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Emission Taxes vs. Environmental Standards under Partial Ownership Arrangements

by

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Abstract: This paper analyzes two pollution control instruments, uniform taxes and absolute standards, when polluting firms engage in partial ownership arrangements (POAs). Specifically, we examine the case of a bilateral POA between competing firms in which both hold equity shares on each other's profits as silent investments. We show that taxes and standards are equally efficacious in affecting the firms' output decisions and pollution emissions. Compared to the social planner's solution, a bilateral POA results in suboptimal outcomes with lower industrial output and consumer surplus. Firm profits are higher and environmental quality improves (since emissions decline), but social welfare decreases. We compare the equilibrium results associated with two different types of POAs (bilateral vs. unilateral), and examine their differences in welfare implications for the choice of policy options between taxes and standards.

Keywords**:** Emission tax, Environmental standard, Ownership structure, Welfare implications
JEL Codes**:** Q58, L13, H2

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1. Introduction

How would the choice of environmental policy instruments between uniform emission taxes and absolute emission standards be affected by different types of partial ownership arrangements (POAs) among polluting firms? It is becoming more prevalent that competing firms in an industry hold equity shares on rivals' profits as silent investments. Such cross-ownership arrangements of firms' holding partial equity stakes are increasingly common in industries, such as automobiles (Alley, 1997; Ono, Nakazato, Davis, and Alley 2004), airlines (Clayton and Jorgensen, 2005), electricity power (Amundsen and Bergman, 2002), and steel (Gilo, Moshe, Spiegel 2006). Considerable studies have contributed to our understanding of the economic effects of bilateral POAs by rival firms in oligopoly (e.g., Flath 1992; Malueg 1992; Reitman 1994; Gilo, Moshe, Spiegel 2006; Clayton and Jorgensen 2005; Dietzenbacher and Temurshoev 2008; Fanti 2013, 2016; Lopez and Vives 2019). Analyzing the case of symmetric Cournot duopoly, Reitman (1994) shows that both competing firms have incentives to acquire a passive stake in each other's profits.

Considering the frequently observed bilateral POAs (in the form of cross-shareholding agreements) by firms in industries, we analyze the choice of policy options in environmental regulation. We concentrate our analysis on two pollution control instruments: uniform taxes and absolute standards. Explicitly, we incorporate bilateral POAs into a stylized duopoly model of competition between firms that produce a homogenous good while generating pollution. We show that taxes and standards are equally efficient in affecting the firms' output decisions and pollution emissions. Using the social planner's solution as a reference base, we find that a bilateral POA results in a suboptimal equilibrium with lower total industry output and consumer surplus. Despite that firms make higher profits and there is environmental quality improvement (since emissions are lower), overall welfare decreases. A bilateral POA thus generates conflict between welfare maximization and environmental quality.

Our study is an extension of Bárcena-Ruiz and Campo (2017). They have a model with a unilateral POA whereby only one firm holds an equity share on its competitor's profit.[1] We take that model and extend it by considering the case of bilateral POA. Compared to the equilibrium when a POA is unilateral, how would a bilateral POA affect the policy choice between an emission tax and an emission standard? From the social welfare perspective, it is well-known that bilateral POAs affect market competition negatively (e.g., Reynolds and Snapp 1986; Farrell and Shapiro 1990; Reitman 1994). One policy issue concerns how differences between unilateral and bilateral participation in ownership arrangements affect the choice of environmental policies. In this paper, we provide answers to this question. We show that the choice of policies for imperfectly competitive polluting industries cannot be isolated from the ownership structure with rival firms acquiring each other's profit in the form of cross-shareholding arrangements, which affect production and hence emission decisions of the polluting firms.[2]

An earlier contribution by Bárcena-Ruiz and Campo (2012) is the first to stress the importance of considering bilateral POAs in analyzing the design and choice of environmental policy with imperfectly competitive polluting industries.[3] The authors focus their analysis on strategic environmental taxes in international competition.

The present study focuses on domestic competition and finds that comparison in the

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[1] Such unilateral (or one-sided) POAs assume away the frequently observed cases of bilateral (or two-sided) POAs with each one acquiring a share of the other's equity or profits (see, e.g., Flath 1992; Fanti 2016; Lopez and Vives 2019).

[2] Note the industrial organization and the antitrust literature (e.g., O'Brien and Salop, 2000) that there is an important distinction between *financial interest* and *corporate control*. We focus our analysis on the aspect of financial interest, which refers to an investment in receiving a positive share of a firm's profit without having any discretions on the firm's operations and decisions. Corporate control refers to situations under which shareholders/investors can make the decisions for the firm.

[3] Interesting cases of two-sided ownership arrangements as mentioned in Bárcena-Ruiz and Campo (2012) include the automobile industry. The Renault as a French auto firm has engaged in ownership arrangements with the Nissan as a Japanese auto manufacturer. Bárcena-Ruiz and Campo (2012) indicate that Renault acquires a 44.3% equity stake in Nissan Motor and Nissan Motor acquires a 15% stake in Renault. For more examples see, e.g., Flath (1992), Alley (1997), Fanti (2016), and Lopez and Vives (2019).

relative efficiency between emission taxes and absolute standards depends crucially on whether a POA is bilateral or unilateral. For a POA being unilateral, the case analyzed by Bárcena-Ruiz and Campo (2017), social welfare is higher with an emission tax (standard) when the equity share on a rival firm's profit low (high). However, for a POA being bilateral, we show that taxes and standards are equally efficacious. We further compare differences in policy implications between the two types of POAs for environmental regulations. We find that the socially optimal emission standard is lower, the abated pollution emissions are less, the industrial output is lower, the regulated firms are better off, but consumers are worse off when a POA is bilateral than when it is unilateral. Nevertheless, environmental quality is relatively higher whereas social welfare is relatively lower under a bilateral POA. The economic intuitions behind these results are as follows. A bilateral POA generates a relatively higher degree of inter-firm output coordination causing the industry output to be relatively lower. That is, there is a greater dampening of market competition when a POA is bilateral. Thus, different types of POAs (bilateral or unilateral) play a role in affecting the choice of policy options between taxes and standards. When comparing differences between bilateral and unilateral POAs, we also discuss how different values of equity shares affect social welfare and environmental quality.

We organize the remainder of the paper as follows. In Section 2, we present a duopoly model of competition between two polluting firms engaging in a bilateral POA. We first solve for the social planner's welfare maximization problem (as a benchmark), and then evaluate the alternative equilibrium outcomes with uniform taxes and absolute standards. In Section 3, we conduct a comparison between bilateral and unilateral POAs, and discuss their differences in implications for policy choice between taxes and standards. Section 4 examines how equity shares affect social welfare and the environment. Section 5 concludes.

2. Environmental Regulation under Bilateral POA

2.1 *Basic Assumptions*

As in Bárcena-Ruiz and Campo (2017), we consider a market with two firms (1 and 2) producing a homogeneous product and engaging in Cournot competition. But unlike Bárcena-Ruiz and Campo (2017), we examine a bilateral POA under which both competing firms acquire equities on a share $\alpha(>0)$ of each other's profits.[4] Following the literature on POAs, we assume $\alpha < 1/2$ to ensure that the equity share does not exert any direct influence on the decision making of its rival. For simplicity, market demand is taken to be linear: $p = A-(q_1+q_2)$, where p is the market price, the parameter $A(>0)$ represents the product's "chock price," or its market size, and q_i is the quantity of output produced by firm $i(i=1,2)$. The corresponding consumer surplus (CS) is given by $CS=(q_1+q_2)^2/2$.

Each firm's production process unavoidably generates pollution. To reduce pollution, a firm can incur a cost to abate its pollutant emission. We consider that one unit of output results in one unit of pollutant emission. Denoting a_i as the abatement level of firm i, the firm's emission level is: $e_i = q_i - a_i$. The cost to each polluting firm of abating its emissions is assumed to be a quadratic function: ka_i^2, where $k(>0)$ represents the cost-effectiveness of abatement.

The objective of the government is to maximize social welfare in choosing an environmental policy. We consider two policy options. (i) The first option is to impose a uniform emission tax under which each firm pays a tax, denoted by t, for each unit of pollutant emitted. The total environmental tax collected by the government from the polluting firms is then given by $T = t[(q_1-a_1)+(q_2-a_2)]$. (ii) The second policy option is to implement an absolute

[4] A bilateral POA resembles the overlapping ownership arrangements (OOAs) as discussed in Lopez and Vives (2019).

environmental standard. That is, the government sets a prohibitive upper level of emission by the firms, denoted by s. Given the emission standard s, the level of abatement by firm i is: $a_i = q_i - s$.

Under the environmental tax policy, each firm's profit is:

$$\pi_i = pq_i - t(q_i - a_i) - ka_i^2,\ i = 1, 2. \tag{1}$$

Under the environmental standard policy, each firm's profit is:

$$\pi_i = pq_i - k(q_i - s)^2,\ i = 1, 2. \tag{2}$$

Since each firm acquires a positive share of its rival's profit as passive investment, the competing firms maximize their total profits in production decisions. The total profit functions of the firms are given, respectively, as

$$\Pi_1 = (1-\alpha)\pi_1 + \alpha\pi_2 \text{ and } \Pi_2 = (1-\alpha)\pi_2 + \alpha\pi_1, \tag{3}$$

where π_i is firm i's operating profit as specified in (1) under the emission tax policy or that in (2) under the environmental standard policy. Note for the bilateral POA that producer surplus equals the sum of the firms' gross (or operating) profits:

$$PS = \Pi_1 + \Pi_2 = \pi_1 + \pi_2. \tag{4}$$

Define λ as a parameter reflecting the extent to which the environment deteriorates due to the total pollutant emissions by the polluting firms. The total environmental damage (ED) is taken to be a quadratic function of emissions:

$$ED = \lambda(e_1 + e_2)^2, \tag{5a}$$

and hence the marginal environmental damage (MED) is:

$$MED = 2\lambda(e_1 + e_2). \tag{5b}$$

As in the literature, social welfare is the sum of producer surplus, consumer surplus, the total environmental tax revenues that the government collects, and the overall environmental damage:

$$SW = CS + PS + T - ED, \tag{6}$$

where $T > 0$ (or $T = 0$) when there is an emission tax (or an emission standard).

To analyze and compare various effects associated with alternative environmental policies when two competing firms engage in a bilateral POA, we consider a two-stage game with the following timing. At stage one, the government imposes an emission tax or sets an emission standard. At stage two, the firms simultaneously and independently make their output and abatement decisions. We solve the game by backward induction to obtain a subgame-perfect Nash equilibrium. For simplicity and facilitating comparison with related studies, we follow Bárcena-Ruiz and Campo (2017) and assume $k = \lambda = 1/3$. For a POA being bilateral, we denote all the associated variables with a superscript "*B*".

2.2 *Social planner's welfare maximization problem when POA is bilateral*

We first solve for the equilibrium outputs and abatements from the social planner's perspective of welfare maximization (denoted with a superscript "*SP*"). In this case, government determines for the polluting firms their output and abatement levels, $\{q_i, e_i\}$, that maximize social welfare as given by (6) when $t = 0$ and $s = 0$. Solving the first-order conditions (FOCs), and using (1)-(6), we obtain the equilibrium results as summarized in Lemma 1.

Lemma 1. *When polluting firms engage in a bilateral POA, the social planner's problem of welfare maximization implies that the equilibrium results are:*

$$q_i^{B,SP} = \frac{9}{22}A,\ \ a_i^{B,SP} = \frac{3}{11}A,\ \ e_i^{B,SP} = \frac{3}{22}A,\ \ \pi_i^{B,SP} = \frac{6}{121}A^2,$$

$$ED^{B,SP} = \frac{3}{121}A^2,\ CS^{B,SP} = \frac{81}{242}A^2,\ \ SW^{B,SP} = \frac{9}{22}A^2. \tag{7}$$

Lemma 1 shows that the optimal levels of output and abatement by each polluting firm are identical to those under unilateral POA, as shown by Bárcena-Ruiz and Campo (2017). We present economic explanations as follows. Whether a POA is bilateral or unilateral, producer surplus remains unchanged as the sum of the firms' profits (gross or operating shown in equation 2). Given that consumer surplus and environmental damage remain unchanged for the two different types of POAs (bilateral and unilateral), without policy instruments ($t = 0$ and $s = 0$), the polluting firms make their output and abatement decisions as set forth by the social planner. Different types of POAs do not exert differing effects on environmental damage and social welfare in the benchmark case. The competing firms internalize their pollution emissions, leading to an equilibrium at which social welfare is maximized.

2.3 *An emission tax policy when POA is bilateral*

When government imposes an emission tax, each polluting firm's operating profit is given by (1). We denote this case with the superscript "T." In the second stage of a two-stage game, each firm decides on abatement and output levels that maximize its total profit, as shown in (3). Solving backward this game, we have the optimal levels of each firm's abatement and output as functions of the emission tax:

$$a_i^{B,T} = \frac{3t}{2} \text{ and } q_i^{B,T} = \frac{(1-\alpha)(A-t)}{3-2\alpha}. \tag{8}$$

The results in (8) indicate that the tax policy affects each firm's abatement positively, and its output negatively. An increase in the equity share incentivizes each firm to produce less output.

In the first stage of the game, the government determines an optimal emission tax that maximizes social welfare. Substituting the results from (8) back into (1)-(5), we have:

$$t^B = \frac{2A(1-\alpha)(19-16\alpha)}{(335-484\alpha+176\alpha^2)}. \tag{9}$$

It follows from (9) that the optimal emission tax is inversely related to the equity share. When the equity share increases, both firms decrease their outputs and hence pollutant emissions, causing consumer surplus to decline and the environmental quality to improve. Moreover, as seen from (9), a higher emission tax reduces outputs and emissions, with the result that consumer surplus decreases. In response to the increase in equity share, the government finds it welfare-increasing to cut the emission tax which encourages the firms to increase their outputs.[5]

Plugging t^B from (9) back into (1)-(6), we solve for the reduced-form solution under the emission tax policy. This yields:

Lemma 2. *For the case in which the government imposes an optimal emission tax on polluting firms that engage in a bilateral POA, the equilibrium results are:*

$$q_i^{B,T} = \frac{9A(1-\alpha)(11-8\alpha)}{335-484\alpha+176\alpha^2},\ a_i^{B,T} = \frac{3A(1-\alpha)(19-16\alpha)}{335-484\alpha+176\alpha^2},$$

$$e_i^{B,T} = \frac{6A(1-\alpha)(7-4\alpha)}{335-484\alpha+176\alpha^2},\ \pi_i^{B,T} = \frac{3A^2(1-\alpha)(3628-5721\alpha+2592\alpha^2-256\alpha^3)}{(335-484\alpha+176\alpha^2)^2},$$

$$ED^{B,T} = \frac{48A^2(7-11\alpha+4\alpha^2)^2}{(335-484\alpha+176\alpha^2)^2},\ MED^{B,T} = \frac{8A(1-\alpha)(7-4\alpha)}{335-484\alpha+176\alpha^2},$$

$$CS^{B,T} = \frac{162A^2(11-19\alpha+8\alpha^2)^2}{(335-484\alpha+176\alpha^2)^2},\ SW^{B,T} = \frac{18A^2(7-11\alpha+4\alpha^2)}{335-484\alpha+176\alpha^2}. \tag{10}$$

We see from the results in Lemma 2 and equation (9) that the optimal emission tax is lower than the marginal environmental damage. That is,

$$t^B < MED^{B,T}.$$

This result is consistent with the environmental economics literature (see, e.g., Buchanan 1969; Barnett 1980; Levin 1985) that examines optimal emission taxation under imperfect competition. We find that this result continues to hold for the case of bilateral POA.

All else being equal, an increase in equity share causes each firm's output to decline

[5]Since the sum of environmental tax is the transfer payment in social welfare, in this paper the decision on environmental tax by a welfare-maximizing government is not affected by the total tax income, *T*.

which, in turn, lowers its emission. Consumer surplus decreases and environmental damage declines, but each firm's profit increases. Since the decrease in consumer surplus outweighs the increase in producer surplus and the decline in environmental damage, social welfare decreases.

2.4 *An emission standard policy when POA is bilateral*

We turn to the alternative policy of an optimal standard set by the government in the first stage of a two-stage game. Under the emission standard policy, each firm's profit is given by (2). In the second stage, each firm determines its output and abatement decisions that maximize its objective function, as shown in (3). Solving the FOCs for the firms, we obtain each firm's output as a function of the equity share and the emission standard:

$$q_1^{B,S} = q_2^{B,S} = \frac{(1-\alpha)(3A+2s)}{11-8\alpha}. \qquad (11)$$

We have from (11) that each firm's output increases with the emission standard, but decreases with the equity share. That is, $\partial q_i^{B,S} / \partial s > 0$ and $\partial q_i^{B,S} / \partial \alpha < 0$.[6] When the emission standard is set higher, both firms abate less emissions and produce more outputs. An increase in the equity share implies a greater weight to be placed on rival's profit, causing each firm to reduce its own output. For a sufficiently high equity share, the extent to which each firm increases its output becomes lower when the emission standard increases.

In the first stage of the game, the government chooses an optimal emission standard that maximizes social welfare as given by (6). Substituting $q_1^{B,S}$ and $q_2^{B,S}$ from (11) back into (1)-(6), solving for the optimal standard, we have:

$$s^{B,S} = \frac{6A(1-\alpha)(7-4\alpha)}{335-484\alpha+176\alpha^2} > 0. \qquad (12)$$

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[6] Lambertini and Tampieri (2012) introduce a minimum quality standard into a vertically differentiated model of duopoly where firms' production generate pollution. The authors show that under Cournot competition, a binding minimum quality standard results in lower output and pollution.

From (12), we see that the optimal emission standard decreases with the equity share, i.e., $\partial s^B / \partial \alpha < 0$. Also, we have from (11) and (12) that the polluting firms reduce their outputs when α increases. This leads to an increase in producer surplus, and a decrease in both environmental damage and consumer surplus. Moreover, when the emission standard is at a higher level, each firm's output increases. With a higher degree of market competition (or a lesser degree of output coordination), producer surplus decreases, but both consumer surplus and environmental damage increase. Recall that the extent to which each firm's output increases with s is decreasing with α. This implies that for a sufficiently high emission standard, the negative effect of the equity share on consumer surplus becomes dominating such that social welfare decreases. Thus, in response to an increase in the equity share, government finds it socially desirable to lower the emission standard for mitigating the associated negative effect.[7] From (10) and (12), we also observe that each firm's pollutant emission is $e_i^{B,T} = s^{B,S}$. We thus obtain the following results.

Lemma 3. *When the government implements an optimal emission standard on polluting firms that engage in a bilateral POA, the equilibrium results are:*

$$q_i^{B,S} = \frac{9A(1-\alpha)(11-8\alpha)}{335-484\alpha+176\alpha^2},\ \ a_i^{B,S} = \frac{3A(1-\alpha)(19-16\alpha)}{335-484\alpha+176\alpha^2},$$

$$\pi_i^{B,S} = \frac{3A^2(1-\alpha)(4160-7005\alpha+3600\alpha^2+512\alpha^3)}{(335-484\alpha+176\alpha^2)^2},$$

$$ED^{B,S} = \frac{48A^2(1-\alpha)^2(7-4\alpha)^2}{(335-484\alpha+176\alpha^2)^2},\ \ MED^{B,S} = \frac{8A(1-\alpha)(7-4\alpha)}{335-484\alpha+176\alpha^2},$$

$$CS^{B,S} = \frac{162A^2(1-\alpha)^2(11-8\alpha)^2}{(335-484\alpha+176\alpha^2)^2},\ \ SW^{B,S} = \frac{18A^2(1-\alpha)(7-4\alpha)}{335-484\alpha+176\alpha^2}. \tag{13}$$

For a POA being bilateral, we can see from Lemma 3 that $\Pi_i^{B,S} = \pi_i^{B,S}$. Both

[7] Specifically, we have $\partial s^{B,S} / \partial \alpha = -[162A(11-8\alpha)] / [(335-484\alpha+176\alpha^2)^2] < 0.$

environmental damage and social welfare decrease with the equity share. Furthermore, we compare $s^{B,S}$ in (12) to $MED^{B,S}$ (13) and find that

$$s^{B,S} - MED^{B,S} = -\frac{2A(1-\alpha)(7-4\alpha)}{176\alpha^2 - 484\alpha + 335} < 0. \tag{14}$$

This indicates that the optimal emission standard is set at a level *strictly lower* than the marginal environmental damage. The reason is that increasing the equity share facilitates a higher degree of inter-firm output coordination, causing the total industry output to decline. As a result, producer surplus increases, the environmental damage becomes less severe, but consumer surplus declines. Since the negative effect on consumer surplus dominates, social welfare decreases with the equity share. In response, the government finds it welfare-improving to set a lower emission standard for encouraging the firms to increase their outputs.

2.5 *Comparing the alternative policies under bilateral POA*

We proceed to evaluate the two pollution control instruments. Based on the results in Lemma 2 and Lemma 3, we establish the following proposition:

PROPOSITION 1. *Under bilateral POA, emission tax and standard policies are equally efficacious in reducing emissions, improving environmental quality, and increasing welfare.*

Proposition 1 indicates that a welfare-maximizing government is indifferent between taxes and standards under bilateral POA. Since competing firms have the same objective function under symmetry, a welfare-maximizing government can use either policy to achieve the socially desirable levels of outputs, environmental quality, and the overall welfare. This finding is consistent with the result of Helfand (1999). The author contends that if firms are symmetric, then uniform taxes and absolute standards are equally efficient in reducing emissions and maximizing social welfare. Moner-Colonques and Rubio (2016) show that under regulatory commitment, both an emission tax or an environmental standard as policy instruments are equivalent as they yield the same welfare level. [8]

Next, we compare the equilibrium outcomes when the government implements an environmental policy (taxes or standards) to the social planner's welfare maximization solution. Note Proposition 1 that the two environmental policies are equivalent. By comparing Lemma 3 with Lemma 1, we obtain the following results.[9]

PROPOSITION 2. *Compared to the social planner's solution, a bilateral POA between polluting firms causes each firm's output to decline, the amount of emission to go down, and both firms' profits to increase. Consumers are worse off and social welfare decreases. Nevertheless, environmental quality improves.*

Proposition 2 shows that, under an environmental policy, each firm's output is lower than that in the social planner's solution (see Proposition 1). This is because the regulated firms take advantage of their bilateral POA to coordinate production in lowering their outputs. In case there is an environmental policy in place, both consumer surplus and the environmental damage are lower than their socially optimal levels. Proposition 2 also shows that firms' profits under either policy (taxes or standards) are higher than those in the social planner's solution. The reason is that the bilateral POA constitutes a device for facilitating the inter-firm output coordination.

Finally, with a bilateral POA, the resulting lower industry output results in lower consumer surplus than that in the social planner's solution. Despite that the environmental damage decreases, the adverse effect on consumer surplus becomes dominating in welfare comparison. These results indicate that bilateral ownership arrangements are welfare-reducing.

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[8] Adar and Griffin (1976) show that when the environmental marginal damage function or marginal control cost are subject to uncertainty, other things being equal, emission taxes and emission standards may yield the same expected social surplus. Simpson (1995) examines the case of a Cournot duopoly with production cost asymmetry and finds that the optimal tax rate may exceed the marginal environmental damage. This result emerges since the tax is an effective device in inducing the high-cost firm to produce less and the low-cost firm to produce more. See Requate (2006) for a systematic review of environmental policies and their effects under imperfect competition.

[9] See details in Appendix A-2.

3. Effects of Different POA Types on Social Welfare and the Environment

We now analyze how different types of POAs affect the choice of pollution control instruments and their impacts on welfare and the environment. First, we conduct a comparison in equilibrium outcomes between bilateral and unilateral POAs, relative to the social planner's solution. To do so, we look at the social planner's solution, as discussed in Bárcena-Ruiz and Campo (2017), and the results of Lemma 1 in our study. This yields

PROPOSITION 3. *The social planner's welfare-maximizing solution is independent of whether polluting firms' POA is unilateral or bilateral, all else being equal.*

Next, we investigate how different POAs affect industrial output, firm profits, the incentives of polluting firms in abatement decisions, environmental quality, the government's choice of environmental policies, consumer surplus, and social welfare. To answer this question, we compare equilibrium outcomes when POA is bilateral, as discussed in Section 2, relative to the scenario when it is unilateral (denoted with a superscript "*U*"), as discussed in Bárcena-Ruiz and Campo (2017). We record the results as follows:

$$Q^{B,N} < Q^{U,N}, \;\; ED^{B,N} < ED^{U,N}, \;\; SW^{B,N} - SW^{U,N} = \frac{\alpha A^2(6-21\alpha+8\alpha^2)}{6(9-9\alpha+2\alpha^2)^2}. \quad (15)$$

It follows from (15) that there are two possibilities for welfare comparison:

$$SW^{B,N} > SW^{U,N} \text{ for } 0 < \alpha < 32.627\%;$$

$$SW^{B,N} < SW^{U,N} \text{ for } 32.627\% < \alpha < 50\%. \quad (16)$$

We thus have:[10]

PROPOSITION 4. *In the absence of environmental regulation, the industry output is lower and hence the environmental damage is less severe when a POA is bilateral than when it is unilateral.*

[10] See detailed proof in Appendix A-3.

When equity share is low, social welfare is relatively higher under a bilateral POA. When equity share is moderate, social welfare is relatively higher under a unilateral POA.

Proposition 4 implies that different POA types affect equilibrium outcomes differently. Compared to the equilibrium under a unilateral POA, bilateral holdings of equities help facilitate a higher degree of inter-firm output coordination. This generates a greater internalization of their outputs. That is why a bilateral POA results in lower outputs, higher profits, less environmental damage, and lower consumer surplus.

The extent of a bilateral POA, as measured by the value of equity share, plays a role in welfare comparison. There is a higher degree of output coordination when polluting firms engage in a bilateral POA than when the POA is unilateral. This result emerges since the difference in outputs between the two types of POAs is greater the higher the equity share. For the case without any environmental policy, since both firms lower their outputs under a bilateral POA, producer surplus is higher, and the environmental damage becomes less severe. This contributes to a higher level of welfare. On the other hand, the resulting decrease in consumer surplus has a negative effect on social welfare. As the equity share increases from zero but remains at a low level, the inter-firm output coordination becomes less significant regardless of the types of POAs. In this case, the positive effects associated with producer surplus and the environmental damage outweigh the adverse effect on consumer surplus. This explains why welfare is relatively higher for a bilateral POA. However, when the equity share is higher (but is lower than 50%), the rival firms coordinate their outputs to a higher degree when a POA is bilateral. A further increase in the equity share leads to a situation where the adverse effect associated with lower consumer surplus becomes dominating. In this case, social welfare becomes relatively lower.

4. Effects of Equity Shares on Social Welfare and the Environment

One significant issue concerns whether comparing the equilibrium results of the two different POA types for the same equity share is restrictive.[11] If, for example, we have α = 0.25 in a unilateral POA such that only one firm acquires 25% of the other's profit. In a bilateral POA, this means that each firm has 25% of its rival's profits, a total of 50%. Does this imply that the two different type of POAs are non-equivalent? To answer this question, we denote α_i^B and α_i^U, respectively, as the bilateral and unilateral equity shares. We investigate two cases of interest:

(i) the equity shares are identical such that $\alpha_i^B = \alpha_i^U = \alpha$;

(ii) the equity shares differ, i.e., that $\alpha_i^B \neq \alpha_i^U$.

For case (i) with an identical equity share, we directly compare our results of Lemma 2 and Lemma 3 under bilateral POA with those derived by Bárcena-Ruiz and Campo (2017) under unilateral POA. This comparison allows us to establish the next proposition:[12]

PROPOSITION 5. *In the presence of environmental regulation, given an identical equity share in a POA (either bilateral or unilateral), we have the following results:*

$$s^{B,S} < s^{U,S},\ t^B < t^U,\ 2a_i^{B,S} < (a_1^{U,S} + a_2^{U,S}),\ Q^{B,S} < q_1^{U,S} + q_2^{U,S},$$

$$(\Pi_1^{B,S} + \Pi_2^{B,S}) > PS^{U,S},\ CS^{B,S} < CS^{U,S},\ ED^{B,S} < ED^{U,S},\ \text{and}\ SW^{B,S} < SW^{U,S}.$$

Proposition 5 has interesting policy implications. The government with an objective of welfare maximization sets a *lower* emission tax (or standard) when a POA is bilateral than when it is unilateral. The economic reasons are as follows. In a bilateral POA, the competing firms undertake a higher degree of coordination that lower their outputs and raise their profits at the

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[11] This section is due to Juan Carlos Bárcena-Ruiz who suggests that we discuss this issue when comparing differences between bilateral and unilateral POAs in terms of equity share.
[12] See Appendix A-4 for detailed calculations.

expense of consumers. When the equity share increases, the discrepancy in industrial production between the alternative types of POAs increases for each of the two environmental policies. Intending to achieve welfare maximization, the government lowers the restrictions on pollution emissions by encouraging firms to increase their outputs. In the meanwhile, the firms find it profitable to reduce emission abatements. However, the output-reducing effect under the bilateral POA is strong enough to dominate that under the unilateral POA. Despite that producer surplus is higher and environmental damage is lower, consumer surplus is relatively lower, the latter of which becomes dominating. This explains why given an identical equity share in a POA (either bilateral or unilateral), social welfare is relatively lower when the POA is bilateral.

For case (ii) with differing equity shares $\alpha_i^B \neq \alpha_i^U$, we show detailed derivations in Appendix A-5 under an optimal emission tax policy. This analysis leads to the last proposition:

PROPOSITION 6. *In the presence of environmental regulation, there are two sets of results.*

(i) When the equity shares are such that $\alpha^B < \alpha^U/2$, *we have:*

$$t^B > t^U,\ a_i^{B,T} > a_i^{U,T},\ Q^{B,T} > (q_1^{U,T} + q_2^{U,T}),\ (\Pi_1^{B,T} + \Pi_2^{B,T}) < PS^{U,T},$$

$$CS^{B,T} > CS^{U,T},\ ED^{B,T} > ED^{U,T},\ SW^{B,T} > SW^{U,T}.$$

(ii) When the equity shares are such that $\alpha^B > \alpha^U/2$, *we have:*

$$t^B < t^U,\ a_i^{B,T} < a_i^{U,T},\ Q^{B,T} < (q_1^{U,T} + q_2^{U,T}),\ (\Pi_1^{B,T} + \Pi_2^{B,T}) > PS^{U,T},$$

$$CS^{B,T} < CS^{U,T},\ ED^{B,T} < ED^{U,T},\ SW^{B,T} < SW^{U,T}.$$

The results in Proposition 6 indicate that differences in equity shares of the alternative POA types affect their equilibrium outcomes differently. If the equity share of a bilateral POA is relatively lower such that $a_i^B < a_i^U/2$, the total industrial output turns out to be relatively higher as compared to that in a unilateral POA. In response, the government finds it welfare-improving to set a relatively higher emission tax for encouraging firms to increase production. The firms' cost of emission abatements are accordingly higher. As a result, producer surplus is lower, the environmental damage is more severe, and consumer surplus is higher when the firms engage in a bilateral POA. Since the effect of higher consumer surplus is dominating, social welfare ends up to be relatively higher.

If the equity share of a bilateral POA is relatively higher, $a_i^B > a_i^U/2$, the degree of inter-firm output coordination is higher such that total industrial output is lower than when the ownership is unilateral. Under this circumstance, the reverse result holds. It should be noted that the main results and implications in Proposition 6 remain valid qualitatively when the government sets an emission standard. The reason is analogous to the case of an emission tax, as discussed above. We thus omit the comparisons between different ownership arrangements under an emission standard policy (see Appendix A-6 for detailed calculations).[13]

Note the results in Proposition 1 that an optimal emission tax and an optimal emission standard are equivalent when POA is bilateral. Nevertheless, this is not the case when POA is unilateral because the two environmental policies are non-equivalent in their effects. The main reason is that for a bilateral POA, firms are symmetric such that both environmental policies have symmetric impacts on the polluting firm's production and emission decisions. Under unilateral ownership, two competing firms become asymmetric and hence are affected by policies asymmetrically in that outputs and emissions differ under the alternative emission policies. Accordingly, the welfare consequences differ under the alternative ownership arrangements. This suggests that in designing and choosing environmental policies, a government with welfare maximization as its objective should consider not only the size of

[13] The results in Proposition 6 suggest that even for a low value of profit share, differences in ownership arrangements may result in different levels of an optimal emission tax (standard), which, in turn, affect environmental quality and social welfare.

equity share, but also the type of a POA as unilateral or bilateral.

5. Concluding Remarks

In this paper, we compare two emission policies: uniform taxes and absolute standards, when polluting firms engage in a bilateral POA relative to the case when the POA is unilateral. We show for the case of a bilateral POA that taxes and standards are equally efficient in reducing emissions by polluting firms and affecting social welfare. Compared to the social planner's solution, a bilateral POA results in sub-optimal outcomes since total production declines, consumer surplus decreases, firm profits are higher, but the aggregate welfare decreases. Environmental quality improves due to lower emissions.

Furthermore, we compare the equilibrium outcomes under different types of POAs (bilateral vs. unilateral), and discuss their differences in policy implications for environmental regulations. As a social planner, the government can achieve social welfare maximization regardless of whether a POA is bilateral or unilateral. However, in reality, if the government is debating to choose between an emission tax and an emission standard, the policy option depends on the nature of a POA being bilateral or unilateral. We show that environmental quality is higher (lower), but social welfare is relatively lower (higher) under a bilateral (unilateral) POA. These results suggest that the environmental policy choice between emission taxes and emission standards cannot be isolated from different types of POAs between polluting firms, which significantly affect their abatement decisions and the resulting impacts on environmental quality.

Appendix

A-2. ***Proof of Proposition 2***

It follows from Proposition 1 that the equilibrium outcomes are identical for an emission tax policy or an emission standard policy. Without loss of generality, we compare results in Lemma 3 with those in Lemma 1 and Lemma 2. These exercise yields:

$$a_i^{B,S} - a_i^{B,SP} = -\frac{27A(14-11\alpha)}{11(335-484\alpha+176\alpha^2)} < 0,$$

$$s^{B,S} - e_i^{B,SP} = -\frac{81A}{22(335-484\alpha+176\alpha^2)} < 0,$$

$$ED^{B,S} - ED^{B,SP} = -\frac{81A^2(643-968\alpha+352\alpha^2)}{121(335-484\alpha+176\alpha^2)^2} < 0,$$

$$\pi_1^{B,S} - \pi_1^{B,SP} = \frac{3A^2\{214538-11\alpha[43879-\alpha(27411-352\alpha(1+8\alpha))]\}}{121(335-484\alpha+176\alpha^2)^2} > 0,$$

$$CS^{B,S} - CS^{B,SP} = -\frac{243A^2(-7744\alpha^3+30756\alpha^2-40656\alpha+17887)}{242(335-484\alpha+176\alpha^2)^2} < 0,$$

$$SW^{B,S} - SW^{B,SP} = -\frac{243A^2}{22(335-484\alpha+176\alpha^2)} < 0.$$

We thus have:

$$q_i^{B,S} < q_i^{B,SP},\ s^{B,S} < e_i^{B,SP},\ ED^{B,S} < ED^{B,SP},\ \pi_1^{B,S} > \pi_1^{B,SP},\ CS^{B,S} < CS^{B,SP},\ SW^{B,S} < SW^{B,SP}.$$

A-3. ***Proof of Proposition 4***

Under a bilateral POA without environmental policy, we have:

$$q_i^{B,N} = \frac{A(1-\alpha)}{3-2\alpha},\quad ED^{B,N} = \frac{4A^2(1-\alpha)^2}{3(3-2\alpha)^2},\ CS^{B,N} = \frac{2A^2(1-\alpha)^2}{(3-2\alpha)^2},\quad SW^{B,N} = \frac{2A^2(1-\alpha)(4-\alpha)}{3(3-2\alpha)^2}.$$

The detailed calculations of the results in (15) and (16) are as follows:

$$Q^{B,N} - Q^{U,N} = \frac{2A(1-\alpha)}{3-2\alpha} - \frac{A(2-\alpha)}{3-\alpha} = -\frac{A\alpha}{9-9\alpha+2\alpha^2} < 0,$$

$$ED^{B,N} - ED^{U,N} = \frac{4A^2(1-\alpha)^2}{3(3-2\alpha)^2} - \frac{A^2(2-\alpha)^2}{3(3-\alpha)^2} = -\frac{A^2\alpha(12-15\alpha+4\alpha^2)}{3(9-9\alpha+2\alpha^2)^2} < 0.$$

$$SW^{B,N} - SW^{U,N} = \frac{2A^2(1-\alpha)(4-\alpha)}{3(3-2\alpha)^2} - \frac{A^2(16-10\alpha+\alpha^2)}{6(3-\alpha)^2} = \frac{A^2\alpha(6-21\alpha+8\alpha^2)}{6(9-9\alpha+2\alpha^2)^2}.$$

The welfare comparison, as shown above, depends on the term $(6-21\alpha+8\alpha^2)$ in the numerator, which decreases with α and equals to zero when $\alpha = 0.32627$.

A-4. ***Proof of Proposition 5***

By comparing results in Lemma 4 under bilateral ownership with corresponding results under unilateral ownership, as discussed in Bárcena-Ruiz and Campo(2017), when the government sets an environmental standard, we have the following results:

$$s^{B,S}-s^{U,S}=\frac{6A(1-\alpha)(7-4\alpha)}{335-484\alpha+176\alpha^2}-\frac{3A(700-270\alpha+9\alpha^2)}{16750-5400\alpha+468\alpha^2}$$
$$=-\frac{81A\alpha(550-91\alpha+60\alpha^2-80\alpha^3)}{2(335-484\alpha+176\alpha^2)(8375-2700\alpha+234\alpha^2)}<0,$$

$$2a_i^{B,S}-(a_1^{U,S}+a_2^{U,S})=2\,\frac{3A(1-\alpha)(19-16\alpha)}{335-484\alpha+176\alpha^2}-\frac{3A(950-990\alpha+153\alpha^2)}{2(8375-2700\alpha+234\alpha^2)}$$
$$-\frac{3A(950-9\alpha^2)}{2(8375-2700\alpha+234\alpha^2)}$$
$$=-\frac{27A\alpha(7025-3888\alpha-2132\alpha^2+576\alpha^3)}{(335-484\alpha+176\alpha^2)(8375-2700\alpha+234\alpha^2)}<0,$$

$$Q^{B,S}-(q_1^{U,S}+q_2^{U,S})=\frac{18A(1-\alpha)(11-8\alpha)}{335-484\alpha+176\alpha^2}-\frac{9A(5-3\alpha)(55-9\alpha)}{8375-2700\alpha+234\alpha^2}$$
$$-\frac{45A(55-9\alpha)}{8375-2700\alpha+234\alpha^2}$$
$$=-\frac{27A\alpha(8675-4161\alpha-1952\alpha^2+336\alpha^3)}{(335-484\alpha+176\alpha^2)(8375-2700\alpha+234\alpha^2)}<0,$$

$$\frac{\partial(q_1^{U,S}+q_2^{U,S}-Q^{B,S})}{\partial\alpha}=\frac{\{27A(24338796875-23348411250\alpha-20602975250\alpha^2+33336503600\alpha^3-14099181896\alpha^4+2264108928\alpha^5-117330048\alpha^6)\}}{(335-484\alpha+176\alpha^2)^2(8375-2700\alpha+234\alpha^2)^2}>0,$$

$$(\Pi_1^{B,S}+\Pi_2^{B,S})-PS^{U,S}=\frac{6A^2(1-\alpha)(4160-7005\alpha+3600\alpha^2-512\alpha^3)}{(335-484\alpha+176\alpha^2)^2}$$
$$-\frac{3A^2(10400000-5636250\alpha+517950\alpha^2+99630\alpha^3-13203\alpha^4)}{2(8375-2700\alpha+234\alpha^2)^2}$$
$$=\frac{\{81A^2\alpha(19300608\alpha^7-326814336\alpha^6+1912704544\alpha^5-4058524040\alpha^4-394354455\alpha^3+11844405750\alpha^2-13586688750\alpha+4445031250)\}}{2(335-484\alpha+176\alpha^2)^2(8375-2700\alpha+234\alpha^2)^2}>0,$$

$$CS^{B,S}-CS^{U,S}=\frac{162A^2(1-\alpha)^2(11-8\alpha)^2}{(335-484\alpha+176\alpha^2)^2}-\frac{81A^2(55-9\alpha)^2(10-3\alpha)^2}{2(8375-2700\alpha+234\alpha^2)^2}$$
$$=-\frac{\{243A^2\alpha(8675-4161\alpha-1952\alpha^2+336\alpha^3)(368500-729275\alpha+471013\alpha^2-110040\alpha^3+8496\alpha^4)\}}{2(335-484\alpha+176\alpha^2)^2(8375-2700\alpha+234\alpha^2)^2}<0,$$

$$ED^{B,S}-ED^{U,S}=\frac{48A^2(1-\alpha)^2(7-4\alpha)^2}{(335-484\alpha+176\alpha^2)^2}-\frac{3A^2(700-270\alpha+9\alpha^2)^2}{(8375-2700\alpha+234\alpha^2)^2}$$

$$=-\frac{\{81A^2\alpha(550\text{-}91\alpha+60\alpha^2\text{-}80\alpha^3)(469000-873350\alpha+516247\alpha^2-105372\alpha^3+5328\alpha^4)\}}{2(335-484\alpha+176\alpha^2)^2(8375-2700\alpha+234\alpha^2)^2}<0,$$

$$SW^{B,S}-SW^{U,S}=\frac{18A^2(1-\alpha)(7-4\alpha)}{335-484\alpha+176\alpha^2}-\frac{9A^2(700-270\alpha+9\alpha^2)}{16750-5400\alpha+468\alpha^2}$$

$$=-\frac{243A^2\alpha(550-91\alpha+60\alpha^2-80\alpha^3)}{2(335-484\alpha+176\alpha^2)(8375-2700\alpha+234\alpha^2)}<0.$$

Under an optimal emission tax policy, we have:

$$t^B-t^U=\frac{2A(1-\alpha)(19-16\alpha)}{335-484\alpha+176\alpha^2}-\frac{A(38-35\alpha+8\alpha^2)}{335-242\alpha+44\alpha^2}$$

$$=-\frac{9A\alpha(281-336\alpha+88\alpha^2)}{(335-484\alpha+176\alpha^2)(335-242\alpha+44\alpha^2)}<0.$$

The comparisons have similar results as those under an emission standard policy and hence are omitted.

A-5. ***Proof of Proposition 6***

For $a_i^B \neq a_i^U$, we define $H_1 \equiv [335-484\alpha^B+176(\alpha^B)^2][335-242\alpha^U+44(\alpha^U)^2]>0.$ Following the same procedure as that in the proof of Proposition 6, we have the following results for an optimal emission tax policy:

$$t^B-t^U=\frac{2A(1-\alpha^B)(19-16\alpha^B)}{335-484\alpha^B+176(\alpha^B)^2}-\frac{A(38-35\alpha^U+8(\alpha^U)^2)}{335-242\alpha^U+44(\alpha^U)^2}$$

$$=-[9A(2\alpha^B-\alpha^U)(281-224\alpha^B-112\alpha^U+88\alpha^B\alpha^U)]/H_1,$$

$$a_i^{B,T}-a_i^{U,T}=\frac{3A(1-\alpha^B)(19-16\alpha^B)}{335-484\alpha^B+176(\alpha^B)^2}-\frac{3A[38-35\alpha^U+8(\alpha^U)^2]}{2[335-242\alpha^U+44(\alpha^U)^2]}$$

$$=-\frac{27A(2\alpha^B-\alpha^U)(281-224\alpha^B-112\alpha^U+88\alpha^B\alpha^U)}{2H_1},$$

$$Q^{B,T}-(q_1^{U,T}+q_2^{U,T})=\frac{18A(1-\alpha^B)(11-8\alpha^B)}{335-484\alpha^B+176(\alpha^B)^2}-\frac{9A[11-15\alpha^U+4(\alpha^U)^2]}{335-242\alpha^U+44(\alpha^U)^2}-\frac{9A(11-4\alpha^U)}{335-242\alpha^U+44(\alpha^U)^2}$$

$$=-\frac{27A(2\alpha^B-\alpha^U)(347-124\alpha^U-248\alpha^B+88\alpha^B\alpha^U)}{H_1},$$

$$CS^{B,T}-CS^{U,T}=\frac{162A^2(1-\alpha^B)^2(11-8\alpha^B)^2}{[335-484\alpha^B+176(\alpha^B)^2]^2}-\frac{81A^2[11-19\alpha^U+4(\alpha^U)^2]^2}{2[335-242\alpha^U+44(\alpha^U)^2]^2}$$

$$=-\frac{\begin{array}{l}\{243A^2(2\alpha^B-\alpha^U)(347-248\alpha^B-124\alpha^U+88\alpha^B\alpha^U)(14740\\ -23378\alpha^B+9232(\alpha^B)^2-11689\alpha^U+18392\alpha^B\alpha^U\\ -7216(\alpha^B)^2\alpha^U+2308(\alpha^U)^2-3608\alpha^B(\alpha^U)^2+1408(\alpha^B)^2(\alpha^U)^2)\}\end{array}}{2H_1^2},$$

$$ED^{B,T}-ED^{U,T}=\frac{48A^2(1-\alpha^B)^2(7-4\alpha^B)^2}{[335-484\alpha^B+176(\alpha^B)^2]^2}-\frac{12A^2(14-11\alpha^U+2(\alpha^U)^2)^2}{[335-242\alpha^U+44(\alpha^U)^2]^2}$$

$$=-\frac{\begin{array}{l}\{324A^2(2\alpha^B-\alpha^U)(11-4\alpha^B-2\alpha^U)(9380-14146\alpha^B\\ +5144(\alpha^B)^2-7073\alpha^U+10648\alpha^B\alpha^U-3872(\alpha^B)^2\alpha^U\\ +1286(\alpha^U)^2-1936\alpha^B(\alpha^U)^2+704(\alpha^B)^2(\alpha^U)^2)\}\end{array}}{H_1^2},$$

$$SW^{B,T}-SW^{U,T}=\frac{18A^2(1-\alpha^B)(7-4\alpha^B)}{335-484\alpha^B+176(\alpha^B)^2}-\frac{9A^2[14-11\alpha^U+2(\alpha^U)^2]}{335-242\alpha^U+44(\alpha^U)^2}$$

$$=-\frac{243A^2[\alpha^B(22-8\alpha^B)-\alpha^U(11-2\alpha^U)]}{H_1}.$$

All the above expressions are equal to zero for $\alpha^B=\alpha^U/2$, and are positive (negative) for $\alpha^B<\alpha^U/2$ ($\alpha^B>\alpha^U/2$).

$$(\Pi_1^{B,T}+\Pi_2^{B,T})-PS^{U,T}$$

$$=\frac{6A^2(1-\alpha^B)(3628-5721\alpha^B+32(\alpha^B)^2(81-8\alpha^B)}{(335-484\alpha^B+176(\alpha^B)^2)^2}$$

$$-\frac{3A^2(2-\alpha^U)[7256-5721\alpha^U+16(\alpha^U)^2(81-4\alpha^U)]}{2(335-242\alpha^U+44(\alpha^U)^2)^2}$$

$$=\frac{\begin{array}{l}\{(2\alpha^B-\alpha^U)(1239040(\alpha^B)^3(\alpha^U)^3-4648512(\alpha^B)^2(\alpha^U)^2+5738304\alpha^B(\alpha^U)^3\\ -2323648(\alpha^U)^3-9297024(\alpha^B)^3(\alpha^U)^2+33436160(\alpha^B)^2(\alpha^U)^2-41826240\alpha^B(\alpha^U)^2\\ +16582128(\alpha^U)^2+22953216(\alpha^B)^3\alpha^U-83652480(\alpha^B)^2\alpha^U+99470232\alpha^B\alpha^U\\ -38307567\alpha^U\ \ -18589184(\alpha^B)^3+66328512(\alpha^B)^2-76615134\alpha^B+28288070)\}\end{array}}{2H_1^2},$$

which equals to zero for $\alpha^B=\alpha^U/2$, and is negative (positive) for $\alpha^B<\alpha^U/2$ ($\alpha^B>\alpha^U/2$).

A-6. ***Proof of comparisons between ownership shares under a mission standard policy***

For the case of an emission standard policy, we conduct a comparison as that in Proposition 6 by setting $a_i^B\neq a_i^U$. Denote α^{B1} as the value of α^B such that $Q^{B,S}=(q_1^{U,S}+q_2^{U,S})$, α^{B2} as the value of α^B such that $s^B=s^U$, α^{B3} as the value of α^B such that $2a_i^{B,S}=(a_1^{U,S}+a_2^{U,S})$. Specifically, we have:

$$\alpha^{B1} = \frac{\{8675 + 3740\alpha^U - 696(\alpha^U)^2 - \sqrt{75255625 - 47365500\alpha^U + 11214900(\alpha^U)^2 - 1188000(\alpha^U)^3 + 47952(\alpha^U)^4}\}}{16(775 + 7\alpha^U(5 - 3\alpha^U)},$$

$$\alpha^{B2} = \frac{55[(55-9\alpha^U)\sqrt{5+\alpha^U(2+\alpha^U)}] - \sqrt{5}(55-9\alpha^U)^2}{40(55-9\alpha^U)\sqrt{5+\alpha^U(2+\alpha^U)}},$$

$$\alpha^{B3} = \frac{\{7025 + 2\alpha^U(1405 - 513\alpha^U) - [49350625 - 39199500\alpha^U + 11869200(\alpha^U)^2(\alpha^U)^3 + 78084(\alpha^U)^4]^{1/2}\}}{16(700 + \alpha^U(5 - 36\alpha^U)}.$$

Moreover, let $H_2 \equiv [335 - 484\alpha^B + 176(\alpha^B)^2][8375 - 2700\alpha^U + 234(\alpha^U)^2] > 0$. It follows that

$$Q^{B,S} - (q_1^{U,S} + q_2^{U,S}) = \frac{18A(1-\alpha^B)(11-8\alpha^B)}{335 - 484\alpha^B + 176(\alpha^B)^2} - \frac{9A\left(5-3\alpha^U\right)(55-9\alpha^U)}{8375 - 2700\alpha^U + 234(\alpha^U)^2} - \frac{45A(55-9\alpha^U)}{8375 - 2700\alpha^U + 234(\alpha^U)^2}$$

$$= -\frac{\{27A(13750\alpha^B - 12400(\alpha^B)^2 - 8675\alpha^U + 6940\alpha^B\alpha^U - 560(\alpha^B)^2\alpha^U + 1299(\alpha^U)^2 - 1392\alpha^B(\alpha^U)^2 + 336(\alpha^B)^2(\alpha^U)^2\}}{H_2},$$

which is negative (positive) for $\alpha > \alpha^{B1}$ ($\alpha < \alpha^{B1}$).

$$s^B - s^U = \frac{6A(1-\alpha^B)(7-4\alpha^B)}{335 - 484\alpha^B + 176(\alpha^B)^2} - \frac{3A(700 - 270\alpha^U + 9(\alpha^U)^2)}{16750 - 5400\alpha^U + 468(\alpha^U)^2}$$

$$= \frac{\{81A(-1100\alpha^B + 400(\alpha^B)^2 + 550\alpha^U - 440\alpha^B\alpha^U + 160\alpha^U(\alpha^B)^2 + 131(\alpha^U)^2 - 220\alpha^B(\alpha^U)^2 + 80(\alpha^U)^2(\alpha^B)^2\}}{2H_2^2},$$

which is negative (positive) for $\alpha > \alpha^{B2}$ ($\alpha < \alpha^{B2}$).

$$2a_i^{B,S} - (a_1^{U,S} + a_2^{U,S}) = \frac{6A(1-\alpha^B)(19-16\alpha^B)}{335 - 484\alpha^B + 176(\alpha^B)^2} - \frac{3A(950 - 990\alpha^U + 153(\alpha^U)^2)}{2[8375 - 2700\alpha^U + 234(\alpha^U)^2]} - \frac{3A[950 - 9(\alpha^U)^2]}{2[8375 - 2700\alpha^U + 234(\alpha^U)^2]}$$

$$= -\frac{\{27A[10450\alpha^B - 11200(\alpha^B)^2 - 7025\alpha^U + 5620\alpha^U\alpha^B - 80\alpha^U(\alpha^B)^2 + 1692(\alpha^U)^2 + 2052\alpha^B(\alpha^U)^2 + 576(\alpha^B)^2(\alpha^U)^2]\}}{H_2},$$

which is negative (positive) for $\alpha > \alpha^{B3}$ ($\alpha < \alpha^{B3}$).

$$CS^{B,S} - CS^{U,S} = \frac{162A^2(1-\alpha^B)^2(11-8\alpha^B)^2}{[335 - 484\alpha^B + 176(\alpha^B)^2]^2} - \frac{81A^2(55-9\alpha^U)^2(10-3\alpha^U)^2}{2[8375 - 2700\alpha^U + 234(\alpha^U)^2]^2},$$

which is negative (positive) for $\alpha > \alpha^{B1}$ ($\alpha < \alpha^{B1}$).

$$ED^{B,S} - ED^{U,S} = \frac{48A^2(1-\alpha^B)^2(7-4\alpha^B)^2}{[335-484\alpha^B+176(\alpha^B)^2]^2} - \frac{3A^2[700-270\alpha^U+9(\alpha^U)^2]^2}{[8375-2700\alpha^U+234(\alpha^U)^2]^2},$$

which is positive (negative) for $\alpha < \alpha^{B2}$ ($\alpha > \alpha^{B2}$).

Denote α^{B4} as the value of α^B such that $PS^B = PS^U$.

$$(\Pi_1^{B,S} + \Pi_2^{B,S}) - PS^{U,S}$$
$$= \frac{6A^2(1-\alpha^B)[4160-7005\alpha^B+3600(\alpha^B)^2-512(\alpha^B)^3]}{(335-484\alpha^B+176(\alpha^B)^2)^2}$$
$$- \frac{3A^2[10400000-5636250\alpha^U+517950(\alpha^U)^2+99630(\alpha^U)^3-13203(\alpha^U)^4]}{2(8375-2700\alpha^U+234(\alpha^U)^2)^2},$$

which is positive (negative) for $\alpha > \alpha^{B4}$ ($\alpha < \alpha^{B4}$). We omit the complicated expression α^{B4} for the sake of limited space. It is available upon request from the authors.

$$SW^{B,S} - SW^{U,S} = \frac{18A^2(1-\alpha^B)(7-4\alpha^B)}{335-484\alpha^B+176(\alpha^B)^2} - \frac{9A^2(700-270\alpha^U+9(\alpha^U)^2)}{16750-5400\alpha^U+468(\alpha^U)^2}$$
$$= \frac{\{243A^2[-1100\alpha^B+400(\alpha^B)^2+550\alpha^U-440\alpha^U\alpha^B+160(\alpha^B)^2\alpha^U+131(\alpha^U)^2-220\alpha^B(\alpha^U)^2+80(\alpha^B)^2(\alpha^U)^2]\}}{2H_2},$$

which is negative (positive) for $\alpha > \alpha^{B2}$ ($\alpha < \alpha^{B2}$). By a simulation approach, we find that $\alpha^U > \alpha^{B2} > \alpha^{B1} > \alpha^{B3}$. Moreover, with simulation $\alpha^{B4} < \alpha^{B3}$. Therefore, if $\alpha^U > \alpha^B > \alpha^{B2}$, we have the following results:

$s^B < s^U$, $Q^{B,S} < (q_1^{U,S} + q_2^{U,S})$, $(\Pi_1^{B,S} + \Pi_2^{B,S}) > PS^{U,S}$, $CS^{B,S} < CS^{U,S}$,

$2a_i^{B,S} < (a_1^{U,S} + a_2^{U,S})$, $ED^{B,S} < ED^{U,S}$, and $SW^{B,S} < SW^{U,S}$.

If $\alpha^B < \alpha^3$, we have the following results:

$s^B > s^U$, $Q^{B,S} > (q_1^{U,S} + q_2^{U,S})$, $CS^{B,S} > CS^{U,S}$, $2a_i^{B,S} > (a_1^{U,S} + a_2^{U,S})$,

$ED^{B,S} > ED^{U,S}$, and $SW^{B,S} > SW^{U,S}$.

Additionally,

$(\Pi_1^{B,S} + \Pi_2^{B,S}) - PS^{U,S} < 0$ if $\alpha^B < \alpha^4$.

Thus, the main results of proposition 6 continue to hold for an emission standard policy.

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