Economic Society and Humanities Vol. 2 No. 7, 2025

Environmental Corporate Social Responsibility, The Organization of E-R&D and Environmental Regulations: Taxes Versus Standards

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Abstract: A substantial body of empirical research indicates a growing corporate engagement with Environmental Corporate Social Responsibility (ECSR). By integrating environmental damage into the firms' objective function, this study examines and contrasts two types of environmental regulation—emissions taxes (ET) and emissions standards (ES)—within a Cournot competition framework. The model incorporates product differentiation and three distinct organizational forms of "green" innovation (E-R&D). From a firm's perspective, it is crucial to align environmental instruments with both ECSR and market power. In a highly competitive market, where the level of social concern is minimal, the most profitable strategies are, in the case of ET and ES, respectively, Environmental Research Joint Venture (ERJV) cartelization and ERJV competition. When societal concern reaches a sufficiently high level, non-cooperative R&D emerges as the optimal choice for ET. On the other hand, for the ES scenario, engaging in ERJV competition is the most advantageous approach. In a monopolistic market with low social concern, firms achieve the highest profits under ET through ERJV cartelization, while under ES, non-cooperative R&D proves most beneficial. However, as societal concern intensifies, non-cooperative R&D emerges as the dominant strategy under both regulatory instruments. Additionally, we analyze the influence of environmental regulations on environmentally friendly innovation and derive implications for environmental instruments.

Keywords: E-R&D; Taxes; Standards; Cournot; ECSR; Production Differentiation

1. Introduction

Over recent decades, corporate social responsibility (CSR) has evolved into a key business strategy, with mounting empirical studies confirming active firm engagement in CSR practices. This trend has drawn growing scholarly interest. Empirical evidence shows that high-quality sustainability reporting is closely associated with firms' environmental, social, and governance (ESG) performance, especially for firms with high institutional ownership [1]. Firms' voluntary initiatives to mitigate environmental impacts are central to the concept of environmental corporate social responsibility (ECSR). Factors that influence ECSR include R&D investments [2-4], cross-ownership [5], international trade [6], and the strategic use of ECSR [7,8].

Without government-led environmental regulations, firms lack the economic motivation to account for the negative externalities of pollution, and thus have little reason to invest in emission reduction. To address this, policymakers implement environmental instruments aimed at compelling businesses to internalize the costs associated with their emissions. In context of ECSR, the model setting of this research consists of two kinds of environmental instruments: emissions taxes (ET) and emissions standards (ES). Under an ET regime, firms are levied a fixed charge per unit of pollutant released. In contrast, an ES policy imposes a uniform cap on total permissible emissions, compelling firms to undertake necessary abatement measures to remain within the mandated limit.

To compare these instruments, we develop a duopoly model in which firms undertake "green" innovation (E-R&D) under three organizational modes: (i) R&D competition, characterized by noncooperative investment and voluntary knowledge disclosure; (ii) Environmental Research Joint Venture (ERJV) competition, featuring noncooperative investment alongside full knowledge sharing; and (iii) ERJV cartelization, with cooperative investment and full information sharing.

The results indicate that optimal policy and R&D organization depend on firms' ECSR level and market competition. In competitive markets with low social concern, highest profits arise under ET with ERJV cartelization and under ES with ERJV competition. With high social concern, non-cooperative R&D is optimal under ET, while ERJV competition remains preferable under ES. In monopolistic settings with low social concern, ERJV cartelization (ET) and non-cooperative R&D (ES) yield the highest profits; under high concern, non-cooperative R&D is optimal under both policies. We further analyze how environmental regulations affect green innovation and derive policy implications. Under ES, environmental regulators should promote ERJV cartelization, while welfare-oriented regulators should support non-cooperative R&D. Under ET, ERJV cartelization is preferred overall. Environmental regulators should favor ES, whereas economically oriented regulators should implement ET.

The remainder of this paper is structured as follows: Section 2 reviews literature on ECSR and E-R&D; Sections3-5present the basic model and analytical results; Section6 contrasts key findings; Section 7 draws conclusions.

2. Literature Review

This study aligns with two primary streams of scholarly work: one examining E-R&D under emission regulations, and the other comparing different environmental policy instruments.

2.1 Emission Regulation and E-R&D

This stream of literature examines firms' E-R&D investments under emission taxes, utilizing game-theoretic frameworks to analyze strategic choices in R&D organization—cooperative versus noncooperative—under varying market structures (e.g., Bertrand vs. Cournot) and policy commitment regimes.

A seminal contribution by Poyago-Theotoky [9] compares cooperative and noncooperative R&D, showing that cooperative E-R&D leads to higher investment when innovation efficiency is high. Pan et al. [10] further demonstrate that firms abstain from abatement and E-R&D when environmental awareness is low. Requate [11] explores the role of policy commitment in technology adoption, finding that committing to a tax menu yields higher social welfare. Ulph and Ulph [12] show that without government commitment to long-term taxation, industry profits decline, underscoring the need for additional regulatory incentives. Lambertini et al. [13] observe an inverted U-shaped pattern linking market competition to E-R&D investment.

2.2 Comparison of Environmental Policies

A second strand of literature compares two primary environmental policy instruments: taxes and standards. Helfand [14] synthesizes core viewpoints, indicating that under conditions of certainty and homogeneous firms, taxes and standards may achieve equivalent efficiency in social welfare maximization. In contrast, Baumol and Oates [15] demonstrate the superiority of taxes under heterogeneous firms. Heuson [16] demonstrates that taxes maintain a comparative advantage in markets with imperfect competition and uncertain abatement costs. Conversely, Lahari and Ono [17] find that under fixed firm numbers, relative emission standards can be welfare-superior to equivalent taxes. Moreover, the efficacy of these instruments depends critically on regulatory commitment [18,19]. Recent extensions incorporate cross-ownership and R&D cooperation [20,21], though these studies typically omit ECSR and product differentiation, which are central to our analysis.

3. Theoretical Background and the Model

3.1 Theoretical Background

This paper employs a Cournot duopoly framework to analyze environmental regulation in an industry where firms undertake "green" innovation (E-R&D) to curb production emissions. We consider three E-R&D organizational modes: (i) R&D competition, with noncooperative investment and voluntary knowledge disclosure; (ii) Environmental Research Joint Venture (ERJV) competition, featuring noncooperative investment but full knowledge sharing; and (iii) ERJV cartelization, involving cooperative investment and full information sharing.

We compare firm profits and social welfare under two environmental regulations. One is Emissions Taxes ET with uniform tax per unit pollution. The other is Emissions Standards ES with uniform total emission upper limit and firms must abate to comply. Key variables are defined in Table 1.

Table 1. Variables in our model

Symbols	Variables
i,j	Firms
U	the utility function
m	The consumption of a numeraire good
p	the price of products
t	Emission tax per unit
T	Total emission tax
$\bar{e}$	The emission standard
e	Firms' emissions
θ	The degree of ECSR
z	E-R&D efforts
δ	The efficiency of E-R&D
γ	The degree of product differentiation
c	The cost functions
q	Products quantities
d	The coefficient of environmental damage
β	E-R&D spillovers
π	Firm's profits
V	The objective function
CS	Consumer surplus
SW	Social welfare
superscript *	Equilibrium results
superscript N	non-cooperative R&D under emissions taxes
superscript C	ERJV competition under emissions taxes
superscript A	ERJV cartelization under emissions taxes
superscript NS	non-cooperative R&D under emissions standards
superscript CS	ERJV competition under emissions standards
superscript AS	ERJV cartelization under emissions standards

3.2 The model

In a duopoly where firms i and j produce quantities qi and qj, the consumer's utility function is given by:

$$U=a(q_i+q_j)-\frac{(q_i^2+2\gamma q_i q_j+q_j^2)}{2}+m \quad (1)$$

where m denotes the consumption of a numeraire good, a stands for market size, and product differentiation is measured by γ ∈ [0, 1].

$$p_i=1-q_i-\gamma q_j, p_i=1-q_j-\gamma q_i \quad (2)$$

We assume production generates emissions, which the government either taxes at a per-unit rate t (emissions taxes) or regulates via emissions standards. Firms i and j can lower their tax costs through E-R&D efforts i.e., z_i and z_j, to reduce emissions, but they must invest in E-R&D individually, with the following cost functions:

$$C_i=\frac{\delta z_i^2}{2}, C_j=\frac{\delta z_j^2}{2} \quad (3)$$

where δ denotes E-R&D efficiency. For simplicity, we assume δ=1, with each unit of output generating one unit of pollution. Thanks to E-R&D investment, firms' emissions are reduced to

$$e_i=(1-z_i-\beta z_j)q_i, \quad e_j=(1-z_j-\beta z_i)q_j \quad (4)$$

where β measures E-R&D spillovers. For simplicity, we assume β=0 in the case of E-R&D competition and β=1 for both ERJV competition and ERJV cartelization. Additionally, aggregate E-R&D efforts are $Z=z_i+z_j$. Thus, the profits of firms i and j are

$$\pi_i=p_i q_i-C_i-te_i-F, \pi_j=p_j q_j-C_j-te_j-F \quad (5)$$

where emission taxation T is a linear function of firms' emissions. Thus, total emissions from firms are $E=e_i+e_j$, and environmental damage (D) follows a quadratic function of emissions, dE^2, with d representing marginal damages. To simplify result presentation, we assume d=1/2 without loss of generality. Additionally, F denotes fixed costs, which are assumed to be zero.

In line with prior research Lambertini and Tampieri [17], Lee and Park [9], and Fukuda and Ouchida [2], this study posits that firms internalize a portion of the environmental damage they generate, reflecting their sense of environmental responsibility. Consequently, each firm incorporates the cost of its own emissions into its objective function, creating an incentive to invest in cleaner production technologies. Furthermore, a firm's decision to share R&D knowledge may also affect the emissions of its competitor. Thus, the objective function for firm i is specified as:

$$V_i=\pi_i-\theta D_i \quad (6)$$

where parameter θ (θ∈ [0, 1]) is assumed to be exogenously determined and identical for both firms, representing the degree of ECSR—i.e., the weight firm i assigns to the environmental damage it causes, beyond its own profits. Thus, θ=0 indicates firm i solely focuses on profits, while a higher θ reflects greater concern for environmental damage on the firm's part. ECSR can therefore be treated as exogenously given. As is standard, consumer surplus is defined as

$$CS=(q_i^2+q_j^2+2\gamma q_i q_j)/2 \tag{7}$$

and the total tax revenue collected by the government amounts to

$$T=t(e_i+e_j) \tag{8}$$

Consistent with the mainstream literature on E-R&D, social welfare is defined as the sum of industry profits and consumer surplus, minus environmental damage, with emission tax revenues excluded:

$$W=\pi_i+\pi_j+CS+T-D \tag{9}$$

4. Environmenal R&D Under Emissions Taxes

Under the ET policy, the game sequence unfolds in three stages. Initially, the government sets the welfare-maximizing emission tax. Firms then decide on entry and invest in emission-reduction technologies. Finally, firms choose output levels simultaneously. The subgame perfect Nash equilibrium is derived through backward induction.

4.1 Environmental R&D Competition

Under R&D competition, firms make noncooperative decisions regarding their R&D investments, and this scenario is marked by the superscript N.

4.1.1 Production

In the final stage of this game, firm i selects the output level qi that maximizesVi, with the first-order condition expressed as

$$\frac{\partial V_i}{\partial q_i}=1-t-q_j\gamma-\frac{\theta(2q_i-2z_i)}{2}-2q_i=0, \tag{10}$$

Solving the aforementioned equation yields

$$q_i^N(q_j,z_i,z_j,t)=\frac{1-t+\theta z_1-\gamma q_j}{\theta+2} \tag{11}$$

The output and objective function of the firms are given by

$$q_i^N(z_i,z_j,t)=\frac{1-t+\theta z_1}{\theta+2},$$
$$V_i^N(z_i,z_j,t)=\frac{2\theta z_i-2t+2\theta z_j+4tz_i+4tz_j-4\theta z_i^2-2\theta z_j^2+t^2-4z_i^2-4\theta z_i z_j+1}{2(\theta+2)}. \tag{12}$$

4.1.2 "Green" innovation

In this E-R&D phase, firms i and j undertake abatement efforts to lower their tax burdens, with the first-order condition given as

$$\frac{\partial V_i}{\partial z_i}=\frac{\theta-4z_i+2t-4\theta z_i}{\theta+2}=0, \tag{13}$$

which gives rise to the following corporate reaction functions:

$$z_i^N(z_j)=\frac{\theta+2t}{4(\theta+1)}. \tag{14}$$

From the aforementioned equation, the coefficients of zj in zi(zj) and zi in zj(zi) are zero, leading to the following lemma:

Lemma 1: There is no connection between the effort of E-R&D by two firms under environmental R&D competition case.

Solving the firms' E-R&D effort reaction functions yields:

$$z_i^N(t)=\frac{\theta+2t}{4(\theta+1)},$$
$$\pi_i^N(t)=\frac{\theta^2+8\theta t^2-8\theta t+4\theta+4t^2-4t+2}{8(\theta+1)^2}, \tag{15}$$
$$W_i^N(t)=\frac{5\theta^2-20\theta t+20\theta-28t^2+8t+8}{16(\theta+1)^2}.$$

4.1.3 Environmental taxation

In the first stage, the government commits to a welfare-maximizing emissions tax. Solving the first-order condition from the social welfare equation yields the optimal tax rate in equilibrium.:

$$t^{N*}=\frac{2-5\theta}{14}. \tag{16}$$

Where the subscript * indicates the equilibrium result, applying emissions taxes to the above equations yields the equilibrium E-R&D efforts, firm profits, consumer surplus, and other variables.

$$q_i^{N*}=q_j^{N*}=\frac{3}{7},z_i^{N*}=z_j^{N*}=\frac{1}{14},$$
$$e_i^{N*}=e_j^{N*}=\frac{5}{14}, \tag{17}$$
$$\pi_i^{N*}=\pi_j^{N*}=\frac{37+25\theta}{196},CS^{N*}=\frac{9}{49},$$

We then derive the aggregate equilibrium emissions, total tax revenue, and environmental damage. Finally, substituting Eq. (17) into Eq. (9) yields total welfare.

$$SW^{N*}=\pi_i^{N*}+\pi_j^{N*}+CS^{N*}+T^{N*}-D^{N*}=\frac{15}{28} \tag{18}$$

4.2 Environmental Research Joint Venture Competition

Under the Environmental Research Joint Venture (ERJV) framework, firms independently set their R&D investment levels but agree to fully share all innovation results. This scenario is labeled with superscript C.

4.2.1 Production

In the final stage of this game, firm i selects the output level qi that maximizes Vi, with the first-order condition expressed as

$$\frac{\partial V_i}{\partial q_i}=1-t-q_j\gamma-\frac{\theta(2q_i-2z_i-2z_j)}{2}-2q_i=0. \quad (19)$$

Solving the aforementioned equation yields

$$q_i^C\left(q_j,z_i,z_j,t\right)=\frac{1-t+\theta z_i+\theta z_j-\gamma q_j}{\theta+2}. \quad (20)$$

The output and the objective function of the firms are given by

$$q_i^C(z_i,z_j,t)=\frac{\theta z_i-t+\theta z_j+1}{\theta+2},$$
$$V_i^C(z_i,z_j,t)=\frac{2\theta z_i-2t+2\theta z_j+4tz_i+4tz_j-4\theta z_i^2-2\theta z_j^2+t^2-4z_i^2-4\theta z_iz_j+1}{2(\theta+2)}. \quad (21)$$

4.2.2 "Green" innovation

In this E-R&D phase, firms i and j undertake abatement efforts to lower their tax burdens, with the first-order condition given as

$$\frac{\partial V_i}{\partial z_i}=\frac{\theta-(4z_i-2t+4\theta z_i+2\theta z_j)}{\theta+2}=0, \quad (22)$$

which gives rise to the following corporate reaction functions:

$$z_i^C(z_j)=\frac{\theta+2t-2\theta z_j}{4(\theta+1)}. \quad (23)$$

From the aforementioned equation, the coefficients of zj in zi(zj) and zi in zj(zi) are negative, leading to the following lemma:

Lemma 2: the effort of E-R&D by two firms is substitutable under environmental research joint venture competition case.

The intuition behind this lemma stems from strategic substitution in abatement efforts: when one firm commits to E-R&D investment, it reduces the rival's incentive to undertake similar R&D activities. By solving the reaction functions of both firms, we obtain:

$$z_i^C(t)=\frac{\theta+2t}{6\theta+4},$$
$$\pi_i^C(t)=\frac{7\theta^2+36\theta t^2-20\theta t+12\theta+16t^2-8t+4}{(3\theta+2)^2}, \quad (24)$$
$$W_i^C(t)=\frac{9\theta^2-12\theta t+16\theta-24t^2+8t+4}{(3\theta+2)^2}.$$

4.2.3 Environmental taxation

In this part, the government commits to a welfare-maximizing emissions tax. Solving the first-order condition from the social welfare function yields the optimal tax rate in equilibrium.

$$t^{C*}=\frac{2-3\theta}{12}. \quad (25)$$

Here, the subscript * denotes the equilibrium outcome. After incorporating emission taxes into the model, the resulting equilibrium levels of E-R&D effort, firm profits, and consumer surplus are derived as follows.

$$q_i^{C*}=q_j^{C*}=\frac{5}{12},$$
$$z_i^{C*}=z_j^{C*}=\frac{1}{12},$$
$$e_i^{C*}=e_j^{C*}=\frac{1}{4}, \quad (26)$$
$$\pi_i^{C*}=\pi_j^{C*}=\frac{7+9\theta}{144},$$
$$CS^{C*}=\frac{25}{144},$$

Finally, substituting Eq. (26) into Eq. (9) yields total welfare.

$$SW^{C*}=\pi_i^{C*}+\pi_j^{C*}+CS^{C*}+T^{C*}-D^{C*}=\frac{7}{12} \quad (27)$$

4.3 Environmental Research Joint Venture Cartelization

Under ERJV cartelization, firms collaboratively determine their R&D investments to maximize joint profits and agree to fully share R&D result-related information. This scenario is marked by the superscript A.

4.3.1 Production

In the final stage of this game, firm i selects the output level qi that maximizes Vi, with the first-order condition expressed as

$$\frac{\partial V_i}{\partial q_i}=1-t-q_j\gamma-\frac{\theta(2q_i-2z_i-2z_j)}{2}-2q_i=0. \quad (28)$$

Solving the aforementioned equation yields

$$q_i^A(q_j,z_i,z_j,t)=\frac{1-t+\theta z_i+\theta z_j-\gamma q_j}{\theta+2}. \quad (29)$$

For simplicity, we present the results when γ=0 in the following part of this section. The output and the objective function of the firms are given by

$$q_i^A(z_i,z_j,t)=\frac{\theta z_i-t+\theta z_j+1}{\theta+2},$$
$$V_i^A(z_i,z_j,t)=\frac{2\theta z_i-2t+2\theta z_j+4tz_i+4tz_j-4\theta z_i^2-2\theta z_j^2+t^2-4z_i^2-4\theta z_iz_j+1}{2(\theta+2)}. \quad (30)$$

4.3.2 "Green" innovation

In this phase of environmental R&D, both firms undertake abatement initiatives to alleviate their tax liabilities. Firm i determines its R&D investment level to optimize the collective objective function of the firms. The first-order condition is derived as follows

$$\frac{\partial(V_i+V_j)}{\partial z_i}=\frac{\theta-2(2z_i-2t+3\theta z_i+2\theta z_j)}{\theta+2}=0, \tag{31}$$

which gives rise to the following corporate reaction functions:

$$z_i^A(z_j)=\frac{\theta+2t-2\theta z_j}{3\theta+2}. \tag{32}$$

From Lemma 2 and the derived reaction function, E-R&D efforts between the two firms are strategic substitutes. Consequently, one firm's increased investment in E-R&D reduces its rival's incentive to undertake similar activities. Solving the system of reaction functions yields the following equilibrium:

$$z_i^A(t)=\frac{\theta+2t}{5\theta+2},\quad \pi_i^A(t)=\frac{5\theta^2+25\theta t^2-10\theta t+5\theta+5t^2-2t+1}{(5\theta+2)^2},\quad W_i^A(t)=\frac{2(7\theta^2-7\theta t+7\theta-17t^2+4t+1)}{(5\theta+2)^2}. \tag{33}$$

4.3.3 Environmental taxation

In this part, the government commits to a welfare-maximizing emissions tax. Solving the first-order condition of the social welfare function yields the optimal tax rate in equilibrium:

$$t^{A*}=\frac{4-7\theta}{34}. \tag{34}$$

The subscript * denotes equilibrium outcomes. After incorporating emission taxes into the model, the resulting equilibrium values for E-R&D efforts, firm profits, consumer surplus, and other key variables are derived as follows.

$$q_i^{A*}=q_j^{A*}=\frac{15}{34},\quad z_i^{A*}=z_j^{A*}=\frac{2}{17},\quad e_i^{A*}=e_j^{A*}=\frac{7}{34},\quad \pi_i^{A*}=\pi_j^{A*}=\frac{241+49\theta}{1156},\quad CS^{A*}=\frac{225}{1156}, \tag{35}$$

Finally, substituting Eq. (35) into Eq. (9) yields total welfare.

$$SW^{A*}=\pi_i^{A*}+\pi_j^{A*}+CS^{A*}+T^{A*}-D^{A*}=\frac{2}{3} \tag{36}$$

4.4. Comparative Statics and Comparison of the Equilibrium Results

This section conducts a specific analysis of the impacts of product differentiation and ECSR degree. We perform comparative static analysis on the equilibrium outcomes across the three cases.

Based on the equilibrium results, the comparative static findings associated with θ can be summarized as follows:

Proposition 1: (i) for $1\geq\gamma>0$, under ERJV competition and ERJV cartelization cases, $\frac{\partial t}{\partial\theta}<0, \frac{\partial q}{\partial\theta}<0, \frac{\partial z}{\partial\theta}<0, \frac{\partial e}{\partial\theta}<0, \frac{\partial\pi}{\partial\theta}>0, \frac{\partial CS}{\partial\theta}<0, \frac{\partial W}{\partial\theta}<0$; (ii) while uner non-cooperative R&D case ($1\geq\gamma>0$), $\frac{\partial t}{\partial\theta}<0, \frac{\partial q}{\partial\theta}>0, \frac{\partial z}{\partial\theta}>0, \frac{\partial e}{\partial\theta}>0, \frac{\partial\pi}{\partial\theta}>0, \frac{\partial CS}{\partial\theta}>0, \frac{\partial W}{\partial\theta}>0$; (iii) for $\gamma=0$, under all three cases, $\frac{\partial t}{\partial\theta}<0, \frac{\partial q}{\partial\theta}=0, \frac{\partial z}{\partial\theta}=0, \frac{\partial e}{\partial\theta}=0, \frac{\partial\pi}{\partial\theta}>0, \frac{\partial CS}{\partial\theta}=0, \frac{\partial W}{\partial\theta}=0$.

Proof. Case i and ii are nearly same as those in Barcena-Ruiz et al. (2023). However, when $\gamma=0$, $\frac{\partial t^{N*}}{\partial\theta}=-2/7$, $\frac{\partial t^{N*}}{\partial\theta}=-1/6$, $\frac{\partial t^{N*}}{\partial\theta}=-13/98$, $\frac{\partial\pi_i^{N*}}{\partial\theta}=4/49$, $\frac{\partial\pi_i^{N*}}{\partial\theta}=1/36$, and $\frac{\partial\pi_i^{N*}}{\partial\theta}=169/9604$. As a result, we have $\frac{\partial t}{\partial\theta}<0$ and $\frac{\partial\pi}{\partial\theta}>0$. In addition, we check that $\frac{\partial q}{\partial\theta}=0, \frac{\partial z}{\partial\theta}=0, \frac{\partial e}{\partial\theta}=0, \frac{\partial CS}{\partial\theta}=0, \frac{\partial W}{\partial\theta}=0$.

The optimal emissions taxes are decreasing in θ beacause of two factors: the under-production effect and the pollution-internalization effect. First, under imperfect competition, the optimal tax addresses underproduction from firms' market power, which tends to lower the tax. Second, the tax increases to push firms to internalize environmental damage and reduce pollution. When firms prioritize ECSR, the optimal tax is also influenced by parameter θ: a higher θ boosts firms' environmental awareness, making them account for more of their generated damage—for a given tax, this encourages production and emission cuts. This strengthens the underproduction effect and weakens the pollution-internalization effect, causing the environmental tax to decrease with θ ($\frac{\partial t}{\partial\theta}<0$).

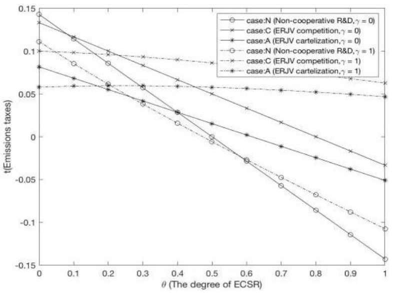
Firms' output is shaped by two opposing factors: the government-imposed tax and their level of ECSR concern. First, a higher θ leads the government to set a lower tax, which incentivizes firms to boost production. Second, as θ increases, firms become more attentive to their pollutant emissions by internalizing their pollution share, driving them to reduce output. According to thess two effects, we have the following intuition: (i) (i) In case i, when firms collaborate on R&D, the ECSR effect (which reduces output) outweighs the tax effect; thus, a rise in θ prompts firms to cut production ($\frac{\partial q}{\partial \theta}<0$); (ii) In case ii, since firms do not disclose information, the tax effect dominates the ECSR effect. Therefore, an increase in θ encourages firms to boost production ($\frac{\partial q}{\partial \theta}>0$); (iii) Under case iii, in amonopoly market, two opposite factors totally counteract with each other, so the change in θ makes no difference to firms' output ($\frac{\partial q}{\partial \theta}=0$); A graphical representation of results is shown in Figure 1~3.

Finally, on the basis of the above analysis, we can explain the rest factors. Take the case i for instance. As firms' output decreases with θ, consumer surplus and firms' profits also decline with γ ($\frac{\partial \pi}{\partial \theta}<0, \frac{\partial CS}{\partial \theta}<0$). While firms reduce abatement efforts as the variable decreases, the reduced production leads to lower pollutant emissions ($\frac{\partial e}{\partial \theta}<0$). Ultimately, social welfare falls with the variable, driven by lower industry profits and consumer surplus ($\frac{\partial W}{\partial \theta}<0$).

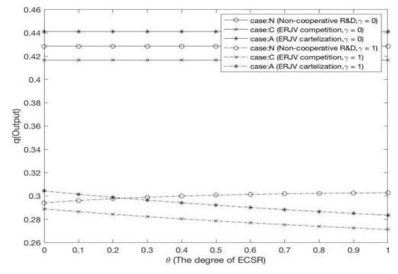
Based on the equilibrium results, the comparative static findings associated with γ can be summarized as follows:

Proposition 2: under all three cases, $\frac{\partial t}{\partial \gamma}>0, \frac{\partial q}{\partial \gamma}<0, \frac{\partial z}{\partial \gamma}<0, \frac{\partial e}{\partial \gamma}<0, \frac{\partial \pi}{\partial \gamma}<0, \frac{\partial CS}{\partial \gamma}<0, \frac{\partial W}{\partial \gamma}<0$.

Proof. To simplify the result, we present the proof when γ=0 and γ=1. From the results of comparative statics in following table, we have $\frac{\partial t}{\partial \gamma}>0, \frac{\partial q}{\partial \gamma}<0, \frac{\partial z}{\partial \gamma}<0, \frac{\partial e}{\partial \gamma}<0, \frac{\partial \pi}{\partial \gamma}<0, \frac{\partial CS}{\partial \gamma}<0, \frac{\partial W}{\partial \gamma}<0$ under all three cases. The comparative static results of variables with respect to γ under ET policy are presented in Table 2.

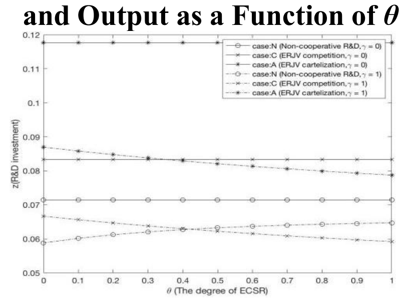


(a) Tax rate

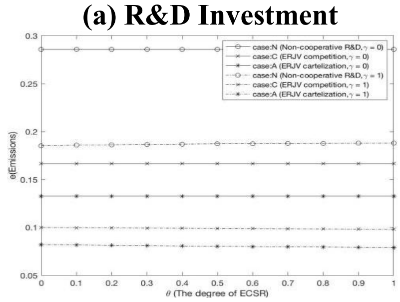


(b) Output level

Figure 1. The Equilibrium Results of Taxes and Output as a Function of *θ*

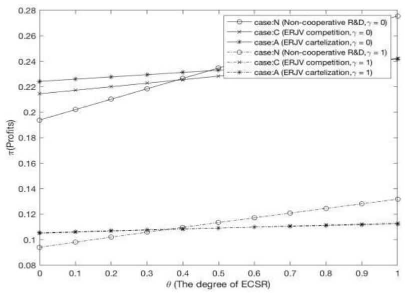


(a) R&D Investment

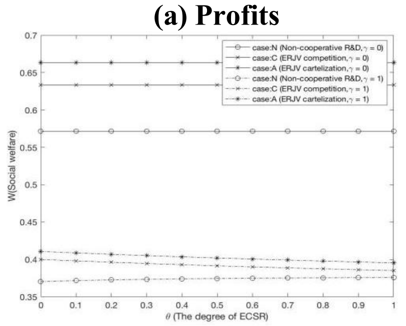


(b) Emissions

Figure 2. The Equilibrium Results of R&D Investment and Emissions as a Function of *θ*



(a) Profits



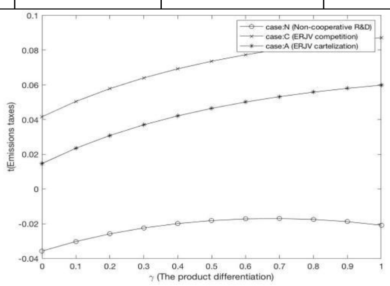
(b) Social welfare

Figure 3. The Equilibrium Results of Profits and Social Welfare as a Function of *θ*

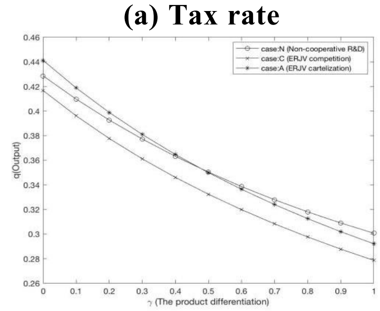
The optimal emission tax exhibits a negative relationship with γ, primarily attributable to the under-production effect. Under imperfect competition, the optimal tax accounts for output reduction resulting from firms' market power, thereby lowering the tax rate. As γ increases, intensified competition diminishes firms' market power. Under a constant tax rate, this induces greater output and higher abatement efforts, attenuating the under-production effect. Consequently, to curb excessive production, regulators must raise the tax rate correspondingly with γ ($\frac{\partial t}{\partial \gamma}>0$), which in turn discourages abatement. Declining output levels subsequently reduce both consumer surplus and firms' profits γ ($\frac{\partial \pi}{\partial \gamma}<0, \frac{\partial CS}{\partial \gamma}<0$). Despite reduced abatement, lower output ultimately leads to lower pollutant emissions ($\frac{\partial e}{\partial \gamma}<0$). Overall, social welfare declines as γ increases, owing to reduced industry profits and consumer surplus ($\frac{\partial W}{\partial \gamma}<0$). These relationships are illustrated graphically in Figures 4~6.

Table 2. The Results of Comparative Statics When Γ=0 and Γ=1 under ET Case

Case N	comparative statics (∂/∂γ)		Case C	comparative statics (∂/∂γ)		Case A	comparative statics (∂/∂γ)	
	γ=0	Θ=1		γ=0	γ=1		γ=0	γ=1
t^{N*}	0.11	0.03	t^{C*}	0.19	0.04	t^{A*}	0.2	0.04
q_i^{N*}	-0.19	-0.07	q_i^{C*}	-0.25	-0.09	q_i^{A*}	-0.28	-0.1
z_i^{N*}	-0.04	-0.01	z_i^{C*}	-0.07	-0.03	z_i^{A*}	-0.1	-0.03
e_i^{N*}	-0.15	-0.06	e_i^{C*}	-0.12	-0.04	e_i^{A*}	-0.09	-0.03
π_i^{N*}	-0.26	-0.08	π_i^{C*}	-0.25	-0.07	π_i^{A*}	-0.25	-0.07
CS^{N*}	-0.02	-0.01	CS^{C*}	-0.03	-0.03	CS^{A*}	-0.05	-0.03
W^{N*}	-0.31	-0.12	W^{C*}	-0.42	-0.15	W^{A*}	-0.46	-0.16

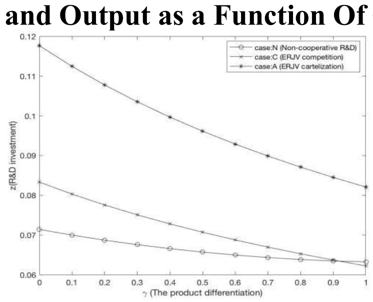


(a) Tax rate

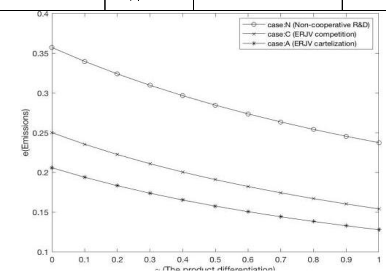


(b) Output level

Figure 4. The Equilibrium Results of Taxes and Output as a Function Of γ

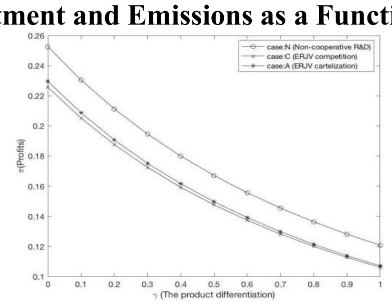


(a) R&D investment

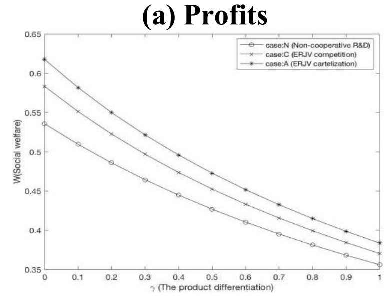


(b) emissions

Figure 5. The Equilibrium Results Of R&D Investment and Emissions as a Function Of γ



(a) Profits



(b) Social Welfare

Figure 6. The Equilibrium Results of Profits and Social Welfare as a Function of γ

Next, we examine and contrast governmental tax levels, output, environmental R&D investment, emissions, profits, consumer surplus, and aggregate social welfare across the three scenarios.

Proposition 3: (i) for $1 \geq \gamma > 0$, when degree of ECSR of firms is small ($\theta \to 0$), $t^{N*} > t^{C*} > t^{A*}$, $q_i^{A*} > q_i^{C*} > q_i^{N*}$, $z_i^{A*} > z_i^{N*} > z_i^{C*}$, $e_i^{N*} > e_i^{C*} > e_i^{A*}$, $\pi_i^{A*} > \pi_i^{C*} > \pi_i^{N*}$, $CS^{A*} > CS^{C*} > CS^{N*}$, $W^{A*} > W^{C*} > W^{N*}$ and when degree of ECSR of firms is large ($\theta \to 1$), $t^{C*} > t^{A*} > t^{N*}$, $q_i^{N*} > q_i^{A*} > q_i^{C*}$, $z_i^{N*} > z_i^{A*} > z_i^{C*}$, $e_i^{N*} > e_i^{C*} > e_i^{A*}$, $\pi_i^{N*} > \pi_i^{A*} > \pi_i^{C*}$, $CS^{N*} > CS^{A*} > CS^{C*}$, $W^{A*} > W^{C*} > W^{N*}$; (ii) for $\gamma=0$, $t^{N*} > t^{C*} > t^{A*}$ ($\theta \to 0$), $t^{C*} > t^{A*} > t^{N*}$ ($\theta \to 1$), $q_i^{A*} > q_i^{C*} > q_i^{N*}$, $z_i^{A*} > z_i^{N*} > z_i^{C*}$, $e_i^{N*} > e_i^{C*} > e_i^{A*}$, $\pi_i^{A*} > \pi_i^{C*} > \pi_i^{N*}$ ($\theta \to 0$), $\pi_i^{N*} > \pi_i^{A*} > \pi_i^{C*}$ ($\theta \to 1$), $CS^{A*} > CS^{N*} > CS^{C*}$, $W^{A*} > W^{C*} > W^{N*}$.

Proof. To simplify the result, we present the proof when γ=0 and γ=1. From the equilibrium results in the following tables, we can directly compare the government-set taxes, production levels, E-R&D investments, emissions, profits, consumer surplus, and total social welfare. Table 3 reports the equilibrium results of the three E-R&D scenarios under the ET policy when γ=0.

Table 3. The Equilibrium Result When Γ=0 under ET Case

Case N	Equilibrium results	Case C	Equilibrium results	Case A	Equilibrium results
t^{N*}	$\frac{2-5\theta}{14}$	t^{C*}	$\frac{2-3\theta}{12}$	t^{A*}	$\frac{4-7\theta}{34}$
q_i^{N*}	$\frac{3}{7}$	q_i^{C*}	$\frac{5}{12}$	q_i^{A*}	$\frac{15}{34}$
z_i^{N*}	$\frac{1}{14}$	z_i^{C*}	$\frac{1}{12}$	z_i^{A*}	$\frac{2}{17}$
e_i^{N*}	$\frac{5}{14}$	e_i^{C*}	$\frac{1}{4}$	e_i^{A*}	$\frac{7}{34}$
π_i^{N*}	$\frac{37+25\theta}{196}$	π_i^{C*}	$\frac{7+9\theta}{144}$	π_i^{A*}	$\frac{241+49\theta}{1156}$
CS^{N*}	$\frac{9}{49}$	CS^{C*}	$\frac{25}{144}$	CS^{A*}	$\frac{225}{1156}$
W^{N*}	$\frac{15}{28}$	W^{C*}	$\frac{7}{12}$	W^{A*}	$\frac{21}{34}$

The equilibrium outcomes of the three E-R&D scenarios under ET policy when γ=1 are shown in Table 4.

Table 4. The Equilibrium Result When Γ=1 under ET Case

Case N	Equilibrium results		Case C	Equilibrium results		Case A	Equilibrium results	
	Θ=0	Θ=1		Θ=0	Θ=1		Θ=0	Θ=1
t^{N*}	1/9	-87/809	t^{C*}	1/10	23/367	t^{A*}	4/69	45/961
q_i^{N*}	8/27	248/809	q_i^{C*}	3/10	308/1101	q_i^{A*}	65/207	280/961
z_i^{N*}	1/9	96/809	z_i^{C*}	1/10	100/1101	z_i^{A*}	8/69	102/961
e_i^{N*}	5/27	152/809	e_i^{C*}	1/10	36/367	e_i^{A*}	17/207	76/961
π_i^{N*}	$\frac{137}{1458}$	$\frac{86240}{654481}$	π_i^{C*}	21/200	$\frac{136928}{1212201}$	π_i^{A*}	$\frac{4513}{42849}$	$\frac{103658}{923521}$
CS^{N*}	128/729	$\frac{123008}{654481}$	CS^{C*}	9/50	$\frac{189728}{1212201}$	CS^{A*}	$\frac{8450}{42849}$	$\frac{156800}{923521}$
W^{N*}	10/27	304/809	W^{C*}	2/5	424/1101	W^{A*}	85/207	380/961

Our findings indicate that the relative performance of different R&D organizational forms is highly sensitive to firms' degree of ECSR. A comparison of the equilibrium tax rates across the three regimes shows that when θ = 0, we have $t^{N*} > t^{C*} > t^{A*}$. This ordering arises because under non-cooperative R&D, firms withhold knowledge; emissions reduction stems solely from private R&D efforts. In contrast, under ERJV arrangements, full information sharing allows each firm to benefit from the other's R&D, leading to lower overall abatement costs and thus inducing the government to set a lower tax. Furthermore, enhanced coordination under ERJV cartelization results in even lower taxes compared to ERJV competition.

As θ rises, equilibrium taxes decline due to the under-production effect, which stimulates output. The tax in the non-cooperative R&D case (t^{N*}) drops most significantly, since the absence of knowledge sharing amplifies the under-production incentive. Meanwhile, the coordination effect maintains $t^{C*} > t^{A*}$ for all θ, as firms invest more in green R&D under cartelization. Consequently, as θ approaches 1, the ordering reverses to $t^{C*} > t^{A*} > t^{N*}$.

We further compare output and welfare levels. When θ→0 and and 1≥γ>0, output ranks as $q_i^{A*} > q_i^{C*} > q_i^{N*}$, primarily because lower tax payments and greater abatement under ERJV cartelization allow higher production. Under non-cooperation, higher taxes and limited abatement lead to lower output. For large θ (θ→1), the order becomes $q_i^{N*} > q_i^{A*} > q_i^{C*}$, since q_i^{N*} increases with θ while the others decrease. This output ranking directly affects consumer surplus: $CS^{A*} > CS^{C*} > CS^{N*}$ when θ→0, and $CS^{N*} > CS^{A*} > CS^{C*}$ when θ→1. Social welfare rankings align closely with these results.

In addition, as shown in Propositions 1, ∂q/∂θ=0 when γ=0. It means that in this situation the ranking of the output remains as the case of θ→0. Hence, for all level of θ, when γ=0, $q_i^{A*} > q_i^{C*} > q_i^{N*}$.

5. Environmenal R&D Under Emissions Standards

Under the ES scenario, First, the government commits to and sets the optimal emission standards to maximize social welfare, while firms decide whether to enter the market. Second, output levels are determined by the emissions cap and R&D efforts. Firms do not engage in quantity competition, and the total emissions level is simply $\bar{e}$. Taking the emission standard as given, firms select green R&D investment levels to maximize their individual profits. Thus, the subgame perfect Nash equilibrium is derived through backward induction.

5.1 Environmental R&D Competition

In the final stage of this game, the two firms select green R&D investment levels to maximize their individual profits, with the emission standard taken as given. The optimal production for firm i is:

$$q_i^{NS}(z_i,z_j,\bar{e}^N)=\bar{e}^N+z_i, \tag{37}$$

5.1.1 "Green" innovation

In this E-R&D phase, firms i and j undertake abatement efforts to cut emissions and boost production under emission standards.

Solving $\left.\frac{\partial V_i}{\partial z_i}\right|_{\beta=0}=0$, the first-order condition is

$$z_i^{NS}(z_j)=\frac{1-(2\bar{e}^N+2\bar{e}^N\gamma+\gamma z_j)}{4}, \tag{38}$$

From the aforementioned equation, the coefficients of zj in zi(zj) and zi in zj(zi)are negative, leading to the following lemma:

Lemma 3: the effort of E-R&D by two firms is substitutable under environmental R&D competition case.

The intuition behind this lemma stems from strategic substitutability in abatement efforts: when one firm commits to E-R&D investment, it reduces the rival's incentive to undertake similar R&D activities. By solving the reaction functions of both firms, we obtain:

$$\begin{aligned} z_i^{NS}(\bar{e}^N)&=\frac{1-(2\bar{e}^N+\bar{e}^N\gamma)}{\gamma+4},\\ \pi_i^{NS}(\bar{e}^N)&=\frac{2-(\bar{e}^{N2}\gamma^2+8\bar{e}^{N2}\gamma+8\bar{e}^{N2}-8\bar{e}^N)}{(\gamma+4)^2},\\ W^{NS}(\bar{e}^N)&=\frac{5-3\bar{e}^{N2}\gamma^2-20\bar{e}^{N2}\gamma-28\bar{e}^{N2}+4\bar{e}^N\gamma+20\bar{e}^N+\gamma}{(\gamma+4)^2}. \end{aligned} \tag{39}$$

5.1.2 The optimal emissions standards

In this stage, the government establishes the welfare-maximizing emission standard. The optimal standard is derived by solving the first-order condition of the social welfare function:

$$\bar{e}^{N*}=\frac{2\gamma+10}{3\gamma^2+20\gamma+28}. \tag{40}$$

The subscript * denotes equilibrium values. Substituting the optimal tax into the equations yields the corresponding equilibrium levels of green R&D, profits, and consumer surplus.

$$\begin{aligned} q_i^{NS*}&=q_j^{NS*}=\frac{3(\gamma+4)}{3\gamma^2+20\gamma+28},\\ z_i^{NS*}&=z_j^{NS*}=\frac{1}{3\gamma+14},\\ \pi_i^{NS*}&=\pi_j^{NS*}=\frac{2(7\gamma^2+52\gamma+94)}{(3\gamma^2+20\gamma+28)^2},\\ CS^{NS*}&=\frac{9(\gamma+4)^2(\gamma+1)}{(3\gamma^2+20\gamma+28)^2}, \end{aligned} \tag{41}$$

Finally, substituting Eq. (41) into Eq. (9) yields total welfare.

$$SW^{NS*}=\pi_i^{NS*}+\pi_j^{NS*}+CS^{NS*}+T^{NS*}-D^{NS*}=\frac{3(\gamma+5)}{3\gamma^2+20\gamma+28} \quad (42)$$

5.2. Environmental Research Joint Venture Competition

In the last stage of this game, the two firms select green R&D investment levels to maximize their individual profits, taking the emission standard as given. The optimal production for firm i is:

$$q_i^{CS}(z_i,z_j,\overline{e}^C)=\overline{e}^C+z_i+z_j, \quad (43)$$

5.2.1 “Green” innovation

In this E-R&D phase, firms i and j undertake abatement efforts to cut emissions and boost production under emission standards.

Solving $\left.\frac{\partial V_i}{\partial z_i}\right|_{\beta=1}=0$, the first-order condition is

$$z_i^{CS}(z_j)=\frac{1-(2\overline{e}^C+2z_j+2\overline{e}^C\gamma+2\gamma z_j)}{2(\gamma+2)}, \quad (44)$$

By solving the reaction functions of these firms’ E-R&D efforts, we obtain:

$$z_i^{CS}(\overline{e}^C)=\frac{1-(2\overline{e}^C+2\overline{e}^C\gamma)}{2(2\gamma+3)},$$
$$\pi_i^{CS}(\overline{e}^C)=\frac{7-4\overline{e}^{C2}\gamma^2-12\overline{e}^{C2}\gamma-8\overline{e}^{C2}+4\overline{e}^C r+8\overline{e}^C+4\gamma}{36\gamma}, \quad (45)$$
$$W^{CS}(\overline{e}^C)=\frac{4\overline{e}^C-6\overline{e}^{C2}\gamma-8\overline{e}^{C2}+3}{4\gamma+6}.$$

5.2.2 The optimal emissions standards

In this part, the government commits to a welfare-maximizing emission standard. By solving the first-order condition of the social welfare function, the optimal standard in equilibrium is derived.

$$\overline{e}^{CS*}=\frac{1}{3\gamma+4}. \quad (46)$$

Here, the subscript * denotes equilibrium values. Substituting the optimal tax into the preceding equations yields the corresponding equilibrium outcomes for R&D, profits, and consumer surplus.

$$q_i^{CS*}=q_j^{CS*}=\frac{3\gamma+5}{6\gamma^2+17\gamma+12},$$
$$z_i^{CS*}=z_j^{CS*}=\frac{\gamma+2}{2(6\gamma^2+17\gamma+12)},$$
$$\pi_i^{CS*}=\pi_j^{CS*}=\frac{36\gamma^3+167\gamma^2+260\gamma+136}{(6\gamma^2+17\gamma+12)^2}, \quad (47)$$
$$CS^{CS*}=\frac{(3\gamma+5)^2(\gamma+1)}{(6\gamma^2+17\gamma+12)^2},$$

Finally, substituting Eq. (47) into Eq. (9) yields total welfare.

$$SW^{CS*}=\pi_i^{CS*}+\pi_j^{CS*}+CS^{CS*}+T^{CS*}-D^{CS*}=\frac{9r+14}{6\gamma^2+17\gamma+12} \quad (48)$$

5.3 Environmental Research Joint Venture Cartelization

In the last stage of this game, the two firms select green R&D investment levels to maximize their individual profits, taking the emission standard as given. The optimal production for firm i is:

$$q_i^{AS}(z_i,z_j,\overline{e}^A)=\overline{e}^A+z_i+\beta z_j, \quad (49)$$

5.3.1 “Green” innovation

In this E-R&D phase, firms i and j undertake abatement efforts to cut emissions and boost production under emission standards. Firm i selects the environmental R&D level to maximize the sum of the firms’ objective functions. Solving $\left.\frac{\partial(V_i+V_j)}{\partial z_i}\right|_{\beta=1}=0$, the first-order condition is

$$z_i^{AS}(z_j)=\frac{1-(2\overline{e}^A+2z_j+2\overline{e}^A\gamma+2\gamma z_j)}{2(\gamma+2)}, \quad (50)$$

By solving the reaction functions of these firms’ E-R&D efforts, we obtain:

$$z_i^{AS}(\overline{e}^A)=\frac{1-(2\overline{e}^A+2\overline{e}^A\gamma)}{2(2\gamma+3)},$$
$$\pi_i^{AS}(\overline{e}^A)=\frac{7-4\overline{e}^{A2}\gamma^2-12\overline{e}^{A2}\gamma-8\overline{e}^{A2}+4\overline{e}^A r+8\overline{e}^A+4\gamma}{36\gamma}, \quad (51)$$
$$W^{AS}(\overline{e}^A)=\frac{4\overline{e}^A-6\overline{e}^{A2}\gamma-8\overline{e}^{A2}+3}{4\gamma+6}.$$

5.3.2 The optimal emissions standards

In this part, the government sets the welfare-maximizing emission standard. Solving the first-order condition of the social welfare function yields the equilibrium standard.

$$\overline{e}^{AS*}=\frac{6\gamma+7}{24\gamma^2+57\gamma+34}. \quad (52)$$

The subscript * denotes equilibrium values. Substituting the optimal tax into the equations yields the corresponding equilibrium levels of green R&D investment, firm profits, consumer surplus, and other outcomes.

$$q_i^{AS*}=q_j^{AS*}=\frac{3(4\gamma+5)}{24\gamma^2+57\gamma+34},$$
$$z_i^{AS*}=z_j^{AS*}=\frac{3\gamma+4}{24\gamma^2+57\gamma+34},$$
$$\pi_i^{AS*}=\pi_j^{AS*}=\frac{144\gamma^3+531\gamma^2+654\gamma+269}{(24\gamma^2+57\gamma+34)^2}, \quad (53)$$
$$CS^{AS*}=\frac{9(4\gamma+5)^2(\gamma+1)}{(24\gamma^2+57\gamma+34)^2},$$

Total welfare is then derived by inserting Eq. (53) into Eq. (9).

$$
\begin{aligned}
SW^{AS*} &= \pi_i^{AS*} + \pi_j^{AS*} + CS^{AS*} + T^{AS*} - D^{AS*} \\
&= \frac{3(6\gamma+7)}{24\gamma^2+57\gamma+34}
\end{aligned}
\tag{54}
$$

5.4. Comparative Statics and Comparison of the Equilibrium Results

This section analyzes the effects of product differentiation by conducting a comparative static analysis of equilibrium outcomes across the three scenarios. The main findings regarding comparative statics are summarized as follows.

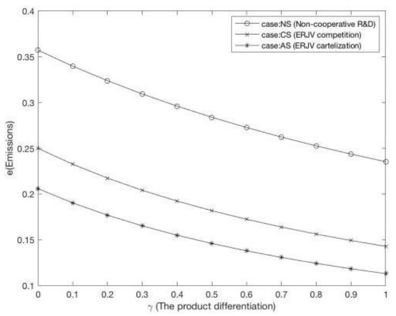
Proposition 4: under all three cases, $\frac{\partial \bar{e}}{\partial \gamma}<0, \frac{\partial q}{\partial \gamma}<0, \frac{\partial z}{\partial \gamma}<0, \frac{\partial \pi}{\partial \gamma}<0, \frac{\partial CS}{\partial \gamma}<0, \frac{\partial W}{\partial \gamma}<0.$

Proof. To simplify the result, we present the proof when γ=0 and γ=1. From the results of comparative statics in following table, we have $\frac{\partial \bar{e}}{\partial \gamma}<0, \frac{\partial q}{\partial \gamma}<0$, $\frac{\partial z}{\partial \gamma}<0$, $\frac{\partial \pi}{\partial \gamma}<0, \frac{\partial CS}{\partial \gamma}<0, \frac{\partial W}{\partial \gamma}<0$ under all three cases. The comparative static results of variables with respect to γ under ES policy are provided in Table 5.

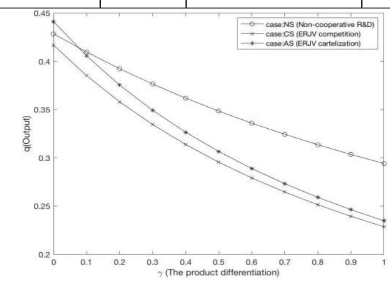
Table 5. The Results of Comparative Statics When Γ=0 and Γ=1 under ES Case

Case	comparative statics (∂/∂γ)		Case	comparative statics (∂/∂γ)		Case	comparative statics (∂/∂γ)	
N	γ=0	γ=1	C	γ=0	γ=1	A	γ=0	γ=1
$\bar{e}^{NS*}$	-0.15	-0.07	$\bar{e}^{CS*}$	-0.14	-0.04	$\bar{e}^{AS*}$	-0.12	-0.03
q_i^{NS*}	-0.19	-0.09	q_i^{CS*}	-0.37	-0.11	q_i^{AS*}	-0.42	-0.11
z_i^{NS*}	-0.04	-0.02	z_i^{CS*}	-0.12	-0.03	z_i^{AS*}	-0.15	-0.04
π_i^{NS*}	-0.21	-0.07	π_i^{CS*}	-0.22	-0.06	π_i^{AS*}	-0.22	-0.06
CS^{NS*}	-0.04	-0.02	CS^{CS*}	-0.14	-0.05	CS^{AS*}	-0.18	-0.05
W^{NS*}	-0.31	-0.13	W^{CS*}	-0.53	-0.16	W^{AS*}	-0.59	-0.17

The stringency of optimal standards is positively influenced by γ due to the under-production effect inherent in imperfectly competitive markets. As γ rises, intensifying competition diminishes firms' market power, prompting greater output and abatement effort for any given standard, thereby attenuating the under-production effect. To curb excessive output, regulators set lower standards as γ increases ($\frac{\partial \bar{e}}{\partial \gamma}<0$), which in turn reduces abatement incentives. Although diminished abatement and output both accompany a decline in γ, the net effect on emissions remains negative ($\frac{\partial e}{\partial \gamma}<0$). Consequently, both consumer surplus and firm profits decline with γ ($\frac{\partial \pi}{\partial \gamma}<0, \frac{\partial CS}{\partial \gamma}<0$), leading to a reduction in overall social welfare ($\frac{\partial W}{\partial \gamma}<0$) as illustrated in Figures 7~9.

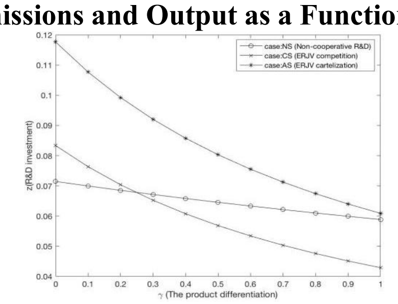


(a) Emissions

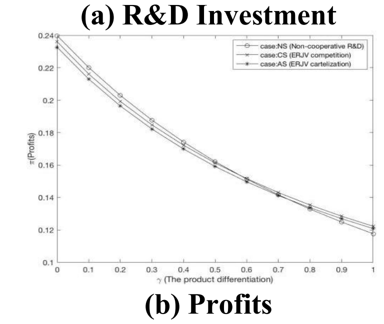


(b) Output level

Figure 7. The Equilibrium Results of Emissions and Output as a Function of γ

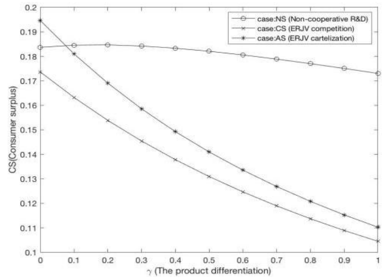


(a) R&D Investment

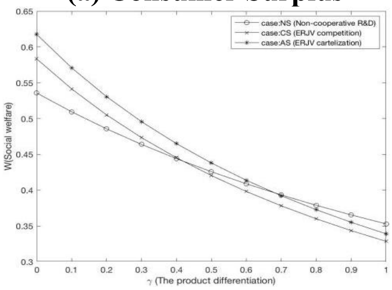


(b) Profits

Figure 8. The Equilibrium Results of R&D Investment and Profits as a Function of γ



(a) Consumer Surplus



(b) Social Welfare

Figure 9. The Equilibrium Results of Consumer Surplus and Social Welfare as A Function of γ

We proceed to compare the government-mandated standards, output levels, environmental R&D investments, firm profits, consumer surplus, and aggregate social welfare across the three scenarios.

Proposition 5: (i) when the degree of product differentiation is small ($\gamma\to0$), $\overline{e}^{NS*}>\overline{e}^{CS*}>\overline{e}^{AS*}$, $q_i^{AS*}>q_i^{CS*}>q_i^{NS*}$, $z_i^{AS*}>z_i^{NS*}>z_i^{CS*}$, $\pi_i^{NS*}>\pi_i^{CS*}>\pi_i^{AS*}$, $CS^{AS*}>CS^{CS*}>CS^{NS*}$, $W^{AS*}>W^{CS*}>W^{NS*}$; (ii) when the degree of product differentiation is large ($\gamma\to1$), $\overline{e}^{NS*}>\overline{e}^{CS*}>\overline{e}^{AS*}$, $q_i^{NS*}>q_i^{AS*}>q_i^{CS*}$, $z_i^{NS*}>z_i^{AS*}>z_i^{CS*}$, $\pi_i^{CS*}>\pi_i^{AS*}>\pi_i^{NS*}$, $CS^{NS*}>CS^{AS*}>CS^{CS*}$, $W^{NS*}>W^{AS*}>W^{CS*}$.

Proof. To simplify the result, we present the proof when γ=0 and γ=1.From the equilibrium results in the following tables, we can directly compare the government-set standards, production levels, E-R&D investments, profits, consumer surplus, and total social welfare. The equilibrium results of the three E-R&D scenarios under ES policy when γ=0 are displayed in Table 6.

The equilibrium outcomes of the three E-R&D scenarios under ES policy when γ=1 are presented in Table 7.

A comparison of government-set standards across the three cases reveals that stricter emission caps arise under cooperation. This occurs because cooperative R&D stimulates greater innovation and output—similar to the effect under ET—prompting regulators to tighten standards and curb resulting pollution. The mechanisms differ from those under an ET in the sense that environmental regulations are more stringent when firms cooperate under the optimal ESP but are looser in the case of an ET because firms invest more in green R&D.

Next, we compare output and welfare across different cases. When the degree of product differentiation is small ($\gamma\to0$), we find that $q_i^{AS*}>q_i^{CS*}>q_i^{NS*}$. This result is mainly explained by R&D investment levels. Under ERJV cartelization, firms achieve higher abatement than in the other two cases, leading to greater output. For R&D competition and ERJV competition, firms produce less in the former case due to lower abatement. When γ is big enough, given that q_i^{NS*} decreases slowly with γ while q_i^{AS*} and q_i^{CS*} decreases quickly with γ, it is obtained that $q_i^{NS*}>q_i^{AS*}>q_i^{CS*}$. As the level of firms' output play an important role in the results of consumer surpluse, it emerges that $CS^{AS*}>CS^{CS*}>CS^{NS*}$ for $\gamma\to0$ and $CS^{NS*}>CS^{AS*}>CS^{CS*}$ for $\gamma\to1$. Accordingly, the ranking of social welfare is essentially the same.

Table 6. The Equilibrium Result When Γ=0 under ET Case

Case N	Equilibrium results	Case C	Equilibrium results	Case A	Equilibrium results
$\overline{e}^{NS*}$	2/7	$\overline{e}^{CS*}$	1/6	$\overline{e}^{AS*}$	13/98
q_i^{NS*}	3/7	q_i^{CS*}	13/30	q_i^{AS*}	45/98
z_i^{NS*}	1/7	z_i^{CS*}	2/15	z_i^{AS*}	8/49
π_i^{NS*}	23/98	π_i^{CS*}	71/300	π_i^{AS*}	2257/9604
CS^{NS*}	9/49	CS^{CS*}	169/900	CS^{AS*}	2025/9604
W^{NS*}	4/7	W^{CS*}	19/30	W^{AS*}	65/98

Table 7. The Equilibrium Result When Γ=1 under ET Case

Case N	Equilibrium results	Case C	Equilibrium results	Case A	Equilibrium results
$\overline{e}^{NS*}$	5/27	$\overline{e}^{CS*}$	1/11	$\overline{e}^{AS*}$	5/71
q_i^{NS*}	8/27	q_i^{CS*}	23/99	q_i^{AS*}	17/71
z_i^{NS*}	1/9	z_i^{CS*}	7/99	z_i^{AS*}	6/71
π_i^{NS*}	167/1458	π_i^{CS*}	2389/19602	π_i^{AS*}	611/5041
CS^{NS*}	128/729	CS^{CS*}	1058/9801	CS^{AS*}	578/5041
W^{NS*}	10/27	W^{CS*}	34/99	W^{AS*}	25/71

6. Comparison of the Results and Policy Recommendations

In this section, we compare ET and ES, the two **environmental regulation** instruments, when firms cooperate in R&D and compete. Moreover, we study the impact of **environmental regulation** on “green” innovation, obtain policy implications for environmental instruments and E-R&D, and provide the following suggestions for policymakers.

6.1 Comparison of the Results

According to the above analysis in Section 4 and 5, we have the following proposition.

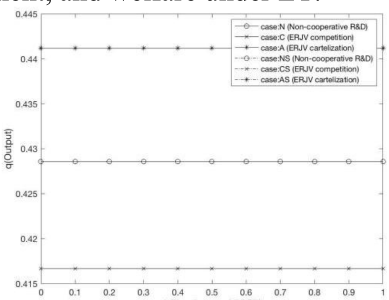
Proposition 6: (i) for 1≥γ>0, $q_i^* > q_i^{S*}$, $z_i^* > z_i^{S*}$, $e_i^* > e_i^{S*}$, $\pi_i^* < \pi_i^{S*}$ ($\theta \to 0$), $\pi_i^* > \pi_i^{S*}$ ($\theta \to 1$), $CS^* > CS^{S*}$, $W^* > W^{S*}$; (ii) for γ=0, $q_i^* = q_i^{S*}$, $z_i^* = z_i^{S*}$, $e_i^* = e_i^{S*}$, $\pi_i^* < \pi_i^{S*}$ ($\theta \to 0$), $\pi_i^* > \pi_i^{S*}$ ($\theta \to 1$), $CS^* = CS^{S*}$, $W^* = W^{S*}$.

Proof. To simplify the result, we present the proof when γ=0 and the case of environmental research joint venture cartelization. From the equilibrium result in the Section 4.3 and 5.3, $q_i^{A*} = q_i^{AS*} = \frac{15}{34}, z_i^{A*} = z_i^{AS*} = \frac{2}{17}, e_i^{A*} = e_i^{AS*} = \frac{7}{34}, \pi_i^{A*}$. Solving $\pi_i^{A*} = \pi_i^{AS*}$, we have $\theta = \frac{8}{13}$. As a result, when $\theta < \frac{8}{13}$, $\pi_i^{A*} < \pi_i^{AS*}$, and when $\theta > \frac{8}{13}$, $\pi_i^{A*} > \pi_i^{AS*}$.

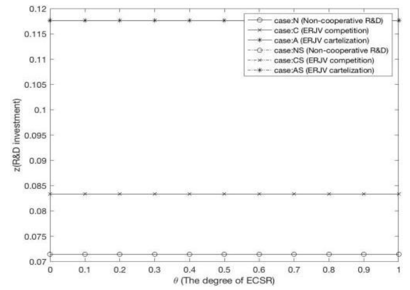
First, we consider case ii which has been partly reported without consideration of ECSR in Moner-Colonques and Rubio, and Cabon-Dhersin and Raffin. In a monoploy market or the market with no competion (γ=0), if we do not consider ECSR (θ=0), the firms’ reaction function when choosing their R&D investments under case ET is same as under case ES. Take case C for an example, recall that $z_i^{CS}(z_j) = \frac{1-(2\overline{e}^C+2z_j+2\overline{e}^C\gamma+2\gamma z_j)}{2(\gamma+2)}$ and $z_i^C(z_j) = \frac{\theta+2t-2\theta z_j}{4(\theta+1)}$.

When γ=0 and θ=0, $z_i^{CS}(z_j) = z_i^C(z_j)$,the government perceives identical competitive conditions under either emission taxes or standards, leading to equivalent output, R&D investment, and welfare levels. However, introducing ECSR (θ>0) influences the optimal tax: as θ rises, firms internalize more environmental damage, reducing output and emissions even under a fixed tax rate. This enhances the under-production effect and diminishes the need for pollution internalization through taxation, thereby lowering the optimal tax and raising profits. For sufficiently high θ, firms achieve higher profits under ET than under ES, due to reduced tax burdens. These outcomes are illustrated graphically in Figures 10~12.

Next, Figure 13~15 show the main results in case i. Considering both product differentiation (γ>0) and ECSR (θ>0), the coefficient of taxes in the the firms’ reaction function (zi(t)) under case ET is positive, while the coefficient of standards (zi ($\overline{e}$)) is negative under case ES. Take case C for an example, recall that $z_i^{CS}(z_j) = \frac{1-(2\overline{e}^C+2z_j+2\overline{e}^C\gamma+2\gamma z_j)}{2(\gamma+2)}$ and $z_i^C(z_j) = \frac{\theta+2t-2\theta z_j}{4(\theta+1)}$. When γ>0 and θ>0, the coefficient of taxes is $\frac{2}{4(\theta+1)}>0$ and the coefficient of standards is $\frac{-(2+2\gamma)}{2(\gamma+2)}<0$ .Given the positive impact of E-R&D expenditure, E-R&D is thus encouraged when the policy instrument is an emission tax—this results in higher levels of output, R&D investment, and welfare under ET.

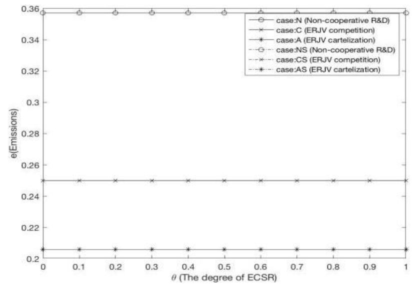


(a) Output as a Function of *θ*

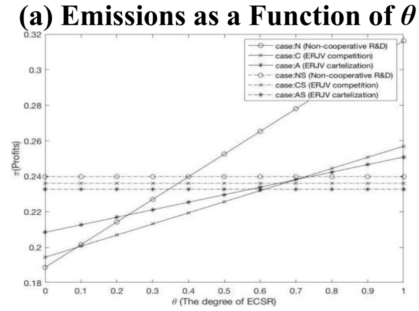


(b) R&D Investment as a Function of θ

Figure 10. The Equilibrium Results of Output and R&D Investment as a Function of θ (γ=0)

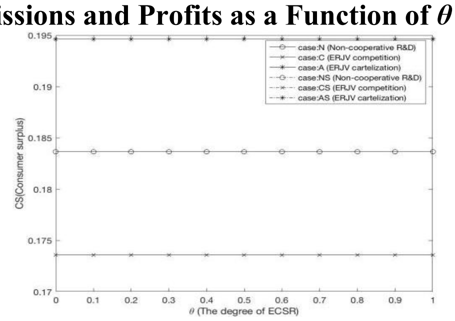


(a) Emissions as a Function of θ

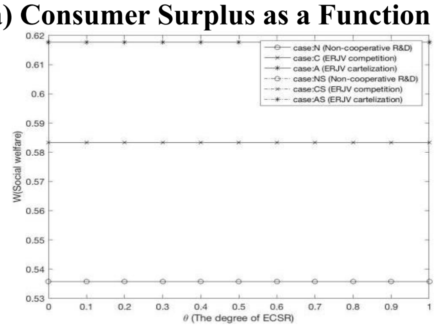


(b) Profits as a Function of θ

Figure 11. The Equilibrium Results of Emissions and Profits as a Function of θ (γ=0)

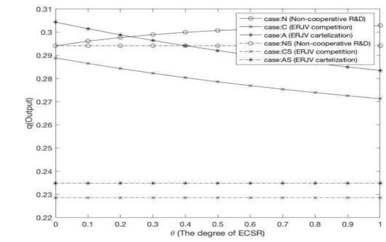


(a) Consumer Surplus as a Function of θ

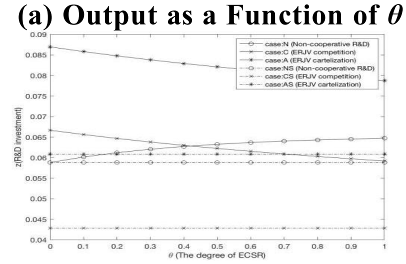


(b) Social Welfare as a Function of θ

Figure 12. The Equilibrium Results of Consumer Surplus and Social Welfare as a Function of θ (γ=0)

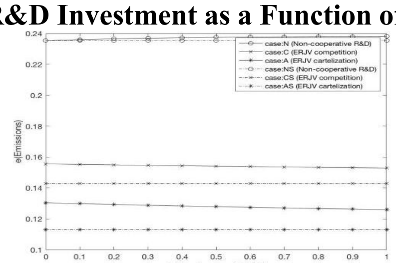


(a) Output as a Function of θ

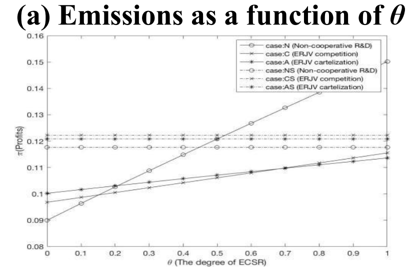


(b) R&D Investment as a Function of θ

Figure 13. The Equilibrium Results of Output and R&D Investment as a Function of θ (γ=1)

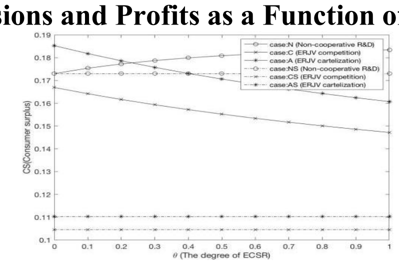


(a) Emissions as a function of θ

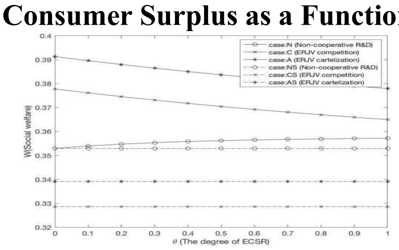


(b) Profits as a Function of θ

Figure 14. The Equilibrium Results of Emissions and Profits as a Function of θ (γ=1)



(a) Consumer Surplus as a Function of θ



(b) Social Welfare as a Function of θ

Figure 15. The Equilibrium Results of Consumer Surplus and Social Welfare as a Function of θ (γ=1)

6.2 Environmental Policies: Taxes Versus Standards

First, From the firm's perspective, ECSR level, product differentiation, and environmental policy type critically influence the choice of E-R&D organization. Under high competition (γ→1), low social concern (θ→0) leads to the highest profit under ET via ERJV cartelization and under ES via ERJV competition. When social concern is high (θ→1), non-cooperative R&D is optimal for ET, while ERJV competition remains best for ES. In non-competitive markets (γ→0) with low θ, ERJV cartelization (ET) and non-cooperative R&D (ES) yield peak profits; under high θ, non-cooperative R&D is preferred under both policies.

Second, We present the environmental damage and social welfare across different types of E-R&D organizations, along with the impacts of product differentiation and environmental policies. We find the preference is same for all level of product differentiation and ECSR: (i) the environmental damage is lowest in ERJV cartelization under both ET and ES case; (ii) Under the ET and ES cases, the highest social welfare corresponds to ERJV cartelization and non-cooperative R&D, respectively. Accordingly, under the ES policy, regulators focused on environmental protection should encourage ERJV cartelization, whereas those prioritizing social welfare ought to promote non-cooperative R&D. In addition, under ET policy, ERJV cartelization is the first option for all kinds of government. A comparison of optimal E-R&D organization forms under ET and ES policies is shown in Table 8.

Table 8. Comparison of the Results under ET and ES Case

γ	θ	The best kind of organization under ET			The best kind of organization under ES		
		profits	social welfare	environmental damage	profits	social welfare	environmental damage
γ→0	θ→0	A	A	A	N	N	A
	θ→1	N	A	A	N	N	A
γ→1	θ→0	A	A	A	C	N	A
	θ→1	N	A	A	C	N	A

Finally, this research highlights the differences between the two environmental instruments when firms are concerned about ECSR in a competitive market. In a competitive market (γ→1), for all level of ECSR, ET is more efficient in social welfare, while ES is better for the environment. However, in a market with no competition (γ→0), for all level of ECSR, ET and ES are same in sense of social welfare and environmental damage. A summary of the regulator's choice between ET and ES policies is provided in Table 9. As a result, the environment-friendly regulator should choose ES, while the regulator concerned with the economy and social welfare should use ET.

Table 9. The Choice of Environmental Instruments

γ	θ	Viewpoint of social welfare	Viewpoint of environmental damage
γ→0	θ→0	ET/ES	ET/ES
	θ→1	ET/ES	ET/ES
γ→1	θ→0	ET	ES
	θ→1	ET	ES

7. Conclusions

Empirical data indicates that companies are becoming more concerned with Environmental Corporate Social Responsibility. Companies proactively undertake measures to mitigate the environmental effects of their operations that go beyond legal obligations. This research employs a thorough modeling method to examine the dynamics of E-R&D organizations and their alignment with environmental responsibility. These measures include expenditures aimed at developing cutting-edge pollution abatement technologies that enhance environmental quality. Their allocation of resources towards environmentally friendly technology is contingent upon whether they approach their research and development endeavors competitively or cooperatively, as well as whether they choose to share their expertise with their competitors or not.

The existing body of literature on the environment has examined the strategies used by enterprises to allocate their research and development (R&D) expenditures towards reducing their pollutant emissions. This analysis assumes that firms want to maximize their profits and evaluate the relative costs and benefits of taxes and regulatory standards in this specific setting. Nevertheless, actual data demonstrates that companies are progressively embracing social responsibility. This research aims to address the existing vacuum in the research by examining the process of establishing effective ecological instruments.

This research examines the inclusion of ecological harm in the objective function of corporations as a reflection of their social responsibility. Environmentally progressive companies have the option to pursue pollution reduction innovation either via competition or cooperation. Furthermore, the regulator can commit to an environmental regulation tool convincingly.

From a firm's perspective, it is crucial to align environmental instruments with both the Environmental Corporate Social Responsibility (ECSR) and market power. In a highly competitive market, where the level of social concern is minimal, the most profitable strategies are, in the case of emissions taxes (ET) and emissions standards (ES), respectively, ERJV cartelization and ERJV competition. If the level of social concern is sufficiently high, opting for non-cooperative R&D is the most optimal decision for ET. On the other hand, for the ES scenario, engaging in ERJV competition is the most advantageous approach. In a market without any competition, where the level of social concern is minimal, the most profitable strategies are ERJV cartelization and non-cooperative R&D under the ET and ES scenarios, respectively. Nevertheless, if the level of societal concern is sufficiently elevated, opting for non-cooperative R&D is the optimal decision for both the ET and ES scenarios.

Additionally, we analyze the influence of environmental regulation on environmentally friendly innovation and derive policy recommendations for environmental instruments. Within this study, we provide the following recommendations for policymakers. According to the ES strategy, the regulator responsible for environmental sustainability should support the formation of ERJV cartelization. In contrast, the regulator focused on social welfare should foster non-cooperative R&D. Furthermore, according to the ET strategy, the formation of ERJV cartelization is the primary choice for any administration. Furthermore, the regulator with a focus on environmental sustainability should choose the ES strategy, while the regulator responsible for economic matters should adopt the ET policy.

Our current model has limitations, and this extension could be explored in future research.

Acknowledgments

This paper is supported by the University Humanities and Social Science Research Project of Jiangxi Province (No. JJ20110).

This paper is supported by the Key Project of Philosophy and Social Sciences Research of the Ministry of Education of Hubei Province (No. 23D105).

This paper is supported by the Science and Technology Research Project of the Education Department of Jiangxi Province (No. GJJ201712).

This paper is supported by the Doctoral Research Foundation of Hubei University of Automotive Technology (No. BK202225).

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