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Environmental policies with consumer-friendly firms and cross-ownership☆

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ABSTRACT

This paper analyzes what environmental policy is implemented by governments when there is cross-ownership between polluting firms that care about social concerns. We compare the equilibrium outcomes under environmental taxes, tradable emission permits and emission standards. We find that the concern of firms about corporate social responsibility (CSR), which is decided endogenously, depends on the environmental policy implemented by the government. The greatest concern is obtained under tradable emission permits and the lowest under emission standards. We also find that cross-ownership between firms affects the CSR level that they choose. Finally, social welfare is at its highest with tradable permits and at its lowest with an emission standard, implying that the government prefers, when possible, to set tradable emission permits rather than the other two policies.

1. Introduction

This paper analyzes the environmental policy implemented by governments to make firms internalize the externalities generated by their production processes. Three types of environmental policy are considered: Environmental taxes, tradable emission permits, and emission standards. The literature analyzing these policies considers different factors that influence them, such as the technology used by firms, the type of market competition, and the size of the market. In this paper we consider two factors that can be observed in modern economies and which influence the environmental policy of governments: The fact that firms care about corporate social responsibility (CSR) and the existence of cross-ownership between firms.[1]

Firms may be interested in acquiring a stake in their rivals which gives them a share in the profit but not in the decision making of those rivals (see Gilo et al., 2006). This is because cross-ownership may facilitate collusion by reducing the incentives of the firms to compete, which decreases market competition and raises prices and profits (see, e.g., Reynolds and Snapp, 1986; Farrell and Shapiro, 1990; Malueg, 1992; Ono et al., 2004).[2]

In today's economy, firms engaged in cross-ownership care about social concerns. This is important since the fact that firms may have passive investments in their rivals may affect the weight that they attach to CSR (the CSR level) in their objective functions. This means that firms need to take cross-ownership into account when deciding their CSR levels. However, the literature studying CSR usually assumes that each firm is owned by a different shareholder, so the effect of cross-ownership on the CSR level chosen by firms is ignored.[3]

Most papers that analyze the behavior of firms in product markets assume that the objective of private firms is to maximize their

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1 Bárcena-Ruiz and Campo (2012, 2017) and Dong and Chang (2020)show that cross-ownership may affect the environmental policy set by governments assuming pure profit maximizing firms.

2 Alley (1997) discusses why partial ownership arrangements are formed.

3 One exception is the paper by Bárcena-Ruiz and Sagasta (2021), who analyze the CSR level chosen by firms under cross-ownership, but without considering polluting firms.

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own profits. However, the objective function of private firms may also include corporate social responsibility (see, e. g., Porter and Kramer, 2006; Kitzmueller and Shimshack, 2012). In this regard, Kitzmueller and Shimshack (2012) argue that CSR refers to social or environmental behavior of firms that goes beyond their legal requirements. In addition, Lambertini and Tampieri (2015) point out that firms concerned with CSR care not only about the interests of their owners but also about consumers, workers and the environment. In fact, CSR has become an important business strategy, which has earned it increasing attention from researchers.[4] Most of the studies published measure CSR concerns through consumer surplus, so the objective function of a consumer-friendly firm is a convex combination of consumer surplus and its profit (see, e.g., Kopel and Brand, 2012; Lambertini and Tampieri, 2015; Kim et al., 2019). This means that consumer-friendly firms make an effort to satisfy consumers.

In today's economy firms that pollute the environment have to abate emissions, because governments implement environmental policies such as environmental taxes, emission standards, and tradable emission permits. The analysis of optimal environmental taxes under imperfect competition has received a great deal of attention. This problem is analyzed, considering a single market and imperfectly competitive firms, by Buchanan (1969) and Barnett (1980). Their analysis has subsequently been extended to consider an oligopolistic market (see, e.g., Kennedy, 1994). The economic literature that analyzes the environment has also considered the use of standards and tradable emission permits, and compared the different environmental policies. Helfand (1999) and Requate (2006) review the main arguments over pollution taxes versus standards. Requate (1993) characterizes the optimal tax and the optimal tradable permit policy as a function of a critical damage parameter. Montero (2002) compares environmental research and development incentives offered by emission standards and tradeable permits.[5] The papers cited above share one characteristic: Firms are pure profit maximizers.

In view of the increasing empirical evidence that firms engage in CSR activities,[6] in recent years more and more papers have studied the environmental policies implemented by governments, assuming that firms care about social concerns. Some of those studies consider that the CSR level is exogenously given (see, e.g., Lambertini and Tampieri, 2015; Liu et al., 2015; García et al., 2018; Leal et al., 2018; Xu and Lee, 2018; Chen et al., 2019). However, the CSR level may be a strategic variable for firms (see, e.g., Lee and Park, 2019; Hirose et al., 2017) since it affects their behavior in the product market.

In this paper we consider one country with two polluting firms that care about CSR. We consider a symmetric model so the results are not due to the asymmetries of the model. Thus, we assume that there is symmetric cross-ownership between firms. The government may implement environmental taxes, tradable emission permits or emission standards to make firms internalize their polluting emissions. As in Planer-Friedrich and Sahm (2020), we consider the CSR level as a strategic variable decided by the owners of firms, so they choose it taking into account profits only. However, when the outputs of the firms are chosen social concerns are also considered.

Our study extends the paper by García et al. (2018). They consider two firms, assume that only one of them cares about social concerns, and take the CSR level as exogenously given. They assume two regulatory instruments: Taxes and tradable permits. We extend their paper by considering that both firms care about social concerns, that the CSR level is chosen endogenously and that there is cross-ownership between firms. In addition to the cases of taxes and tradable emission permits, we also analyze the case where the government sets an emission standard.

There is empirical evidence supporting the analysis undertaken in the paper. Evidence of cross-ownership between polluting firms that care about CSR can be found, for example, in the automobile sector. One example is given by Toyota which currently owns a 5.1% stake in Mazda, 20% in Subaru and 4.94% in Suzuki, and in return Mazda takes a 0.25% and Suzuki a 0.2% stake in Toyota, respectively. Another example is that of Renault and Nissan Motor (Renault holds a 44.3% equity stake in Nissan Motor and Nissan Motor owns a 15% stake in Renault, see www.renault.com).[7] The firms mentioned in the examples care about CSR, as they report on their corporate websites. In addition, the production plants of these firms pollute the environment and the governments of the countries where their plants are located implement environmental policies to make firms internalize the negative externalities that they generate.

We find that the environmental policy implemented by the government affects the weight attached to social concerns by firms in their objective functions. Moreover, cross-ownership affects the optimal level of CSR chosen by firms because it affects both profits from shares in one's own firm and those from the shares owned in the rival firm. In fact, under both environmental taxes and tradable emission permits the CSR level chosen by firms increases with the degree of cross-ownership between them. However, under emission standards the CSR level increases (decreases) with the degree of cross-ownership between firms when it is low (high) enough. In addition, firms are most (least) concerned about social issues if the government implements tradable emission permits (emission standards). This is because with a standard the abatement cost is quadratic in the production level, so an increase in the CSR level has less effect on output than with the other two policies. Under environmental taxes, when a firm decides its optimal CSR level, it takes into account that a higher CSR level implies greater production, leading the firm to pay greater environmental taxes and reducing its profits. This effect is not present under tradable emission permits as firms do not trade permits in equibrium, so they do not have to pay for permits. Finally, the difference between the CSR levels chosen by firms under tradable emission permits and under taxes decreases with the degree of cross-ownership between firms. However, the difference between the CSR levels chosen by firms under tradable emission permits and standards and under taxes and standards increases with the degree of cross-ownership between firms.

We also find that social welfare is greater with tradable emission permits than with an environmental tax, and that it is greater with a tax than with an emission standard. This result differs from that obtained

[4] Different factors that influence CSR have been analyzed, such as competition in international markets (Chang et al., 2014; Liu et al., 2018), capacity choice (Nakamura, 2014), endogenous timing games (Matsumura and Ogawa, 2014, 2016; Kopel, 2015), first-mover advantages (Hirose et al., 2017), vertically related markets (Chen et al., 2016; Chang et al., 2019), privatization policies (Xu and Lee, 2019; Kim et al., 2019; Dong and Bárcena-Ruiz, 2021), unionized labor (Fanti and Buccella, 2019), R&D investments (Leal et al., 2019; Dong and Bárcena-Ruiz, 2020), the strategic use of CSR (Planer-Friedrich and Sahm, 2020) and financial distress risk (Boubaker et al., 2020).

[5] Kiyono and Okuno-Fujiwara (2003) compare emission taxes, quotas, and standard assuming perfectly competitive economies, international trade, and global externalities. Petrakis and Xepapadeas (2003) analyze location decisions of a monopolist which faces a tax on its emissions under time consistent and precommitment environmental policies.

[6] KPMG (2017) reviews corporate social responsibility and sustainability reporting from a large number of companies in 49 countries. Gallego-Sosa et al. (2021) find that two thirds of the European banks studied show a commitment to CSR.

[7] An additional example is found in media cross-ownership in the United States: The New York Times' former ownership of WQXR Radio and the Chicago Tribune's similar relationship with WGN Radio (WGN-AM) and Television (WGN-TV).

when CSR is not considered, assuming a symmetric model.[8] Taking into account the three environmental policies analyzed, the environmental policy implemented by the government should therefore be tradable emission permits. Empirical evidence shows that for some types of pollutant emissions countries prefer to use tradable permits as an environmental policy measure. This is the case, for example, with the regulation of carbon dioxide emissions. The European Union has an internal market for the trade of Greenhouse Gas (GHG) emission permits between private entities (Colla et al., 2012). Another example is the US Acid Rain Program, a market-based initiative taken by the United States Environmental Protection Agency that seeks to reduce overall atmospheric levels of sulfur dioxide and nitrogen oxides (Chan et al., 2018). However, the problem with the use of tradable permits is that it means creating markets to trade permits, and this has not always been achieved. This is why governments use other environmental policy instruments. One instrument widely used by countries is environmental taxation, which is high on the European political agenda, as indicated in Speck and Paleari (2016). These authors point out that energy, carbon, and transport taxes are by far the most commonly used.

The rest of the paper is organized as follows: Section 2 introduces the model. Sections 3, 4, and 5 analyze the environmental policy implemented by the government and the CSR levels chosen by the firms when the government sets an environmental tax, an emission standard, and a tradable permits regulation, respectively. Section 6 compares the results and provides the main findings. Finally, Section 7 contains some concluding remarks.

2. The model

We consider a duopolistic industry in which firms produce a homogeneous good and are engaged in Cournot competition. The inverse demand function is given by $p = A - (q_i + q_j)$, where p denotes the market price and q_i is the output produced by firm $i, i \neq j; i, j = 1, 2$. Firms have identical technology, with a constant marginal cost c for both firms.

We assume that there is bilateral partial cross-ownership. Firm i owns α_i percent of the stock of firm j, which in turn owns α_j percent of the stock of its rival, where $\alpha_i = \alpha_j < 1/2$.[9] Hence, each firm has a share in its rival's profits but not in the rival's decision making. To simplify the analysis we assume that $\alpha_i = \alpha_j = \alpha$. Given that firm i owns α percent of the stock of firm j and $(1-\alpha)$ percent of its own stock, the income of the owner of firm i is given by:

$$\Pi_i = (1-\alpha)\pi_i + \alpha\pi_j,\ i \neq j;\ i, j = 1,\ 2, \tag{1}$$

where π_i is the profit of firm i.

Following Planer-Friedrich and Sahm (2020), the owner of firm i publicly commits to a certain function V_i. This means that it has the decision-making power to choose how much weight is attached to social concern (the CSR level), θ_i, in the objective function of firm i. This objective function is the following:

$$V_i = (1-\alpha)\pi_i + \alpha\pi_j + \theta_i CS,\ i \neq j;\ i, j = 1,\ 2, \tag{2}$$

where CS denotes the consumer surplus, and $\theta_i \in [0,1]$ denotes the weight that firm i puts on consumer surplus in addition to profits. Hence, $\theta_i = 0$ means that the owner of firm i only cares about its incomes. In contrast, $\theta_i = 1$ implies that the owner of firm i cares about its income and the whole consumer surplus. The weight attached to consumer surplus by firm i, θ_i, is endogenously determined since it is a strategic decision variable for the firm. Thus, firms strategically choose a level of CSR which determines how much weight they put on consumer surplus in their objective function. As usual, consumer surplus is given by $CS = (q_1 + q_2)^2/2$.

As in Planer-Friedrich and Sahm (2020), such a commitment to a given objective function can be achieved by hiring a manager and giving him/her incentives to maximize the above objective function.[10]

Firms release emissions in the production process that damage the environment. Each unit of output produced causes one unit of pollutant emissions. However, firms can prevent pollution by undertaking abatement activities. We denote by a_i the abatement level of firm i. Abating emissions entails a positive cost, and the total cost of pollution abatement is given by $C(a_i) = k\, a_i^2/2$.[11] The total emission level of firm i is denoted by e_i, and the environmental damage function is quadratic in the total emission level; this function is given by $ED = g(e_1 + e_2)^2/2$, where g measures the rate at which greenhouse gas emissions accumulate in the atmosphere.

The government is concerned with maintaining environmental quality. We consider three policy options that the government can use to protect the environment. First we assume that the government sets up an environmental tax per unit of pollution emitted, denoted by t. Firm i abates a_i due to the tax, so its total emission level is given by $e_i = q_i - a_i$. Therefore, the total taxes collected by the government are $T = t(e_1 + e_2)$. In that case, the profits of firm i are given by:

$$\pi_i = (p-c)q_i - t(q_i - a_i) - ka_i^2/2,\ i \neq j; i, j = 1, 2. \tag{3}$$

The second regulatory policy considered is a tradable permits regulation. Following García et al. (2018), we assume that the government chooses the total emission level of the industry that maximizes social welfare and assigns an emission quota (permit) to each firm, denoted by E.[12] In addition, the government allows the firms to trade emission permits in a perfectly competitive emissions market. Permits are traded at the market clearing price, which is denoted by λ. Firms behave as price takers since they do not have market power in the emission market. Let the net demand for emission permits of firm i be $D_i = e_i - E$. Total net demand is zero at the market equilibrium, so $D_1 + D_2 = 0$. Firm i abates emissions by an amount a_i, so its abatement costs are $C(a_i) = k(a_i)^2/2$. The environmental damage caused by the pollutant emissions is $ED = g(2E)^2/2$. Therefore, the profit of firm i can be written as:

$$\pi_i = (p-c)q_i - \lambda(q_i - a_i - E) - k(a_i)^2/2,\ i \neq j;\ i, j = 1, 2. \tag{4}$$

The third regulatory policy consists of applying an emission standard to control pollution. In this case, the government sets specific limits on the amount of pollutants that can be released into the environment by each firm. Abating emissions is expensive, so firms abate pollution emissions to comply exactly with the upper limit. If the government sets an emission standard s, firm i has to abate emissions by $a_i = q_i - s$

[8] Helfand (1999) argues that when firms do not care about CSR, taxes and standards generate the same social welfare if firms are identical and there is no uncertainty. He also points out that the greater efficiency of taxes compared to standards depends on several factors, such as how standards are formulated, whether there are information asymmetries, and how conditions change over time. Baumol and Oates (1988, ch. 4) find that taxes are superior when firms differ. Holland (2012) shows that under certain conditions emission taxes are dominated by intensity standards. Requate (1993) finds that a permit policy leads to a greater welfare than a tax policy for a wide range of parameters.

[9] In line with previous literature (Gilo et al., 2006; De Haas et al., 2016), it is assumed that the values of the shareholding are exogenously given.

[10] Profit maximizing firms have an incentive to commit to higher outputs by delegating the production decision to a manager (see Englmaier, 2011; Kräker, 2005; Fershtman and Judd, 1987; Sklivas, 1987; and Vickers, 1985).

[11] The assumption that the cost of reducing emissions is independent of the cost of production can be justified on the basis of existing evidence. For example, firms can reduce their pollutant emissions through more efficient energy use, responsible water management, efficient resource management, and reducing the volume and pollutant load of waste by installing filters and treatment plants. All these measures entail costly investments that seek to reduce emissions and do not affect production costs. See Cembureau (1999) for different measures for the case of cement production.

[12] The two firms are identical, so we assume that the government must assign the same number of emission permits to each one.

to meet the standard. Abatement costs depend on the level of output and the emission standard, and are given by $C(a_i) = k(q_i - s)^2/2$. The environmental damage caused by pollutant emissions is $ED = g(2s)^2/2$. Therefore, the profit of firm i is given by:

$$\pi_i = (p - c)q_i - k(q_i - s)^2/2, \; i \neq j; \; i,j = 1,2. \tag{5}$$

The social welfare considered by the government comprises the profits of both firms, consumer surplus, the total taxes collected by the government (if any), and the environmental damage caused by the production process:

$$W = \pi_1 + \pi_2 + CS + T - ED. \tag{6}$$

where $T = 0$ except when the government implements an environmental tax.

We consider a five-stage game with the following timing: In stage 0, the government chooses the environmental policy that maximizes social welfare, which may be an environmental tax, a tradable emission permits regulation or an emission standard.[13] In the first stage, the government can commit to a specific level of the environmental policy.[14] In the second stage, the owners of the firms simultaneously choose how much weight to attach to the consumer surplus in V_i to maximize their incomes. In the third stage, the firms observe the environmental policy set by the government and the weight attached to consumer surplus. Under a tradable permits regulation, the price of the permits is set in the market. Then, under an environmental tax and a tradable emission permits, firms independently and simultaneously choose their abatement levels to maximize their objective functions. This stage does not exist under an emission standard as the firms abate emissions to comply exactly with the standard set by the government. Finally, in the last stage the firms choose their optimal production levels. The solution concept used is that of a subgame perfect Nash equilibrium in pure strategies. Therefore, the solutions are derived by backward induction from the last stage. To simplify the presentation of results we assume that $g = k = 1$.[15]

3. Environmental taxes

Next we analyze the case in which the government implements an environmental tax, denoted by superscript t. In the fourth stage of the game both firms choose the production level, q_i, that maximize V_i given by (2), $i \neq j; i,j = 1,2$. The profits of the firms that appear in V_i are given by (3). Solving this problem, we find that the equilibrium outputs of each firm are:

$$q_i = \frac{(A - c - t)(1 - \alpha)\left(1 - 2\alpha + \theta_i - \theta_j\right)}{(1 - 2\alpha)\left(3 - 2\alpha - \theta_i - \theta_j\right)}, \tag{7}$$

In the third stage, firms choose their abatement level, a_i. The differentiation of equation (2) with respect to a_i yields:

$$a_i = a_j = t, \; i \neq j; \; i,j = 1,2. \tag{8}$$

The equilibrium output levels are a function of the shares that each firm has in its rival, the CSR levels, and the tax. The output of firm i is increasing at its CSR level ($\partial q_i/\partial\theta_i > 0$), and decreasing at that of the rival firm ($\partial q_i/\partial\theta_j < 0$) except when $\theta_i = 1$ (only when $\theta_i = 1$, then $\partial q_i/\partial\theta_j = 0$). A higher θ_i implies that the consumer surplus has a greater weight in the objective function of firm i, which means that this firm produces more and its rival less. The outputs of both firms are decreasing under the environmental tax since it is a cost for them. Finally, expression (8) is the usual condition which states that firm i abates pollution to the point where the marginal abatement cost equals the tax. The abatement level of firm i, a_i, increases with the tax, t.

In the second stage of the game, taking into account the quantities and abatement levels given by (7) and (8), the owner of firm i chooses the CSR level θ_i in order to maximize its income given by (1). Given the symmetry of the model, in equilibrium $\theta_1^t = \theta_2^t = \theta^t$.[16] From the first order conditions of this problem, the following result emerges.

Proposition 1. *When the government implements an environmental tax, the CSR level chosen by the owner of each firm is*

$$\theta^t = \frac{5 - 2\alpha - \sqrt{17 - 20\alpha + 4\alpha^2}}{4},$$

where $\partial\theta^t/\partial\alpha > 0$.

This proposition shows that the CSR level chosen by the owner of each firm is positive and increasing in parameter α. In addition, $\theta^t \in [0.2192, 0.2928]$ so θ^t increases slightly with α. Finally, θ^t does not depend on the tax since it is a cost per unit of emission and thus per unit of production, so the tax disappears when calculating θ^t.

The explanation of why θ^t increases with α is the following: When α increases, each owner has more shares in the rival firm and fewer in its own firm. If an owner increases its own consumer concern its own firm produces more and the rival firm produces less, which increases the profit of its own firm at the expense of the rival. The effect of an increase in the profits of its own firm more than offsets the reduction in profits from the shares owned in the rival firm. This causes the CSR level to increase with parameter α.

In the first stage of the game, the government chooses the optimal environmental tax that maximizes social welfare given by (6). Solving, we find that the optimal tax is the following:

$$t = \frac{(A - c)(1 - \alpha)\left(9 - 10\alpha + \sqrt{17 - 20\alpha + 4\alpha^2}\right)}{39 - 64\alpha + 28\alpha^2 + (7 - 10\alpha)\sqrt{17 - 20\alpha + 4\alpha^2}}. \tag{9}$$

From expression (9) it emerges that the optimal environmental tax imposed by the government is positive and decreasing in α ($\partial t/\partial\alpha < 0$). This is because a greater parameter α implies more collusion between firms and thus less production and emissions, so the government levies a lower tax to avoid excessive further reductions in production, which is already below the optimum level.

Substituting the optimal environmental tax and CSR levels in equations (7) and (8), the output and abatement levels of the firms, their profits, consumer and producer surpluses, the total taxes collected by the government, and the social welfare are obtained. These expressions are relegated to Appendix 1.

4. Tradable emission permits

Next we consider that the government decides the total pollutant emissions and assign emission permits to each firm in a non-discriminatory manner. We denote this case by superscript e.

In the fourth stage, firm i chooses the optimal production level, q_i, that maximize V_i given by (2), $i \neq j; i,j = 1,2$. The profits of the firms that appear in V_i are given by (4). Solving this problem we obtain the following:

$$q_i = \frac{(A - c - \lambda)(1 - \alpha)\left(1 - 2\alpha + \theta_i - \theta_j\right)}{(1 - 2\alpha)\left(3 - 2\alpha - \theta_i - \theta_j\right)}, \; i \neq j; \; i,j = 1,2. \tag{10}$$

[13] We assume that the environmental policy chosen by the government (environmental taxes, emission standards or tradable emission permits) is the same for the two firms since they produce a homogeneous good with the same polluting technology and symmetric cross-ownership. If the government were to set up an environmental policy for each firm, in equilibrium, given the symmetry of the model, those environmental policies would be identical.

[14] We consider the cases where the government has the ability to commit to an announced policy. This is because the government wants to maintain a reputation for sticking to its announced policies or the assumption is also reasonable under binding international agreements to reduce greenhouse gas emissions when countries are expected to comply with the agreements.

[15] It can be shown that the main results hold true for values of k and g other than 1.

[16] We make the same simplification in notation throughout the paper.

It is easy to see that firm i's output is increasing in its CSR level ($\partial q_i/\partial\theta_i > 0$), and decreasing in the permit price ($\partial q_i/\partial\lambda < 0$) and in the CSR level considered by the rival firm ($\partial q_i/\partial\theta_j < 0$) except when $\theta_i = 1$ (only when $\theta_i = 1$, then $\partial q_i/\partial\theta_j = 0$).

In the third stage, firms choose their abatement level, a_i. The differentiation of equation (2) with respect to a_i yields

$$a_i = \lambda,\ i \neq j;\ i,j = 1,2. \tag{11}$$

The firms choose abatement efforts such that the permit price equals the marginal cost of abatement.

From (10) and (11), taking into account the total net demand of emission quota $D_1 + D_2 = (q_1 - a_1 - E) + (q_2 - a_2 - E) = 0$, the following is obtained:

$$\lambda = \frac{(A-c)(1-\alpha) - E(3-2\alpha-\theta_1-\theta_2)}{(4-3\alpha-\theta_1-\theta_2)}. \tag{12}$$

It is easy to see that the market price of permits increases if the government reduces the emission quotas of the firms ($\partial\lambda/\partial E < 0$). Moreover, the greater the consumer concern the higher the market price of the permits ($\partial\lambda/\partial\theta_i > 0$) since firms produce more and need more permits.

In the second stage of the game, the owner of firm i chooses the CSR level, θ_i, in order to maximize its income given by (1), taking into account expressions (10), (11) and (12). Solving, we get the following result.

Proposition 2. *When the government sets up tradable emission permits, the CSR level chosen by the owner of each firm is*

$$\theta^e = \frac{6-3\alpha-\sqrt{24-32\alpha+9\alpha^2}}{4},$$

where $\partial\theta^e/\partial\alpha > 0$.

The explanation of this result is similar to that of Proposition 1, so we omit it. It is easy to see that $\theta^e \in [0.2752, 0.3246]$.

Let $I = \sqrt{24-32\alpha+9\alpha^2} > 0$. In the first stage of the game, the government assigns the emission quota to each firm so as to maximize social welfare, given by (6). Solving, we obtain the following:

$$E = \frac{2(A-c)(1-\alpha)(1-I)}{\alpha(68+7I) - 44 - 4I - 27\alpha^2}.$$

The emission quota assigned to each firm, E, is decreasing in α ($\partial E/\partial\alpha < 0$). By acquiring a higher stake in the rival firm, shareholders commit themselves to more cooperative behavior and thus lower output and emissions. As a result, the government sets a lower optimal quota for each firm. Given the symmetry of the model, firms do not trade emissions in equilibrium so $q_i - a_i - E = 0$. This means that firms do not buy permits and thus only have to pay abatement costs.

Substituting the emission quotas and CSR levels in equations (10)–(12), the output levels of the firms, their profits, consumer and producer surpluses, and social welfare are obtained. These expressions are relegated to Appendix 2.

5. Emission standards

Next we analyze the implementation of an emission standard by the government. This case is denoted by superscript s. In the last stage, firm i chooses the optimal production level, q_i, that maximizes V_i given by (2), $i \neq j; i,j = 1,2$. The profits of the firms that appear in V_i are given by (5). Solving this problem we obtain the following:

$$q_i = \frac{(A-c+s)(1-\alpha)\left(2-3\alpha+\theta_i-\theta_j\right)}{(2-3\alpha)\left(4-3\alpha-\theta_i-\theta_j\right)},\ i \neq j;\ i,j = 1,2. \tag{13}$$

An increase in s, which means a less stringent emission standard, reduces the marginal cost of abatement and increases the output of firm i.

In the second stage of the game, the owner of firm i chooses the CSR level, θ_i, in order to maximize its income given by (1), taking into account the second stage production levels. Solving, we get the following result.

Proposition 3. *When the government implements an emission standard, the CSR level chosen by the owner of each firm is*

$$\theta^s = \frac{7-16\alpha+6\alpha^2-\sqrt{41-192\alpha+308\alpha^2-192\alpha^3+36\alpha^4}}{4(1-2\alpha)},$$

where θ^s is increasing in α if $\alpha < (3-\sqrt{3})/6 \approx 0.2113$, and decreasing in α if $\alpha > (3-\sqrt{3})/6$.

This proposition shows that when the government sets up an emission standard, the CSR level increases with α if the degree of cross-ownership between firms is low (i.e. if $\alpha < (3-\sqrt{3})/6$); if that degree is high (i.e. if $\alpha > (3-\sqrt{3})/6$), the CSR level decreases with α. It is easy to see that $\theta^s \in [0.1492, 0.1557]$ when $\alpha \in [0, 0.2113]$, so θ^s increases slightly with α in this case. However, $\theta^s \in [0.1557, 0]$ when $\alpha \in [0.2113, 0.5]$, so θ^s decreases more strongly with α in this case.

This result can be explained as follows: An increase in its own consumer concern leads the firm to produce more and its rival to produce less, which increases the profit of the own firm at the expense of the rival firm. It has been shown that under environmental taxes and tradable emission permits this causes consumer concern to increase strictly with parameter α. However, this does not happen under emission standards since the abatement costs depend on the output level of the firm. Thus, when α is low (which means that collusion between firms is low), the CSR level increases with α because the effect of an increase in the profits of one firm more than offsets the reduction in profits from its shares in its rival. However, when α is high (which means that collusion between firms is high) each owner has a higher stake in the rival firm and a lower stake in its own firm. This leads to a reduction in consumer concern since the reduction in profits from the shares in the rival firm has outweighs the higher profits from the shares in its own firm. Thus, collusion between firms dominates and at the limit (i.e. when α tends to 1/2) the owners of the firms are not concerned about consumer surplus. Denote $H = \sqrt{41-192\alpha+308\alpha^2-192\alpha^3+36\alpha^4} > 0$. In the first stage of the game, the government chooses the emission standard so as to maximize social welfare, given by (6). Solving this problem, we find that the optimal emission standard is the following:

$$s = \frac{2(A-c)(1-\alpha)(1-2\alpha)(-2+3\alpha+H)}{\left(67-408\alpha^3+108\alpha^4+H-12\alpha(27+H)+14\alpha^2(40+H)\right)}.$$

It can be shown that the optimal emission standard s is decreasing in α ($\partial s/\partial\alpha < 0$). Increased cross-ownership between rival firms leads to more collusive outcomes, reducing their outputs. This means that firms pollute less, so the government sets a lower standard.

Substituting the optimal emission standard and CSR levels in equation (13), the output levels of the firms, their profits, consumer and producer surpluses, and social welfare are obtained. These expressions are relegated to Appendix 3.

6. Comparison of results

In this section, we compare the results obtained under the three environmental policies that can be implemented by the government. Then we compare the optimal CSR levels chosen by the owners of the firms under the three environmental policies considered.

Proposition 4. *In equilibrium* $\theta^e > \theta^t > \theta^s$, $\partial(\theta^e-\theta^t)/\partial\alpha < 0$, $\partial(\theta^t-\theta^s)/\partial\alpha > 0$ *and* $\partial(\theta^e-\theta^s)/\partial\alpha > 0$.

Proof. *See* Appendix 4.

This proposition shows that the concern of the owners of the firms about social issues depends on the environmental policy chosen by the government. Concern is greatest when the government implements tradable emission permits, it takes an intermediate value when the government sets up an environmental tax, and it is lowest when the policy chosen by the government is an emission standard. This result can be explained as follows: Without cross-ownership (i.e. when $\alpha = 0$), the owners of the firms choose the CSR level to gain market share and profits at the expense of the rival firm, taking into account only their own profits. If a firm increases its CSR level, for a given CSR level of the other firm it produces more at the expense of the rival. The incentive to increase CSR differs under the three environmental policies considered. When the government sets an emission standard, the abatement cost is quadratic in the production level, which is not the case for the other two policies. This means that with a standard an increase in the CSR level has less effect on output than with the other two policies. As a result, the optimal CSR level chosen under an emission standard is the lowest of the three cases. A comparison of the other two cases shows that $\theta^e > \theta^t$. This is because when firms decide their optimal CSR levels there is an additional effect under environmental taxes that is not present under tradable emission permits. Under environmental taxes, when firm i decides its optimal CSR level it takes into account that a higher CSR level implies greater production, leading the firm to pay greater environmental taxes and reducing its profits. However, under tradable emission permits this negative effect is not present because firms do not trade permits in equilibrium, and thus they do not have to pay for the permits. This leads owners to choose a higher CSR level in the second case.

The above result holds for all values of parameter α. Cross-ownership has been shown above to generate an effect that affects the optimal CSR level (as seen in Propositions 1 to 3), because it affects both profits from shares in one's own firm and those from the shares owned in the rival firm. However, the government takes this effect into account when choosing its environmental policy. As the environmental policy is taken for efficiency reasons, the effect of cross-ownership is not strong enough to alter the result obtained when $\alpha = 0$.

Propositions 1 to 3 show that the difference between the CSR levels chosen by the owners of the firms under tradable emission permits and environmental taxes is decreasing in α ($\partial(\theta^e - \theta^t)/\partial\alpha < 0$). The optimal CSR level is higher under tradable permits than under taxes, but it increases at a lower rate than θ^t with α. As shown above, there is an additional negative effect under taxes that is not present under tradable emission permits because an increase in social concern implies more production, increasing the taxes that the firms have to pay and leading them to choose lower CSR levels. But the optimal taxes are decreasing in α, so this negative effect becomes weaker with higher levels of cross-ownership, reducing the difference between the CSR levels chosen by the owners of the firms under tradable emission permits and environmental taxes.

We also find that the difference between the CSR levels chosen by the owners of the firms under tradable emission permits and under an emission standard and the difference between the levels that they choose under environmental taxes and under an emission standard are increasing in α ($\partial(\theta^t - \theta^s)/\partial\alpha > 0$, $\partial(\theta^e - \theta^s)/\partial\alpha > 0$). As shown above, this is because θ^t and θ^e increase with parameter α while θ^s increases with α only when this parameter is low enough.

Proposition 5. *In equilibrium,* $CS^e > CS^t > CS^s$, $ED^e > ED^t > ED^s$ *and* $\pi^s > \pi^e > \pi^t$ *for any* $\alpha < 1/2$.

Proof. *See* Appendix 5.

This proposition shows that the consumer surplus and environmental damage are lowest when the government sets up an emission standard and highest under tradable emission permits. However, the profits of the firms are highest with an emission standard and lowest with environmental taxes.

Proposition 4 shows that $\theta^e > \theta^t > \theta^s$, which means that firms attach most weight to consumer surplus under tradable emission permits and least under emission standards. This means that industry output is greatest with tradable emission permits and lowest with an emission standard ($q^e > q^t > q^s$). Since consumer surplus depends exclusively on aggregate production levels, the greatest consumer surplus is obtained when the government sets tradable emission permits and the lowest when it sets emission standards ($CS^e > CS^t > CS^s$).

Although the firms reduce emissions at different levels under the three environmental policies, the main factor in explaining environmental damage is their output levels. As $q^e > q^t > q^s$ it emerges that $ED^e > ED^t > ED^s$.

Finally, Proposition 5 states that firms earn higher profits with emission standards than with tradable emission permits, and that with permits they earn higher profits than with environmental taxes. If only production costs are considered, as the marginal cost is constant, then usually more production usually means greater profits. However, the costs associated with the different environmental policies need to be taken into account here. It is easy to check that greater production implies greater abatement costs. It is under emission standards that firms produce the least, face the lowest abatement costs and therefore obtain the greatest profits. Under tradable emission permits firms produce more and have greater abatement costs than under environmental taxes. However, in the first case firms do not acquire permits in equilibrium so they do not pay for them, but in the second case firms pay environmental taxes. As a result, firms obtain greater profits under emission permits than under taxes.

In stage 0, the government chooses the environmental policy that maximizes social welfare. From Proposition 5, the following result emerges.

Proposition 6. *In equilibrium,* $W^e > W^t > W^s$.

Proof. *See* Appendix 6.

This proposition shows that social welfare is lowest when the government sets up an emission standard and highest under tradable emission permits.[17] Comparing the welfare obtained with tradable emission permits and with environmental taxes, it emerges that the greater consumer surplus and profits obtained under tradable emission permits offset the greater environmental damage and taxes collected by the government. A comparison of the welfare obtained under an environmental tax and that obtained under an emission standard reveals that the greater consumer surplus with the tax and the total taxes collected by the government offset the greater environmental damage and lower profits of the firms. Therefore, it is obtained that the environmental policy chosen by the government should be tradable emission permits. Emission permits provide the basis in the United States for both the Sulfur Permit Program to control acid rain and the Lead Elimination Program to facilitate the elimination of lead in gasoline (Tietenberg, 1995). The use of tradable permits implies creating markets to trade permits, which has not always been achieved, so environmental taxes are widely used (OECD, 2001).

It is easy to check that these differences between social welfare levels are increasing in α ($\partial(W^e - W^t)/\partial\alpha > 0$, $\partial(W^t - W^s)/\partial\alpha > 0$ and $\partial(W^e - W^s)/\partial\alpha > 0$). Regarding the first, given that $\partial(CS^e - CS^t)/\partial\alpha < 0$, $\partial(\pi^e - \pi^t)/\partial\alpha < 0$, $\partial(ED^e - ED^t)/\partial\alpha > 0$ and $\partial T/\partial\alpha < 0$, the latter effect leads the revenues of the government to decrease with cross-ownership offsetting the other effects and making the difference between social welfare with tradable permits and taxes decrease with α. With regard to the second, given that $\partial(CS^t - CS^s)/\partial\alpha > 0$, $\partial(\pi^s - \pi^t)/\partial\alpha > 0$ if $\alpha < 0.4741$, $\partial(ED^t - ED^s)/\partial\alpha > 0$ and $\partial T/\partial\alpha < 0$, the first effect (the difference between consumer surpluses increases with α) offsets the others.

7. Extension

In this section we consider two extensions of the main model: First we consider a quadratic cost function; and second we assume that there

[17] It can be shown that if firms do not care about social concerns, social welfare is the same in the three cases: $W^e = W^t = W^s$.

are n firms competing in the product market with constant marginal costs of production. We find that the main results hold in both cases.

We study first whether the structure of the cost function affects the results obtained in the paper. We assume that the firms have the same quadratic production cost function given by $C(q_i) = q_i^2$, $i = 1, 2$. The other assumptions are the same as in the previous section. We omit the resolution of the game, since it is similar to the constant marginal cost case.[18] We denote this case by a cap (circumflex accent mark). A comparison of the results obtained under the three environmental policies that can be implemented by the government reveals that $\widehat{\theta}^e > \widehat{\theta}^t > \widehat{\theta}^s$ and $\widehat{W^e} > \widehat{W^t} > \widehat{W^s}$. Therefore, the same result is obtained as under constant marginal costs of production. This is because the effects that arise under the two cost structures are the same. How firms respond to the policies set by the government is not affected by the structure of production costs. The structure of the cost functions affects the level of production of the firms and therefore the amount of the reduction in their emissions. However, this is not sufficient to change the results of the model as all three cases are affected in a similar way.

Next, we consider that there are n firms competing in the product market that face constant marginal cost of production. We also find in this case that the main results of the model hold. The resolution of this case is cumbersome, so to compare the results obtained we had to run simulations. We find that the main result holds for all values of parameters α and n. To illustrate this case, we present the results obtained for $\alpha = 1/4$.[19] We denote this case by adding an n in the superscript. We omit the resolution of the game, since it is similar to that of the duopoly case. A comparison of the results obtained under the three environmental policies that can be implemented by the government reveals that $\widehat{\theta}^{en} > \widehat{\theta}^{tn} > \widehat{\theta}^{sn}$ and $\widehat{W^{en}} > \widehat{W^{tn}} > \widehat{W^{sn}}$. Therefore, the same result is obtained as with a duopoly market. As the number of firms competing in the product market increases, so does the competition between them, which means that each produces less and has to reduce emissions by less, but as firms are affected similarly in all three cases, the results do not change. Therefore, the response of firms to the policies set by the government is not affected by the number of firms competing in the product market.

8. Conclusions

In this paper we analyze the effects of three environmental regulatory policies (environmental taxes, tradable emission permits, and emission standards) in a quantity setting duopoly where cross-ownership and the corporate social responsibility of firms are used together. We find that the CSR level chosen by the firms is related to the environmental policy implemented by the government: The degree of consumer friendliness is highest when the government sets up a tradable emission permits and lowest under the optimal standards. We also find that cross-ownership affects the optimal level of CSR chosen by firms. With both environmental taxes and tradable emission permits, the CSR level chosen by firms is increasing with the degree of cross-ownership between firms. However, with emission standards the CSR level is increasing (decreasing) with the degree of cross-ownership when it is low (high). We also find that welfare is greatest when tradable emission permits are used to control pollution, and lowest with emission standards.

In a society with increasing concern for the environment and CSR, these contributions may have significant value in environmental regulation, as we find that the environmental policy chosen by the government may be a factor that helps to further influence the CSR level chosen by the firms. Moreover, it is useful for decision-makers to understand the effects of different environmental policies on the level of social concern chosen by firms, on environmental damage and on social welfare.

In our analysis we consider a duopolistic industry with constant marginal costs of production. We find that if there are n firms or if the production cost function is quadratic, our analysis remains valid.

In the paper we consider that the cost of reducing emissions is independent of the cost of production. Therefore, investments in reducing emissions are intended to comply with environmental legislation and not to reduce production costs. We do not consider the adoption of innovative technologies that reduce both production costs and the generation of pollutant emissions. This goes beyond the objectives of the paper: It would imply adding a first step in which the choice between different technologies is analyzed. We leave it for future research.

Declaration of competing interest

No.

APPENDIX

Appendix 1. Results obtained when the government implements an environmental tax.

Denote $G = \sqrt{17 - 20\alpha + 4\alpha^2} > 0$.

$$q_1^t = q_2^t = \frac{6(A-c)(1-\alpha)\left(2(5+G) - 3\alpha(5+G) + 6\alpha^2\right)}{(1-2\alpha+G)\left(39+7G-\alpha(64+10G)+28\alpha^2\right)},$$

$$\pi_1^t = \pi_2^t = 4(A-c)^2(1-\alpha)(1089 + 281G - \alpha(4753 + 911G) + 6\alpha^2(1213 + 196G) -) 8\alpha^3(631 + 75G)$$
$$+ 24\alpha^4(65 + 3G)(-144\alpha^5)/((1 - 2\alpha + G)^2(39 + 7G - 2\alpha(32 + 5G) + 28\alpha^2)^2),$$

$$ED^t = \frac{8(A-c)^2(1-\alpha)^2\left(17+G-3\alpha(7+G)+6\alpha^2\right)^2}{(1-2\alpha+G)^2\left(39+7G-2\alpha(32+5G)+28\alpha^2\right)^2},$$

$$CS^t = \frac{72(A-c)^2(1-\alpha)^2\left(2(5+G)-3\alpha(5+G)+6\alpha^2\right)^2}{(1-2\alpha+G)^2\left(39+7G-2\alpha(32+5G)+28\alpha^2\right)^2},$$

$$T^t = \frac{4(A-c)^2(1-\alpha)^2(9-10\alpha+G)\left(17+G-3\alpha(7+G)+6\alpha^2\right)}{(1-2\alpha+G)\left(39+7G-2\alpha(32+5G)+28\alpha^2\right)^2},$$

[18] The equilibrium results obtained in the three cases are relegated to the appendix.

[19] The equilibrium results obtained in the three cases are relegated to the appendix.

$W^t = 24(A-c)^2(1-\alpha)(867+235G-7\alpha(563+121G)+6\alpha^2(1124+195G)-\alpha^3(5500+696G)+)$
$48\alpha^4(44+3G)-288\alpha^5)/((1-2\alpha+G)^2(39-64\alpha+28\alpha^2+(7-10\alpha)G)^2).$

Appendix 2. Results obtained when the government sets up tradable emission permits. Denote $I=\sqrt{24-32\alpha+9\alpha^2}$.

$$q_1^e = q_2^e = \frac{6\,(A-c)\,(1-\alpha)\left(2\,(7+I)-\alpha\,(22+3I)+9\alpha^2\right)}{(2-3\alpha+I)\left(4(11+I)-\alpha(68+7I)+27\alpha^2\right)},$$

$$a_1^e = a_2^e = \lambda^e = \frac{2\,(A-c)\,(1-\alpha)\left(5\,(4+I)-\alpha\,(37+6I)+18\alpha^2\right)}{(2-3\alpha+I)\left(4(11+I)-\alpha(68+7I)+27\alpha^2\right)},$$

$\pi_1^e = \pi_2^e = 4(A-c)^2(1-\alpha)(4(463+134I)-7\alpha(1300+243I)+)\alpha^2(15817+2167I)-\alpha^3(12691+1200I)+216\alpha^4(22+I)-$
$(684\alpha^5)/((2-3\alpha+I)^2(4(11+I)-\alpha(68+7I)+27\alpha^2)^2),$

$$ED^e = \frac{8(A-c)^2(1-\alpha)^2(1-I)^2}{\left(4(11+I)-\alpha(68+7I)+27\alpha^2\right)^2},$$

$$CS^e = \frac{72(A-c)^2(1-\alpha)^2\left(2\,(7+I)-\alpha\,(22+3I)+9\alpha^2\right)^2}{(2-3\alpha+I)^2\left(4(11+I)-\alpha(68+7I)+27\alpha^2\right)^2},$$

$W^e = 24(A-c)^2(1-\alpha)(4(331+83I)-\alpha(6352+1173I)+)\alpha^2(11449+1615I)-\alpha^3(9883+984I)(+216\alpha^4(19+I)-648\alpha^5)/$
$(2-3\alpha+I)^2(4(11+I)-\alpha(68+7I)+27\alpha^2)^2.$

Appendix 3. Results obtained when the government implements an emission standard. Denote $H=\sqrt{41-192\alpha+308\alpha^2-192\alpha^3+36\alpha^4}$.

$q_1^s = q_2^s = 6(A-c)(1-\alpha)(1-2\alpha)(21+H-6\alpha(17+H)+2\alpha^2(89+3H)-132\alpha^3+36\alpha^4)/(1+H-6\alpha+6\alpha^2)$
$(67+H-12\alpha(27+H)+14\alpha^2(40+H)-408\alpha^3+108\alpha^4),$

$\pi_1^s = \pi_2^s = 4(A-c)^2(1-\alpha)(1-2\alpha)(4(-427+363H)-48\alpha(47+263H)+)\alpha^2(127827+48641H)-15\alpha^3(48725-7327H)$
$+2\alpha^4(1031107+80084H)-6\alpha^5(577548+25445H)+4\alpha^6(918467+22575H)-60\alpha^7(41173+480H)$
$(+72\alpha^8(14083+48H)-228096\alpha^9+20736\alpha^{10})/((1+H-6\alpha+6\alpha^2)^2)(67+H-12\alpha(27+H)+14\alpha^2(40+H)-408\alpha^3+108\alpha^4)^2),$

$ED^s = 8(A-c)^2(1-\alpha)^2(1-2\alpha)^2(3\alpha+H-2)^2/(67+H-12\alpha(27+H)+14\alpha^2(40+H)-408\alpha^3+108\alpha^4)^2,$

$CS^s = 36(A-c)^2(1-\alpha)^2(1-2\alpha)^2(21-132\alpha^3+36\alpha^4+H-6\alpha(17+H)+)2\alpha^2(89+3H))$
$/(67-408\alpha^3+108\alpha^4+H-12\alpha(27+H)+14\alpha^2(40+H))^2,$

$W^s = 24(A-c)^2(1-\alpha)(1-2\alpha)(356+636H-24\alpha(577+253H)+\alpha^2(125451+25913H)-)3\alpha^3(183673+21563H)+$
$14\alpha^4(101839+7346H)-6\alpha^5(391716+17573H)+4\alpha^6(635021+16743H)-12\alpha^7(149273+1968H)+78\alpha^8(10987+48H)-$
$196992\alpha^9+(20736\alpha^{10})/((1+H-6\alpha+6\alpha^2)^2(67+H-12\alpha(27+H)+14\alpha^2(40+H)-408\alpha^3+108\alpha^4)^2).$

Appendix 4. Comparing the equilibrium results for social concern under the three environmental policies analyzed, the following results emerge:

$$\theta^e - \theta^t = \frac{1-\alpha+G-I}{4} > 0,$$

$$\theta^t - \theta^s = \frac{-2-G+H+2\alpha(2+G)-2\alpha^2}{4\,(1-2\alpha)} > 0.$$

Appendix 5. Comparing the equilibrium results for consumer surpluses, firms' profits and environmental damage under the three environmental policies analyzed, the following results emerge:

$$CS^e - CS^t = -(864(A-c)^2(-1+\alpha)^3(62+46G-34I-2GI+\alpha(-172-48G+23I+)))$$
$$((3GI)+\alpha^2(161+G+10I)-50\alpha^3)(2026+506G+418I+98GI-\alpha(9102+1962G+))$$
$$(1549I+329GI)+\alpha^2(15743+2875G+2163I+369GI)-3\alpha^3(4409+615G+)$$
$$((438I+48GI)+18\alpha^4(301+24G+16I)-864\alpha^5)/((I-3\alpha+2)^2)$$
$$((4(11+I)-\alpha(68+7I)+27\alpha^2)^2(G-2\alpha+1)^2(39+28\alpha^2+7G-2\alpha(32+5G))^2)) > 0,$$

$$CS^t - CS^s = -(864(A-c)^2(1-\alpha)^4(-10101-2381G+663H+159GH+))$$
$$+2\alpha(34928+7903G+296H+115GH)-2\alpha^2(87564+18766G+9199H+2257GH)$$
$$+4\alpha^3(38200+7778G+13648H+2875GH)-4\alpha^4(-22700-3216G+16805H+2695GH)$$
$$+8\alpha^5(-29472-3728G+4376H+309GH)+8\alpha^6(6818-142G-325H+141GH)$$
$$-16\alpha^7(-8326-1200G+186H+9GH)-48\alpha^8(2101+189G-6H)$$
$$((+864\alpha^9(26+G)-1728\alpha^{10}))/((1+G-2\alpha)^2(39+7G-2\alpha(32+5G)+28\alpha^2)^2)$$
$$((67+H-12\alpha(27+H)+14\alpha^2(40+H)-408\alpha^3+108\alpha^4)^2) > 0,$$

$$\pi^s - \pi^e = 96(A-c)^2(1-\alpha)^2\,(16(-1409843-366024I+302567H+51856IH)-4\alpha\,(-83828860$$
$$-21296791I+16242732H+2554835IH)+4\alpha^2\,(-560476566-139402439I$$
$$+98190294H-14107107IH)+\alpha^3\,(8868426964+2160634083I-1415388932H$$
$$-184868519IH)+\alpha^4(-22885447867-5471998314I+3394152135H+401657514IH)$$
$$+\alpha^5(39714646498+9388373653I-5734248210H-614822939IH)+\alpha^6\,(-44907557185$$
$$-10793178048I+7067213015H+690797084IH)+\alpha^7\,(26770094048+7534088412I$$
$$-6516845932H-588525390IH)+2\alpha^8\,(3308582354-803770244I+2296578763H$$
$$+194312304IH)+4\alpha^9(8003574518+660285227I+627930216H+49503720IH)$$
$$+12\alpha^{10}(2943043061+274463072I+88253496H+6146448IH)+576\alpha^{11}\,(40224314$$
$$+3355946I+566973H+30615IH)+1728\alpha^{12}(5779984+387474I+37359H+1152IH)$$
$$-10368\alpha^{13}(270261+12827I+576H)+93312\alpha^{14}(5025+128I)-35831808\alpha^{15}\big)\,/$$
$$\Big((I-3\alpha+2)^2\big(4(11+I)-\alpha(68+7I)+27\alpha^2\big)^2\big(1-6\alpha+6\alpha^2+H\big)^2$$
$$\big(67-408\alpha^3+108\alpha^4+H-12\alpha\,(27+H)+14\alpha^2\,(40+H)\big)^2\Big) > 0,$$

$$\pi^e - \pi^t = 32(A-c)^2(1-\alpha)^2\,(4(166017-25895G+369456I+75440GI)+\alpha\,(12734264+2886416G$$
$$+9042661I+1983773GI)+\alpha^2(73319237+18801053G+26198322I+5752672GI)$$
$$+\alpha^3(213859842+49251632G+48105733I+9691213GI)+\alpha^4\,(374476353+72410377G$$
$$+61112922I+10486344GI)-2\alpha^5(211543241+33387252G+26972264I+3765768GI)$$
$$+8\alpha^6(39616418+5027514G+3997035I+440379GI)-24\alpha^7\,(6536725+652101G$$
$$+500370I+40896GI)+144\alpha^8(343799+25056G+17952I+864GI)$$
$$-124416\alpha^9(73+3G+2I)+746496\alpha^{10}\big)\,/\,\Big((1-2\alpha+G)^2(2-3\alpha+I)^2$$

$$(4(11+I)-\alpha(68+7I)+27\alpha^2)^2\left(39+7G-2\alpha\left(32+5G\right)+28\alpha^2\right)^2\Big)>0,$$

$$ED^e-ED^t=-24(A-c)^2(-1+\alpha)^3(-302-30G+30I+14GI\alpha(542+66G-53I-9GI))$$
$$(-3\alpha^2(101+9G-6I)+54\alpha^3)(590-2G+226I+50GI-\alpha(1628+112G))$$
$$(+655I+107GI)+3\alpha^2(589+61G+185I+23GI)-3\alpha^3(293+27G+46I)$$
$$(+162\alpha^4)/((1+G-2\alpha)^2(4(11+I)-\alpha(68+7I)+27\alpha^2)^2)$$
$$((39+7G-2\alpha(32+5G)+28\alpha^2)^2)>0,$$

$$ED^t-ED^s=24(A-c)^2(-1+\alpha)^3\left(-485-53G+47H+15GH+\alpha(2490+288G-134H-40GH)\right.$$
$$\left.+2\alpha^2(-2356-276G+65H+9GH)+36\alpha^3(112+12G-H)-36\alpha^4(43+3G)+216\alpha^5\right)$$
$$\left(823-25G+175H+47GH-3\alpha(1635+9G+331H+65GH)+2\alpha^2\left(5923+272G+\right.\right.$$
$$892H+137GH)-6\alpha^3(2508+204G+205H+23GH)+12\alpha^4(899+87G+23H)-$$
$$\left.36\alpha^5(115+9G)+648\alpha^6\right)/\left((1+G-2\alpha)^2\left(39+7G+H-2\alpha\left(32+5G\right)+28\alpha^2\right)^2\right.$$
$$\left.(67-12\alpha\left(27+H\right)+14\alpha^2\left(40+H\right)-408\alpha^3+108\alpha^4)^2\right)>0.$$

Appendix 6. Comparing the equilibrium results for social welfare under the three environmental policies analyzed, the following results emerge:

$$W^e-W^t=576(A-c)^2(1-\alpha)^2\left(4(-51445-41261G+37915I+3427GI)+\alpha\left(1174908+821652G\right.\right.$$
$$\left.-780891I-68267GI\right)+\alpha^2(-2670925-1709245G++1713106I+137972GI)$$
$$+\alpha^3(2914166+1931652G-2112453I-143141GI)+\alpha^4\left(-1174639-1296575G\right.$$
$$\left.+1623436I+79546GI\right)-2\alpha^5(302190-265543G+400158I+11124GI)$$
$$\left.+4\alpha^6\left(219139-31950G+59496I+612GI\right)+144\alpha^7(-2530+99G-226I)+54432\alpha^8\right)/\left((1+G-2\alpha)^2(2+I-3\alpha)^2\right.$$
$$\left.(4(11+I)-\alpha(68+7I)+27\alpha^2)^2(39+7G-2\alpha\left(32+5G\right)+28\alpha^2)^2\right)>0,$$

$$W^t-W^s=2304(A-c)^2(-1+\alpha)^3\left(-1591550-438734G+271050H+60346GH+\alpha\left(22630694\right.\right.$$
$$\left.+6023146G-3255986H-671198GH\right)+\alpha^2\left(-145244443-37190719G+17321301H\right.$$
$$\left.+3273377GH\right)+\alpha^3(556101155+136329109G-53739353H-9179911GH)$$
$$+\alpha^4(-1414109283-329827465G+107789583H+16304257GH)$$
$$+\alpha^5(2515477453+553970267G-146523221H-19014675GH)+2\alpha^6\left(-1604838206\right.$$
$$\left.-330911439G+68892447H+7287280GH\right)+\alpha^7\left(2961239960+567246908G\right.$$
$$\left.-90089910H-7109142GH\right)+4\alpha^8(-490737737-86934011G+10184412H+508461GH)$$
$$-4\alpha^9(-228594443-37559445G+3127110H+70236GH)+24\alpha^{10}\left(-11918716-1842177\right.$$
$$\left.+102192H+396GH\right)+144\alpha^{11}(381725+56538G-1668H)-5184\alpha^{12}(1020+139G)$$
$$\left.+114048\alpha^{13}\right)/\left((1+G-2\alpha)^2\left(1+H-6\alpha+6\alpha^2\right)^2\left(39+7G+H-2\alpha\left(32+5G\right)+28\alpha^2\right)^2\right.$$
$$\left.(67-12\alpha\left(27+H\right)+14\alpha^2\left(40+H\right)-408\alpha^3+108\alpha^4)^2\right)>0.$$

Appendix 7. Quadratic production costs.

When the government implements an environmental tax, the following results emerge. Let denote $K_1=\sqrt{73-328\alpha+512\alpha^2-320\alpha^3+64\alpha^4}$. Solving this case, we find the following:

$$\hat{\theta}^t=\frac{9-20\alpha+8\alpha^2-K_1}{4-8\alpha},$$

$$\hat{t}=\frac{A\left(1-3\alpha+2\alpha^2\right)\left(13-44\alpha+32\alpha^2+K_1\right)}{K_1(1-4\alpha)(7-8\alpha)+(127-632\alpha+1180\alpha^2-976\alpha^3+304\alpha^4)},$$

$$\widehat{W^t} = 24A^2(1-\alpha)(1-2\alpha)\big(8879 - 159175\alpha + 1121468\alpha^2 - 4345146\alpha^3 + 10518916\alpha^4 - 16835992\alpha^5 + 18156848\alpha^6 - 13059840\alpha^7 + 5991808\alpha^8 - 1576960\alpha^9 + 179200\alpha^{10} + K_1(2219 - 22743\alpha + 107176\alpha^2 - 296122\alpha^3 + 513372\alpha^4 - 563048\alpha^5 + 377872\alpha^6 - 141120\alpha^7 + 22400\alpha^8)\big) / ((1-8\alpha+8\alpha^2+K_1)^2(127 - 632\alpha + 1180\alpha^2 - 976\alpha^3 + 304\alpha^4 + (7 - 36\alpha + 32\alpha^2)K_1)^2).$$

When the government sets up tradable emission permits, the following results emerge. Let denote $K_2 = \sqrt{88 - 408\alpha + 665\alpha^2 - 444\alpha^3 + 100\alpha^4}$. In this case, the following emerges:

$$\hat{\theta}^e = \frac{10 - 23\alpha + 10\alpha^2 - K_2}{4 - 8\alpha},$$

$$\hat{E} = \frac{2A\left(1 - 3\alpha + 2\alpha^2\right)(K_2 - 3 + 4\alpha)}{K_2(4 - 27\alpha + 26\alpha^2) + (144 - 704\alpha + 1275\alpha^2 - 1012\alpha^3 + 300\alpha^4)},$$

$$\widehat{W^e} = 24A^2(1-\alpha)(1-2\alpha)\big(9776 - 192480\alpha + 1426413\alpha^2 - 5718281\alpha^3 + 14203780\alpha^4 - 23216534\alpha^5 + 25510100\alpha^6 - 18692432\alpha^7 + 8758464\alpha^8 - 2368800\alpha^9 + 280000\alpha^{10} + K_2(2956 - 29757\alpha + 137079\alpha^2 - 371278\alpha^3 + 635206\alpha^4 - 692600\alpha^5 + 465120\alpha^6 - 174720\alpha^7 + 28000\alpha^8)\big) / ((2 - 11\alpha + 10\alpha^2 + K_2)^2(144 - 704\alpha + 1275\alpha^2 - 1012\alpha^3 + 300\alpha^4 + K_2(4 - 27\alpha + 26\alpha^2))^2).$$

When the government sets up emission standards, the following results emerge. Let denote $K_3 = \sqrt{113 - 496\alpha + 764\alpha^2 - 480\alpha^3 + 100\alpha^4}$. In this case, the following emerges:

$$\hat{\theta}^s = \frac{11 - 24\alpha + 10\alpha^2 - K_3}{4 - 8\alpha},$$

$$\hat{s} = \frac{2A\left(1 - 3\alpha + 2\alpha^2\right)(K_3 - 4 + 5\alpha)}{K_3(1 - 24\alpha + 26\alpha^2) + (179 - 808\alpha + 1372\alpha^2 - 1040\alpha^3 + 300\alpha^4)},$$

$$\widehat{W^s} = 24A^2(1-\alpha)(1-2\alpha)\big(1160787\alpha^2 - 7298 - 78242\alpha - 5620303\alpha^3 + 14953026\alpha^4 - 24988188\alpha^5 + 27480484\alpha^6 - 19941660\alpha^7 + 9197400\alpha^8 - 2436000\alpha^9 + 280000\alpha^{10} + K_3(4686 - 39250\alpha + 158025\alpha^2 - 396165\alpha^3 + 654980\alpha^4 - 705890\alpha^5 + 472020\alpha^6 - 176400\alpha^7 + 28000\alpha^8)\big) / ((1 - 10\alpha + 10\alpha^2 + K_3)^2(179 - 808\alpha + 1372\alpha^2 - 1040\alpha^3 + 300\alpha^4 + K_3\left(1 - 24\alpha + 26\alpha^2\right))^2).$$

Appendix 8. N firms compete in the product market.

When the government implements an environmental tax, the following results emerge. Let denote $K_{1n} = \sqrt{16 - 72n + 81n^2 - 18n^3 + 9n^4}$. Solving this case, we find the following:

$$\hat{\theta}^{tn} = \frac{4 - 5n - 3n^2 + K_{1n}}{8n(1-n)},$$

$$\hat{t} = \frac{3(A-c)(n-1)^2\left(9n + 3n^2 - 4 + K_{1n}\right)}{(16 + 52n - 69n^2 + 15n^3 + 9n^4 + 9n^5) - K_{1n}(4 + 13n - 6n^2 - 3n^3)},$$

$$\widehat{W^{tn}} = 12(A-c)^2 n(1+n)(n-1)(-2816 + 1312n + 29904n^2 - 62718n^3 + 33039n^4 - 549n^5 +) 2943n^6 - 6345n^7 + 405n^8 + 729n^9 - 243n^{10} + 243n^{11} + K_{1n}(704 + 1256n - 4650n^2 +) (4641n^3 + 180n^4 - 1161n^5 + 54n^6 - 81n^7 + 81n^9))/((3n^2 - 4 - 3n + K_{1n})^2) (((16 + 52n - 69n^2 + 15n^3 + 9n^4 + 9n^5) - K_{1n}(4 + 13n - 6n^2 - 3n^3))^2).$$

When the government sets up tradable emission permits, the following results emerge. Let denote $K_{2n} = \sqrt{1 - 48n + 54n^2 + 9n^4}$. In this case the following emerges:

$$\hat{\theta}^{en} = \frac{7 - 8n - 3n^2 + K_{2n}}{8n(1-n)},$$

$$\hat{E} = \frac{6(A-c)(n-1)(-4 + K_{2n})}{(1 + 25n - 18n^2 + 6n^3 + 9n^4 + 9n^5) - K_{2n}(1 + 13n - 3n^2 - 3n^3)},$$

$$\widehat{W^{en}} = 3(A-c)^2 n(1+n)(n-1)(5+21n+3n^2+3n^3)/$$
$$((-1-46n-213n^2+60n^3+45n^4+18n^5+9n^6)+K_{1n}(1+10n+12n^2+6n^3+3n^4)).$$

When the government sets up emission standards, the following results emerge. Let denote $K_{3n} = \sqrt{256-1824n+4113n^2-3672n^3+1278n^4-216n^5+81n^6}$. In this case, the following emerges:

$$\widehat{\theta}^{sn} = \frac{16-41n+12n^2+9n^3-K_{3n}}{n(32-56n+24n^2)},$$

$$\widehat{s} = 6(A-c)(n-1)(3n-4)(28+24n+K_{3n})/((256+448n-1623n^2+1473n^3-)$$
$$((666n^4+198n^5-135n^6+81n^7)+K_{3n}(16+49n-63n^2-3n^3+9n^4)),$$

$$\widehat{W^{sn}} = 12(A-c)^2 n(1+n)(n-1)(3n-4)\left(8830976-38625280n-24916800n^2+515259600n^3-\right.$$
$$1459293552n^4+2068182648n^5-1680131646n^6+791166069n^7-221396895n^8+65562372n^9-$$
$$31875768n^{10}+2928150n^{11}+7708446n^{12}-4365252n^{13}+1246590n^{14}-334611n^{15}+59049n^{16}+$$
$$K_{3n}\left(551936-510016n-4789680n^2+16017936n^3-23194728n^4+17015886n^5-4416957n^6-\right.$$
$$\left.1732023n^7+1113507n^8+37989n^9-125631n^{10}+54675n^{11}-28431n^{12}+6561n^{13}\right)/$$
$$\left((40-33n-12n^2+9n^3+K_{3n})^2\left((256+448n-1623n^2+1473n^3-666n^4+198n^5-135n^6+\right.\right.$$
$$\left.\left.81n^7)+K_{3n}(16+49n-63n^2-3n^3+9n^4)\right)^2\right).$$

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