulator's welfare function (i.e., Π_r^{SII}) discontinuous which will be examined later. Next, we discuss the tax threshold condition that defines the constraint. Recall that in Corollary 1, we have shown that the equilibrium threshold condition K_1 can be either concave or convex with respect to the environmental tax which depends on the market competition between the two firms and the efficiency of the newly adopted technology. Hence, there exists a unique maximum at $t_1 \in (0,1)$ for K_1 if K_1 concaves with the environmental tax, where a unique minimum at $t_1 \in (0,1)$ exists for K_1 if K_1 is a convex function. The following Corollary summarizes the threshold condition for the environmental tax that makes the constraint hold.

Corollary 2. The environmental tax t needs to satisfy the following conditions to ensure that the constraint $K \le K_1$ holds:

(1) If $0 < \alpha < 2 - \frac{2b}{2-b^2}$, there exist two sub-conditions: (i) if $K \ge K_1(t_1)$, then the constraint $K \le K_1$ is invalid for all $t \in (0,1)$; (ii) if $K < K_1(t_1)$, then there exist two levels t_1^{SII} and t_2^{SII} (detailed in the Appendix and $t_1^{SII} < t_2^{SII}$) such that $K \le K_1$ when $t_1^{SII} < t < t_2^{SII}$.

(2) If $2 - \frac{2b}{2-b^2} < \alpha < 1$ and $\sqrt{3} - 1 < b < 1$, there exist two sub-conditions: (i) if $K \ge K_1(t_1)$, then $K \le K_1$ holds when $0 < t < t_1^{SII}$ or $t_2^{SII} < t < 1$; (ii) if $K < K_1(t_1)$, then for all $t \in (0,1)$ can make the constraint $K \le K_1$ hold.

Corollary 2 states the threshold condition for the environmental tax that satisfies the constraint. Note that, we restrict our attention to the range where $t_1^{SII} \in (0,1)$ and $t_2^{SII} \in (0,1)$ since $t \in (0,1)$ prevails for most industry practice. Other ranges, like $t_1^{SII} < 0$, can also make the constraint $K \le K_1$ hold. The discussion of these ranges is similar to that of the range where $t_1^{SII} \in (0,1)$ and $t_2^{SII} \in (0,1)$. Hence, we omit this. In the following, we examine how should the regulator set the optimal environmental tax that can maximize the total welfare function but with the consideration of the constraint.

Proposition 6. The welfare is maximized at the tax level $t^{SII*} = \arg\max_t \{\Pi_r^{SII}(t^{SII}), \Pi_r^{SII}(t_1^{SII}), \Pi_r^{SII}(t_2^{SII})\}$, and the optimal value of the welfare is $\Pi_r^{SII*} = \max\{\Pi_r^{SII}(t^{SII}), \Pi_r^{SII}(t_1^{SII}), \Pi_r^{SII}(t_2^{SII})\}$. The value of the optimal tax level t^{SII*} satisfies the following conditions:

(1) If $0 < \alpha < 2 - \frac{2b}{2-b^2}$, there exist two sub-conditions that define the optimal tax level: (i) the optimal tax level does not exist, i.e., $t^{SII*} = \varnothing$, if $K \ge K_1(t_1)$ since the whole range of the value for K in invalid for the constraint; (ii) if $K < K_1(t_1)$, then $t^{SII*} = t_1^{SII}$ when $0 < t^{SII} < t_1^{SII}$; $t^{SII*} = t^{SII}$ when $t_1^{SII} < t^{SII} < t_2^{SII}$; and $t^{SII*} = t_2^{SII}$ when $t_2^{SII} < t^{SII} < 1$.

(2) If $2 - \frac{2b}{2-b^2} < \alpha < 1$ and $\sqrt{3} - 1 < b < 1$, there exist two sub-conditions that define the optimal tax level: (i) if $K \ge K_1(t_1)$, then $t^{SII*} = t^{SII}$ when $0 < t^{SII} < t_1^{SII}$;

$t^{SII*} = \arg\max_t \{\Pi_r^{SII}(t_1^{SII}), \Pi_r^{SII}(t_2^{SII})\}$ when $t_1^{SII} < t^{SII} < t_2^{SII}$; and $t^{SII*} = t^{SII}$ when $t_2^{SII} < t^{SII} < 1$; (ii) if $K < K_1(t_1)$, then $t^{SII*} = t^{SII}$ for all $t \in (0,1)$.

Proposition 6 shows how should the regulator set the optimal tax level and the value of the optimal level is selected among three thresholds, i.e., t^{SII}, t_1^{SII}, and t_2^{SII}. The welfare function can achieve its unique maximum value at t^{SII} if there is no constraint. However, the value of t^{SII} may not be valid for the constraint $K \le K_1$ where the equilibrium that the two firms upgrade to new technology arises. According to Proposition 6, the setting of the optimal value of tax level depends on three main factors, namely, the efficiency of the newly adopted technology, the fixed cost incurred for the upgrading, and the market competition between the two firms. Firstly, the optimal tax level may not exist if the newly adopted technology is not so efficient in reducing emissions (i.e., $0 < \alpha < 2 - \frac{2b}{2-b^2}$) and the fixed cost incurred for the technology improvement is relatively large (i.e., $K \ge K_1(t_1)$). As the fixed cost incurred decreases, the optimal setting of the tax level may arise. However, the setting of optimal tax levels does not necessarily mean that the welfare function can achieve the highest. The welfare function can only achieve its maximum value when t^{SII} is at a medium level, i.e., $t_1^{SII} < t^{SII} < t_2^{SII}$. If t^{SII} is too large or too small, i.e., $0 < t^{SII} < t_1^{SII}$ and $t_2^{SII} < t^{SII} < 1$, then the welfare function cannot achieve its maximum value.

Secondly, the optimal tax level always exists for the regulator when the newly adopted technology is relatively efficient in reducing emission (i.e., $2 - \frac{2b}{2-b^2} < \alpha < 1$) and the market competition between the two firms become fierce (i.e., $\sqrt{3} - 1 < b < 1$) whether the fixed cost incurred for the technology improvement is at a relatively high or low level. However, the regulator can always achieve welfare at the maximum value when the fixed incurred is at a low level, and when the fixed cost incurred increases, the regulator's maximum value is only achieved if t^{SII} is too large or too small, i.e., $0 < t^{SII} < t_1^{SII}$ and $t_2^{SII} < t^{SII} < 1$. If t^{SII} is at a medium level, i.e., $t_1^{SII} < t^{SII} < t_2^{SII}$, then the regulator can never achieve its maximum value by setting the optimal tax level.

The results in Proposition 6 imply several managerial implications for the regulator. The regulator can always set an optimal tax level that can maximize the total welfare to coordinate the whole market when the newly adopted technology is highly efficient in reducing emissions and the market competition is fierce, especially when it is not so costly to upgrade to new technology. However, the optimal tax level may not exist for the regulator when the newly adopted technology is not so efficient in emission reduction and is highly costly for upgrading.

These indicate that the regulator should set its tax level according to specific market conditions if its goal is to maximize welfare. Otherwise, the setting of the policy may have an adverse effect on firms' technology improvement decisions.

5.1.2. Numerical Examples

To understand Proposition 6, we provide some illustrative examples. Since the two parameters t_1^{SII} and t_2^{SII} are invariant to the environmental cost, we fixed all other parameters except the environmental cost β to show the impact of the constraint on the regulator's optimal tax setting. The purpose of this setting is to simplify the analysis but without loss of generality. Other parameters setting can also apply, but we only use several sets of parameters to illustrate the results obtained in Proposition 6. The basic parameters are: $a=1$, $b=0.4$, $c=0.2$, $m=0.6$, $\alpha=0.3$, and $K=0.32$. Using these parameter values, we obtain $t_1^{SII}=0.029$ and $t_2^{SII}=0.88$. We consider the following three numerical examples to cover the range of environmental costs that can be at low, medium, and high levels.

Example 1: $\beta=0.1$. We obtain $t^{SII}=0.785$ by substituting $\beta=0.1$. Hence, the regulator should set the optimal tax level at $t^{SII*}=t^{SII}=0.785$ since $t_1^{SII}<t^{SII}<t_2^{SII}$. As such, the welfare is $\Pi_r^{SII*}=\Pi_r^{SII*}(t^{SII*}=0.785)=1.083$, the two firms' profit is $\Pi_1^{SII*}=\Pi_2^{SII*}=0.197$, the two firms' total production quantity is $q_1^{SII*}+q_2^{SII*}=1.438$, and the total environmental cost is $\beta(1-\alpha)\left(q_1^{SII*}+q_2^{SII*}\right)=0.101$.

Example 2: $\beta=0.3$. We obtain $t^{SII}=0.945$ by substituting $\beta=0.3$. Hence, the regulator should set the optimal tax level at $t^{SII*}=t_2^{SII}=0.88$ since $t^{SII}>t_2^{SII}$. As such, the welfare is $\Pi_r^{SII*}=\Pi_r^{SII*}(t^{SII*}=0.88)=0.887$, the two firms' profit is $\Pi_1^{SII*}=\Pi_2^{SII*}=0.162$, the two firms' total production quantity is $q_1^{SII*}+q_2^{SII*}=1.388$, and the total environmental cost is $\beta(1-\alpha)\left(q_1^{SII*}+q_2^{SII*}\right)=0.291$.

Example 3: $\beta=0.7$. We obtain $t^{SII}=1.265$ by substituting $\beta=0.7$. Hence, the regulator should set the optimal tax level at $t^{SII*}=t_2^{SII}=0.88$ since $t^{SII}>t_2^{SII}$. As such, the welfare is $\Pi_r^{SII*}=\Pi_r^{SII*}(t^{SII*}=0.88)=0.498$, the two firms' profit is $\Pi_1^{SII*}=\Pi_2^{SII*}=0.162$, the two firms' total production quantity is $q_1^{SII*}+q_2^{SII*}=1.388$, and the total environmental cost is $\beta(1-\alpha)\left(q_1^{SII*}+q_2^{SII*}\right)=0.680$.

The three examples show how should the regulator set the optimal tax level with consideration of the constraint. The regulator should increase the tax when the environmental cost of the pollutants increases. However, the increase in the tax does not necessarily increase the regulator's welfare. This is because, on the one hand, the increase in the environmental cost will decrease the regulator's welfare directly as the environmental burden increases. On the other hand, the two firms will decrease their production quantity with the increase in tax which will consequently decrease the two firms' profit and then decrease the total welfare. The optimal tax level set by the regulator may not change when the environmental cost further increases as the regulator's welfare function are subject to the constraint where the two firms upgrade to new technology will arise in equilibrium. Hence, the two firms' production quantity and total profit will not change correspondingly. However, the regulator's welfare will decrease as the environmental cost of the pollutants becomes larger.

5.2. Case SNN: Neither Firm Upgrades to New Technology

5.2.1. Equilibrium Analysis

In the case SNN, both the two firms will not upgrade to new technology and hence, the environmental pollution of the two products will not decrease, and the indicator function in the welfare function is equal to 1. Therefore, the regulator's problem is formulated as follows:

$$\max_{t} \prod_r^{SNN} = \prod_1^{NN} + \prod_2^{NN} + t(q_1^{NN} + q_2^{NN}) - \beta(q_1^{NN} + q_2^{NN})$$

$$s.t. K \geq K_2$$

Similarly, we first examine the structural properties of the welfare function $\prod_r^{SNN}$ before moving to the detailed investigation of the setting of the environmental tax.

Theorem 2. The welfare function of the regulator (i.e., $\prod_r^{SNN}$) is continuous and strictly concave in $t \in (0,1)$ which leads to an inverted-U-shape curve with respect to the environmental tax. Hence, there exists a unique maximum at t^{SNN} for the welfare function of the regulator, where $t^{SNN} = \frac{ab + (2-b)(1-b)\beta}{2-2b}$.

Most insights obtained from Theorem 2 are similar to that of Theorem 1. Firstly, the environmental tax can increase the regulator's social welfare if it is at a relatively low level. However, as the environmental tax increases, the welfare function will decrease with the increase of the environmental tax. As such, a high environmental tax does not always mean higher welfare for the regulator even when the two firms will not make technology improvement decisions. This is because the environmental tax will always be a cost burden for the two firms whether they make technology improvement decisions or not. Secondly, for the regulator, the optimal tax level is t^{SNN} if the two firms do not upgrade to new technology. t^{SNN} is only affected by three basic market parameters (i.e., basic market demand, market competition between the two firms, and environmental cost of the pollution) as both firms stay inactive in technology upgrading and there are no market expansion and technology improvement effects. Similarly, the regulator should increase the tax level with the increase in environmental cost.

Similarly, both firms not upgrading to green technology will only arise in equilibrium on the condition that $K \geq K_2$. Hence, the optimization of $\prod_r^{SNN}$ over $t \in (0,1)$ is subject to the constraint $K \geq K_2$ to receive its optimal tax fee. In the following, the threshold condition that defines the constraint is first discussed as the existence of the constraint may cause the regulator's welfare function to be discontinuous. Recall that, in Corollary 1, we have shown that K_2 concaves with respect to the environmental tax and hence, there exists a unique maximum at $t_2 \in (0,1)$ for K_2. Therefore, the threshold condition for $t \in (0,1)$ is summarized as follows.

Corollary 3. The environmental tax t needs to satisfy the following conditions to make the constraint $K \geq K_2$ hold:

(1) If $K \geq K_2(t_2)$, then for all $t \in (0,1)$ can make the constraint $K \geq K_2$ hold.

(2) If $K < K_2(t_2)$, then there exist two levels t_1^{SNN} and t_2^{SNN} (detailed in the Appendix and $t_1^{SNN} < t_2^{SNN}$) such that $K \geq K_2$ when $0 < t < t_1^{SNN}$ or $t_2^{SNN} < t < 1$.

Corollary 3 implies the threshold condition for the environmental tax that defines when both firms do not upgrade to new technology will arise in equilibrium. Similarly, we restrict our attention to scenarios where $t_1^{SNN} \in (0,1)$ and $t_2^{SNN} \in (0,1)$. Other scenarios, such as $t_1^{SNN} < 0$, $t_1^{SNN} > 1$, and so on, are still valid for the constraint, but they are not within the scope of this study. Next, we examine how should the regulator set the optimal level of tax with the results of Corollary 3.

Proposition 7. The welfare is maximized at the tax level $t^{SNN*} = \arg\max_t \left\{\prod_r^{SNN}(t^{SNN}), \prod_r^{SNN}(t_1^{SNN}), \prod_r^{SNN}(t_2^{SNN})\right\}$, and the optimal value of the welfare is $\prod_r^{SNN*} = \max\left\{\prod_r^{SNN}(t^{SNN}), \prod_r^{SNN}(t_1^{SNN}), \prod_r^{SNN}(t_2^{SNN})\right\}$. The value of the optimal tax level t^{SNN*} satisfies the following conditions:

(1) If $K \geq K_2(t_2)$, then $t^{SNN*} = t^{SNN}$ for all $t \in (0,1)$.

(2) If $K < K_2(t_2)$, then $t^{SNN*} = t^{SNN}$ when $0 < t^{SNN} < t_1^{SNN}$; $t^{SNN*} = \arg\max_t \left\{\prod_r^{SNN}(t_1^{SNN}), \prod_r^{SNN}(t_2^{SNN})\right\}$ when $t_1^{SNN} < t^{SNN} < t_2^{SNN}$; and $t^{SNN*} = t^{SNN}$ when $t_2^{SNN} < t^{SNN} < 1$.

The insights obtained from Proposition 7 are quite similar to that of Proposition 6, but the impact of the fixed cost incurred on the setting of the optimal tax level moves in a different direction. This is because Proposition 6 shows the case where both firms upgrade to new technology arise in equilibrium, whereas neither firm upgrade to new technology is examined in Proposition 7. The regulator can always achieve its maximum value by setting the tax level at t^{SNN} when the fixed cost incurred for the technology upgrading is sufficiently large, i.e.,

$K \geq K_2(t_2)$. However, as the fixed cost incurred decreases, the regulator can only achieve its maximum value when t^{SNN} is too large or too small, i.e., $0 < t^{SNN} < t_1^{SNN}$ and $t_2^{SNN} < t^{SNN} < 1$. When t^{SNN} is at a medium level, i.e., $t_1^{SNN} < t^{SNN} < t_2^{SNN}$, the optimal tax level still exists for the regulator, but the setting of the tax cannot maximize the regulator's welfare function. These indicate that the regulator can set the optimal tax level that can maximize welfare in most scenarios when the two firms do not make technology improvement decisions.

5.2.2. Numerical Examples

To understand Proposition 7, we also provide some illustrative examples. Consistent with the previous section, we also fixed other parameters except the environmental cost β to show how the regulator's optimal tax level when neither firm upgrade to new technology is affected by the constraint and the environmental cost. Similarly, the basic parameters are: $a=1$, $b=0.4$, $c=0.2$, $m=0.6$, $\alpha=0.3$, and $K=0.36$. Using these parameters, we obtain $t_1^{SNN}=0.074$ and $t_2^{SNN}=0.861$. Three examples with three levels of environmental cost, i.e., low, medium, and high levels environmental cost, are considered in the following numerical studies.

Example 1: $\beta=0.1$. We obtain $t^{SNN}=0.413$ by substituting $\beta=0.1$. Hence, the regulator should set the optimal tax level at $t^{SNN*}=\arg\max_t\left\{\Pi_r^{SNN}(t_1^{SNN}),\Pi_r^{SNN}(t_2^{SNN})\right\}$ since $t_1^{SNN}<t^{SNN}<t_2^{SNN}$. Then, we have $t^{SNN*}=t_1^{SNN}=0.074$. As such, the welfare is $\Pi_r^{SNN*}=\Pi_r^{SNN*}(t^{SNN*}=0.074)=0.682$, the two firms' profit is $\Pi_1^{SNN*}=\Pi_2^{SNN*}=0.357$, the two firms' total production quantity is $q_1^{SNN*}+q_2^{SNN}=1.195$, and the total environmental cost is $\beta\left(q_1^{SNN*}+q_2^{SNN}\right)=0.119$.

Example 2: $\beta=0.3$. We obtain $t^{SNN}=0.573$ by substituting $\beta=0.3$. Hence, the regulator should set the optimal tax level at $t^{SNN*}=\arg\max_t\left\{\Pi_r^{SNN}(t_1^{SNN}),\Pi_r^{SNN}(t_2^{SNN})\right\}$ since $t_1^{SNN}<t^{SNN}<t_2^{SNN}$. Then, we have $t^{SNN*}=t_2^{SNN}=0.861$. As such, the welfare is $\Pi_r^{SNN*}=\Pi_r^{SNN*}(t^{SNN*}=0.861)=0.522$, the two firms' profit is $\Pi_1^{SNN*}=\Pi_2^{SNN*}=0.091$, the two firms' total production quantity is $q_1^{SNN*}+q_2^{SNN}=0.604$, and the total environmental cost is $\beta\left(q_1^{SNN*}+q_2^{SNN}\right)=0.181$.

Example 3: $\beta=0.7$. We obtain $t^{SNN}=0.893$ by substituting $\beta=0.7$. Hence, the regulator should set the optimal tax level at $t^{SNN*}=t^{SNN}=0.893$ since $t_2^{SNN}<t^{SNN}<1$. As such, the welfare is $\Pi_r^{SNN*}=\Pi_r^{SNN*}(t^{SNN*}=0.893)=0.280$, the two firms' profit is $\Pi_1^{SNN*}=\Pi_2^{SNN*}=0.084$, the two firms' total production quantity is $q_1^{SNN*}+q_2^{SNN}=0.580$, and the total environmental cost is $\beta\left(q_1^{SNN*}+q_2^{SNN}\right)=0.406$.

The three examples numerically show the results obtained in Proposition 7, and how should the regulator set the optimal tax level when neither firm upgrade to new technology. In addition to the insights obtained in Proposition 7, the three illustrative examples also show some new managerial insights. The regulator should set the tax level at a relatively low level when the environmental cost of the pollutants is sufficiently low. However, as the environmental cost of the pollutants increases, the regulator will increase the optimal level of the tax substantially even when the extent that the increase of the environmental cost is small. The increase of the environmental cost will not decrease the regulator's welfare too much, but the two firms' profit will decrease substantially as the two firms will substantially decrease their production quantities when the tax burden imposed by the regulator increases. The regulator should further increase the tax level of the products as the environmental cost of the pollutants further increases. However, the increase of the tax level will not have too much impact on the two firms' profit as they already faced a large tax burden, whereas the regulator's welfare will decrease substantially as the environmental cost of the pollutants is at a high level. These indicate that the regulator can rely on the tax as a lever to affect the two firms' profit and production decisions when the environmental cost of the pollutants is at a low level by increasing or decreasing the level of the tax. However, as the environmental cost of the pollutants is at a relatively high level, the impact of the tax level on the two firms' profit and production decisions is limited.

6. Discussion

By conducting and comparing different equilibrium outcomes in the game models, several meaningful conclusions have emerged. First, the fixed cost incurred for the technology improvement plays a vital role in the firms' technology improvement decision whether the tax level is exogenously given or endogenously determined by the regulator. The two firms should not make technology improvement decisions when the fixed cost incurred for the technology improvement is at a relatively high level, and the two firms should gradually change their technology improvement decision from not improving to improving when the fixed cost incurred for the technology decreases. Note that, the fixed cost incurred for the technology improvement is a combined function and is affected by many operational parameters, such as the basic market demand, the market competition between the two firms, the tax level set by the regulator, and the efficiency of the new technology.

Second, when the fixed cost incurred is at a medium level, multiple equilibria may arise. However, the two firms may fall into a prisoner's dilemma where the two firms both choose to not upgrade their technology when the fixed cost incurred further increases. The two firms making technology improvement decisions is a dominant strategy for both firms whether multiple equilibria arise or prisoner's dilemmas arise. This indicates that the *II* strategy (i.e., both firms making technology improvement decisions) not only has the potential to bring the two firms out of a prisoner's dilemma but also motivates the two firms to coordinate when the regulator imposes the tax. This is because, in addition to the market expansion effect, the firms will generate fewer environmental pollutants by upgrading to new green technology even if they have to incur a relatively high fixed cost for the technology improvement. This result is also completely different from Yang et al. (2021). They show that the two firms may get trapped into a prisoner's dilemma when the two firms both make technology improvement decisions whether the government interferes with the market by subsidy because the market expansion effect brought to the two players cannot outweigh the cost incurred for the improvement. However, we show that the two firms may be trapped in a prisoner dilemma if they both do not make technology improvement decisions even when the tax level is an exogenous parameter.

Third, when the efficiency of the new green technology in removing pollutants is at a relatively low level, the regulator can motivate the two firms to make technology improvement decisions from current a non-green one to a greener one by imposing a low tax level. The impact of the environmental tax on firms' technology improvement decisions is limited when the regulator sets the tax at a relatively high level. However, when the market competition between the two firms becomes fierce and the new technology is highly efficient in removing pollutants, a low tax level cannot motivate the two firms to make technology improvement decisions. Conversely, a high environmental tax policy must be enacted if the regulator wants the two firms to upgrade their current technology. This is because the two firms may easily lose their competitive status in the market by incurring additional costs to upgrade to new technology even when the new technology is relatively efficient in removing pollutants. Hence, the regulator should impose a high tax level to force the two firms to make a change in technology choices. These indicate that, in addition to the fixed cost incurred, the regulator should adjust its tax policy based on the market competition status between the two firms and the efficiency of the new technology.

Finally, when both firms do not upgrade to new technology arises in equilibrium, the regulator can always set an optimal tax level that can maximize the total welfare to coordinate the whole market. However, the optimal tax level may not exist for the regulator when both firms upgrade to new technology arises in equilibrium, especially when the market competition between the two firms is relatively fierce and the new technology is highly efficient in reducing emissions. The scenario happens when the fixed cost incurred for the technology improvement is at a relatively high level. As such, the two firms face a huge cost burden for technology improvement, and hence, any additional tax fee imposed on the two firms may make them change their technology improvement decision.

The results of this study have important managerial implications for firms regarding their technology innovation decisions with considering the impact of environmental tax. The analytical model shows the conditions under which the two firms should make technology improvement decisions, how the two firms' technology improvement decision is affected by operational parameters, and how the regulator should optimally adjust its environmental policy so that the total social welfare can be maximized. Note, however, that such technology improvement decisions are far more complex and whether firms should improve their current technology or not depends on many operational parameters. This study provides a potential alternative explanation for why and how technology improvement decisions are made in a competitive market.

7. Conclusion

The serious environmental problems and energy crises call for many entities in the market to make changes toward the sustainable development of the economy. From the consumers' perspective, many consumers become green-oriented and are more likely to purchase the products that are produced by green technology. From the firms' perspective, many firms begin making technology improvement decisions to upgrade their current non-green technology to a greener one. However, a high cost will be incurred which will affect the firms' cost structure dramatically and consequently affect firms' profitability. In addition, the fierce competition in the market exacerbates technology improvement decisions. The regulator in the market has been conscious of a firm's technology improvement decision and is committed to enacting many environmental policies to compel firms to upgrade their technology. In this research, we consider a supply chain consisting of a regulator and two symmetric competing firms that sell substitutable products to the market. This research aims to examine how should the firm make a technology improvement decision with the consideration of the regulator's environmental policy and the rival firm's upgrade decision.

The analytical result indicates that (a) whether the tax level is exogenously given or endogenously determined by the regulator, the firms' technology improvement decision is highly affected by the fixed cost incurred for the technology improvement; (b) depending on the fixed cost incurred for technology improvement, multiple equilibria may arise that will stabilize the improvement decisions of the two firms; and (c) the regulator can optimally adjust its tax policy to motivate the two firms to upgrade their technology and to maximize the total social welfare. These results are partly consistent with Yang et al. (2021) and Nie et al. (2021), which also found that the fixed cost incurred for the technology improvement is critical for a firm's technology improvement decision and market equilibrium when competition is considered. However, in contrast to Yang et al. (2021), this study finds that the two firms' may be trapped in a prisoner's dilemma when both of them choose to not improve their current technology as during when the market expansion effect caused by technology improvement can outweigh the cost-increasing effect. Furthermore, in contrast to considering the impact of government subsidy on a firm's technology improvement decision, this study indicates that the environmental tax imposed by the regulator can also motivate firms to upgrade to greener technology and achieve higher social welfare. This result complements the studies that examine the role of regulator policy on a firm's operational decisions, such as Cohen et al. (2019), Shen et al. (2020), and others.

We conclude with several limitations of the model and possible directions for future research. First, our model assumes that the regulator interferes with the market by imposing a tax on firms' environmental pollutants to induce them to make technology improvement decisions to decrease the environmental pollutants of the product. This assumption is reasonable as we use environmental emissions to measure the environmental impact of the product, and imposing a tax on firms' environmental emissions prevails in industry practice. In practice, there are many means that the regulator can be used to affect the whole market. For instance, the government can provide financial support to compensate firms' costs incurred for technology improvement as considered by Cohen et al. (2019). It would be interesting to examine how the regulator should interfere with the market, and which kind of policy is more economically and environmentally friendly than other kinds of policies. Second, to simplify the analysis, environmental impact in this research is measured by the production quantities that are manufactured by the firm and the products' emissions per unit. Numerous metrics can be used to measure environmental impact, such as the material used in products' production process, energy consumption, greenhouse gas emission, and so on (Yenipazarli, 2017, 2019). Future research could systematically measure the environmental impact of a product and then investigate how firms' and regulators' decisions are affected by such environmental impact. Third, this study considers that the two firms develop their greener technology independently to comply with most industry practices. However, in reality, it is very likely that the two firms may choose to cooperate with each other by co-developing the new technology as considered by Limoubpratum et al. (2015) and Raz et al. (2021). Future research can be extended to the case that the two firms choose to co-develop the greener technology and apply the cooperative game theory to examine the impact of cooperation on firms' technology improvement and the following environmental impact. Finally, to obtain analytical results, this study considers market competition between two firms and examines how one firm's improvement decision is affected by the other. It should be noted that the real market conditions are far more complex than what has been examined in this study. It would be interesting to examine a firm's technology improvement decision when multiple firms compete in the same market.

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The authors declare no conflict of interest in this research.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Appendix: Proofs

Proof of Proposition 1

In case NN when neither firm makes a technology improvement decision, the decision problems faced by the two firms are given by $\Pi_1^{NN}(p_1) = p_1 q_1 - t q_1$ and $\Pi_2^{NN}(p_2) = p_2 q_2 - t q_2$. The two firms make their pricing decisions independently and simultaneously. The two firms' optimization problem is concave with respect to p_1 and p_2 as $\frac{\partial^2 \Pi_1^{NN}}{\partial {p_1}^2} = -2 < 0$ and $\frac{\partial^2 \Pi_2^{NN}}{\partial {p_2}^2} = -2 < 0$. The first-order conditions of Π_1^{NN} and Π_2^{NN} are:

$$\frac{\partial \Pi_1^{NN}}{\partial p_1} = a - 2p_1 + bp_1 + t$$

$$\frac{\partial \Pi_2^{NN}}{\partial p_2} = a + bp_1 - 2p_2 + t \ .$$

Solving the two formulas by letting $\frac{\partial \Pi_1^{NN}}{\partial p_1} = 0$ and $\frac{\partial \Pi_2^{NN}}{\partial p_2} = 0$, we have $p_1^{NN} = p_2^{NN} = \frac{a+t}{2-b}$.

Then, the equilibrium production quantities for the two firms are: $q_1^{NN} = q_2^{NN} = \frac{a-(1-b)t}{2-b}$, and the corresponding profits for the two firms are: $\Pi_1^{NN} = \Pi_2^{NN} = \frac{(a-(1-b)t)^2}{(2-b)^2}$.

Proofs of Propositions 2 and 3 are similar to that of Proposition 1, so we omit the proving process.

Proof of Proposition 4

Since the two firms are symmetric, we only need to consider the strategy of firm 1 in calculating the Nash equilibrium between the two firms. We first consider the scenario where firm 2 does not make a technology improvement decision. Hence, we calculate

$\Pi_1^{NN}-\Pi_1^{IN}=\frac{(a-(1-b)t)^2}{(2-b)^2}-\frac{\left(a(2+b)-(2-b^2)c+2m-(2-b-b^2-2\alpha+b^2\alpha)t\right)^2}{(4-b^2)^2}+K=0$, which can be treated as a function of K. Letting $\Pi_1^{NN}-\Pi_1^{IN}=0$, we have $K_1=\frac{(a-(1-b)t)^2}{(2-b)^2}-\frac{\left(a(2+b)-(2-b^2)c+2m-(2-b-b^2-2\alpha+b^2\alpha)t\right)^2}{(4-b^2)^2}$. Therefore, $\Pi_1^{NN}>\Pi_1^{IN}$ if $K>K_1$, otherwise, $\Pi_1^{NN}\le\Pi_1^{IN}$.

We then consider the scenario where firm 2 also makes technology improvement decisions. Hence, we calculate $\Pi_1^{II}-\Pi_1^{NI}=\frac{\left(a-(1-b)c+m-(1-b)(1-\alpha)t\right)^2}{(2-b)^2}-K-\frac{\left(a(2+b)+b(c+m)-(2-b-b^2+b\alpha)t\right)^2}{(4-b^2)^2}=0$, which can also be treated as a function of K. Letting $\Pi_1^{II}-\Pi_1^{NI}=0$, we have $K_2=\frac{\left(a-(1-b)c+m-(1-b)(1-\alpha)t\right)^2}{(2-b)^2}-\frac{\left(a(2+b)+b(c+m)-(2-b-b^2+b\alpha)t\right)^2}{(4-b^2)^2}$. Therefore, $\Pi_1^{II}>\Pi_1^{NI}$ if $K<K_2$, otherwise, $\Pi_1^{II}\le\Pi_1^{NI}$.

Based on these, it is easy to prove Proposition 4.

Proof of Proposition 5

On the prisoner's dilemma, $\Pi_1^{II}-\Pi_1^{NN}=\frac{\left(a-(1-b)c+m-(1-b)(1-\alpha)t\right)^2}{(2-b)^2}-K-\frac{(a-(1-b)t)^2}{(2-b)^2}$. To solve the roots of $\Pi_1^{II}-\Pi_1^{NN}=0$, we have $K_3=\frac{\left(a-(1-b)c+m-(1-b)(1-\alpha)t\right)^2}{(2-b)^2}-\frac{(a-(1-b)t)^2}{(2-b)^2}$. Hence, $\Pi_1^{II}>\Pi_1^{NN}$ if $K<K_3$, otherwise $\Pi_1^{II}\le\Pi_1^{NN}$. Besides, $K_3-K_2=\frac{b\left(2a(2+b)+b(c+m)-(4-b(2+2b-\alpha))t\right)(c+m-\alpha t)}{(4-b^2)^2}>0$. Considering the Nash equilibrium outcomes in Proposition 4, it is easy to prove Proposition 5.

Proof of Corollary 1

To examine the monotonicity of K_1, K_2, K_3, and K_3-K_2 with respect to the environmental tax (i.e., t), we first need to calculate the first-order conditions of these parameters regarding the environmental tax. Hence, we have

$$\frac{\partial K_1}{\partial t}=\frac{\begin{pmatrix}2(2-b^2)c(2-b(1+b(1-\alpha))-2\alpha)-4m(2-b-b^2-2\alpha+b^2\alpha)\\+2(2-b^2)\alpha(a(2+b)-2(2-\alpha)t+b(2+2b-b\alpha)t)\end{pmatrix}}{(4-b^2)^2},$$

$$\frac{\partial K_2}{\partial t}=\frac{\begin{pmatrix}2(4-b^2(2+b)-4(2-b-b^2)m)m\alpha+2(2-b^2)c(2-b(1+b)-2\alpha+b(2+b)\alpha)\\-2(2-b^2)\alpha((4-2b(1+b)-2\alpha+b(2+b)\alpha)t-a(2+b))\end{pmatrix}}{(4+b^2)^2},$$

$$\frac{\partial K_3}{\partial t}=\frac{2(1-b)\left((1-b)c(1-\alpha)-m(1-\alpha)+\alpha\left(a-(1-b)(2-\alpha)t\right)\right)}{(2-b)^2},$$

$$\frac{\partial (K_3-K_2)}{\partial t}=\frac{2b\left(\alpha\left(4-b\left(2+2b-\alpha\right)\right)t-a\left(2+b\right)\alpha-(c+m)\left(2-b-b^2+b\alpha\right)\right)}{\left(4-b^2\right)^2}.$$

Based on these, it is difficult to know the monotonicity of K_1, K_2, K_3, and K_3-K_2 with respect to the environmental tax. Hence, we further examine the second-order conditions of K_1, K_2, K_3, and K_3-K_2 with respect to the environmental tax. Then, we have

$$\frac{\partial^2 K_1}{\partial t^2}=\frac{-2\left(2-b^2\right)\left(4-b\left(2+b\left(2-\alpha\right)\right)+2\alpha\right)\alpha}{\left(4-b^2\right)^2},$$

$$\frac{\partial^2 K_2}{\partial t^2}=\frac{-2\left(2-b^2\right)\alpha\left(4-2b\left(1+b\right)-2\alpha+b\left(2+b\right)\alpha\right)}{\left(4-b^2\right)^2},$$

$$\frac{\partial^2 K_3}{\partial t^2}=\frac{-2\left(1-b\right)^2\left(2-\alpha\right)\alpha}{\left(2-b\right)^2},$$

$$\frac{\partial^2 (K_3-K_2)}{\partial t^2}=\frac{2b\alpha\left(4-b\left(2+2b-\alpha\right)\right)}{\left(4-b^2\right)^2}.$$

It is easy to observe that $\frac{\partial^2 K_3}{\partial t^2}<0$ and $\frac{\partial^2 (K_3-K_2)}{\partial t^2}>0$, and hence, we conclude that K_3 concaves with respect to the environmental tax, whereas K_3-K_2 is a convex function. Solving the first-order condition of K_3 and K_3-K_2, thus, letting $\frac{\partial K_3}{\partial t}=0$ and $\frac{\partial (K_3-K_2)}{\partial t}=0$. We have $t_3=\frac{(1-b)c(1-\alpha)-m(1-\alpha)+a\alpha}{(1-b)(2-\alpha)\alpha}$ and $t_4=\frac{\left(2-b-b^2\right)\left(c+m\right)+a\left(2+b\right)\alpha+b\left(c+m\right)\alpha}{\alpha\left(4-b\left(2+2b-\alpha\right)\right)}$, respectively. However, it is difficult to know the property of $\frac{\partial^2 K_1}{\partial t^2}$ and $\frac{\partial^2 K_2}{\partial t^2}$.

To solve the roots of $\frac{\partial^2 K_1}{\partial t^2}=0$, we have $\alpha=0$ or $\alpha=2-\frac{2b}{2-b^2}$. $\alpha=2-\frac{2b}{2-b^2}>1$ if $0<b<\sqrt{3}-1$, and $\alpha=2-\frac{2b}{2-b^2}<1$ if $\sqrt{3}-1<b<1$. Hence, we have (1) if $0<b<\sqrt{3}-1$, then $\alpha = 2 - \frac{2b}{2-b^2} > 1$, and $\frac{\partial^2 K_1}{\partial t^2} < 0$ always exists; and (2) if $\sqrt{3} - 1 < b < 1$, then $\alpha = 2 - \frac{2b}{2-b^2} < 1$, $\frac{\partial^2 K_1}{\partial t^2} < 0$ if $0 < \alpha < 2 - \frac{2b}{2-b^2}$, and $\frac{\partial^2 K_1}{\partial t^2} > 0$ if $2 - \frac{2b}{2-b^2} < \alpha < 1$. To solve the roots of $\frac{\partial K_1}{\partial t} = 0$, we have

$$t_1 = \frac{\left(2-b-b^2\right)\left(\left(2-b^2\right)c - 2m\right) + \left(2-b^2\right)\left(a\left(2+b\right) - \left(2-b^2\right)c + 2m\right)\alpha}{\left(2-b^2\right)\left(4 - b\left(2 + b\left(2-\alpha\right)\right) - 2\alpha\right)\alpha}.$$

To solve the roots of $\frac{\partial^2 K_2}{\partial t^2} = 0$, we have $\alpha = 0$ or $\alpha = 2 + \frac{2b}{2 - b\left(2+b\right)} > 1$. Hence, $\frac{\partial^2 K_2}{\partial t^2} < 0$ always exists. To solve the roots of $\frac{\partial K_2}{\partial t} = 0$, we have

$$t_2 = \frac{\left(2-b-b^2\right)\left(\left(2-b^2\right)c - 2m\right) + \left(\left(2-b^2\right)\left(\left(2+b\right)\left(a+bc\right) - 2c\right) + \left(4 - b^2\left(2+b\right)\right)m\right)\alpha}{\left(2-b^2\right)\alpha\left(4 - 2b\left(1+b\right) - 2\alpha + b\left(2+b\right)\alpha\right)}.$$

Based on these, it is easy to prove Corollary 1.

Proof of Theorem 1

In case SII when both firms upgrade to new technology, the decision problem faced by the regulator is $\prod_r^{SII}(t) = \prod_1^{II} + \prod_2^{II} + t(1-\alpha)(q_1^{II} + q_2^{II}) - \beta(1-\alpha)(q_1^{II} + q_2^{II})$. Substituting the results obtained in Proposition 3, it is easy to calculate $\prod_r^{SII}(t)$. The regulator's optimization problem is concave with respect to the environmental tax as $\frac{\partial^2 \prod_r^{SII}}{\partial t^2} = -\frac{4\left(1-b\right)\left(1-\alpha\right)^2}{\left(2-b\right)^2} < 0$. The first-order conditions of $\prod_r^{SII}(t)$ are:

$$\frac{\partial \prod_r^{SII}}{\partial t} = \frac{2\left(1-\alpha\right)\left(ab - 2\left(1-\alpha\right)\left(t-\beta\right) + b\left(m - c + 2t - 2\alpha t - 3\left(1-\alpha\right)\beta\right) + b^2\left(c + \beta - \alpha\beta\right)\right)}{\left(2-b\right)^2}.$$

Letting $\frac{\partial \prod_r^{SII}}{\partial t} = 0$, we have $t^{SII} = \frac{1}{2}\left(\frac{b\left(a - \left(1-b\right)c + m\right)}{\left(1-b\right)\left(1-\alpha\right)} + \left(2-b\right)\beta\right)$.

Based on these, it is easy to prove Theorem 1.

Proof of Corollary 2

To prove Corollary 2, we need to solve the roots of $K_1 - K = 0$. To solve the roots of $K_1 - K = 0$, we have $t = t_1^{SII}$ or $t = t_2^{SII}$, where $t_1^{SII} = \frac{-B_1 - \sqrt{B_1^2 - 4A_1C_1}}{2A_1}$ and $t_2^{SII} = \frac{-B_1 + \sqrt{B_1^2 - 4A_1C_1}}{2A_1}$. And

$$A_1 = \frac{(1-b)^2}{(2-b)^2} - \frac{\left(2-b-b^2-2\alpha+b^2\alpha\right)^2}{\left(4-b^2\right)^2},$$

$$B_1 = \frac{-2a(1-b)}{(2-b)^2} + \frac{2\left(2-b-b^2-2\alpha+b^2\alpha\right)\left(a(2+b)-\left(2-b^2\right)c+2m\right)}{\left(4-b^2\right)^2},$$

$$C_1 = \frac{a^2}{(2-b)^2} - \frac{\left(a(2+b)-\left(2-b^2\right)c+2m\right)^2}{\left(4-b^2\right)^2} - K .$$

Based on these, it is easy to prove Corollary 2.

Proof of Proposition 6

Combining the results obtained in Theorem 1 and Corollary 2, Proposition 6 can be easily proved.

Proof of Theorem 2

In case SNN when both firms do not upgrade to new technology, the decision problem faced by the regulator is $\prod_r^{SNN}(t) = \prod_1^{NN} + \prod_2^{NN} + t(q_1^{NN} + q_2^{NN}) - \beta(q_1^{NN} + q_2^{NN})$. Substituting the results obtained in Proposition 1, it is easy to calculate $\prod_r^{SNN}(t)$. The regulator's optimization problem is concave with respect to the environmental tax as $\frac{\partial^2 \prod_r^{SNN}}{\partial t^2} = -\frac{4(1-b)}{(2-b)^2} < 0$. The first-order conditions of $\prod_r^{SNN}(t)$ are: $\frac{\partial \prod_r^{SNN}}{\partial t} = \frac{2\left(ab-(1-b)\left(2t-(2-b)\beta\right)\right)}{(2-b)^2}$. Letting $\frac{\partial \prod_r^{SNN}}{\partial t} = 0$, we have $t^{SNN} = \frac{ab+(2-b)(1-b)\beta}{2-2b}$.

Based on these, it is easy to prove Theorem 2.

Proof of Corollary 3

To prove Corollary 3, we need to solve the roots of $K_2 - K = 0$, To solve the roots of $K_2 - K = 0$, we have $t = t_1^{SNN}$ or $t = t_2^{SNN}$, where $t_1^{SNN} = \frac{-B_2 - \sqrt{B_2^{\,2} - 4A_2C_2}}{2A_2}$ and $t_2^{SNN} = \frac{-B_2 + \sqrt{B_2^{\,2} - 4A_2C_2}}{2A_2}$. And $A_2 = \frac{(1-b)^2(1-\alpha)^2}{(2-b)^2} - \frac{\left(2-b-b^2+b\alpha\right)^2}{\left(4-b^2\right)^2}$,

$$B_2 = \frac{-2(1-b)(1-\alpha)\left(a-(1-b)c+m\right)}{(2-b)^2} + \frac{2\left(2-b-b^2+b\alpha\right)\left(a(2+b)+b(c+m)\right)}{\left(4-b^2\right)^2},$$

$$C_2 = \frac{\left(a-(1-b)c+m\right)^2}{(2-b)^2} - \frac{\left(a(2+b)+b(c+m)\right)^2}{\left(4-b^2\right)^2} - K .$$

Based on these, it is easy to prove Corollary 3.

Proof of Proposition 7

Combining the results obtained in Theorem 2 and Corollary 3, Proposition 7 can be easily proved.

This completes the proof.

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