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Yang-Ming Chang and Manaf Sellak*

Environmental Policy in Vertical Markets with Downstream Pollution: Taxes Versus Standards

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Abstract: This paper examines the performance of two environmental regulation policies – emission taxes and absolute standards – in a vertical market where an upstream foreign monopolist sells a specific input to two downstream multiproduct firms that generate pollution in the domestic country. Specifically, we use a three-stage game to analyze and compare the two policies for regulating downstream pollution. In the first stage, the domestic government determines an optimal tariff and sets one of the two instruments (taxes or standards) by maximizing social welfare, in stage two, the upstream foreign monopoly sets its input price, and finally, the downstream domestic firms independently make their output and abatement decisions for profit maximization. We find that total emissions are lower under the absolute standard. Nevertheless, the tax dominates the standard in terms of domestic welfare, consumer surplus, and downstream multiproduct firms' profits. Thus, the tax equilibrium leads to a win-win-win situation compared to the standard equilibrium. These results show the *non-equivalence* of emission taxes and absolute standards in regulating downstream pollution. The analyses suggest that a pollution tax is an economically and politically feasible policy.

Keywords: absolute standards; downstream pollution; emission taxes; vertical markets; welfare

JEL Classification: Q58; L11; L22

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***Corresponding author: Manaf Sellak**, School of Business, Washburn University, Rm 310M Henderson Learning Center, 1700 SW College Ave., Topeka, KS 66621, USA,
E-mail: manaf.sellak@Washburn.edu. https://orcid.org/0000-0002-2885-7052
Yang-Ming Chang, Department of Economics, Kansas State University, 319 Waters Hall, Manhattan, KS 66506-4001, USA, E-mail: ymchang@ksu.edu

1 Introduction

Substantial studies have been devoted to analyzing pollution problems and how policy instruments affect environmental quality, consumer benefits, firm profits, and social welfare under different circumstances. Earlier contributions by Buchanan (1969) and Barnett (1980) investigate issues on the Pigouvian tax rule for the efficient controls of environmental externalities under different market structures. Environmental regulation policies can roughly be classified into two important categories: (i) command-and-control settings and (ii) market-based instruments (Requate 2005a). Command-and-control regulation allows policymakers to implement specific requirements such as emission standards or permissible pollutant limits for maintaining the quality of the environment. Market-based instruments aim to provide economic incentives for encouraging firms to reduce pollution by lowering production and increasing investments in emission-reducing innovations. Market-based instruments include pollution taxes and emission reduction subsidies. Requate (2005b, 2006) surveys the theoretical literature on environmental policy when polluting firms operate under imperfect competition. The regulation instruments he concentrates on are emission taxes, tradable permits, and both absolute and relative standards.[1] Sugeta and Matsumoto (2007) examine environmental policies in a vertical market where an upstream monopolist sells an intermediate input to two downstream firms producing differentiated goods. The upstream monopolist faces an input tax, while the downstream firms face an emissions tax in making their output and abatement decisions. The researchers show that an increase in emission tax leads downstream firms to reduce pollution and that a policy change from an input tax to an emission tax may lower tax revenue

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[1] See, e.g. Requate (1993) examines the performance of emission taxes and permits when polluting firms exercise local monopoly power and finds that the equivalence between the two policy instruments depends on the number of monopolies as large or small. Conrad and Wang (1993) compare pollution taxes and emission reduction subsidies. Ebert (1998) discusses the positive and normative aspects of relative standards in environmental regulation, using a Cournot oligopoly model with symmetric firms. Farzin (2003) analyzes the effects of environmental standards under an oligopoly and shows that a higher standard may increase the number of competing firms in an industry but with lower emissions. Other research works include the study of Bárcena-Ruiz and Campo (2012) on environmental regulation under partial cross-ownership arrangements, that of Walter and Chang (2007) on environmental regulation under green certification, and that of Walter and Chang (2020) on analyzing environmental policies and political feasibility between eco-labels and emission taxes. Bárcena-Ruiz and Sagasta (2021) analyze the environmental policy that is implemented by governments when polluting firms care about social concerns.

but increase social welfare. A recent study by Amir, Gama, and Werner (2018) evaluates emission and performance standards when polluting firms engage in Cournot competition. Using a three-stage game with endogenous environmental policy regulations, the researchers find that the performance standard is welfare superior to the emission standard.

Recognizing the existing contributions to the literature, we still see two challenging questions that need to be answered on how policymakers deal with downstream pollution caused by multiproduct firms that purchase a specific input from an upstream foreign monopoly. Under such a vertical market structure in an open economy, what are the differences between emission taxes and environmental standards in their effects on the input pricing decision of an upstream foreign monopoly supplier and hence on the output and abatement decisions of the downstream polluting firms? Which one of the policy instruments (taxes vs. standards) can achieve the multiple objectives of higher consumer surplus, domestic firms' profits, and social welfare? Answers to these questions have policy implications for the choice between the two alternative instruments and whether one is more economically and politically feasible than the other. This paper provides preliminary answers to the questions on downstream pollution of an open economy in a vertically related market, which appear not to have been systematically examined yet.

Issues on the equivalence (or non-equivalence) between an emission tax and an absolute standard as environmental policy instruments have been studied extensively. For example, Adar and Griffin (1976) show that when the environmental marginal damage function (or marginal control cost) is subject to uncertainty, emission taxes and environmental standards may yield the same expected social surplus. Baumol and Oates (1988) show that the welfare effects are higher for emission taxes than emission standards when polluting firms have different abatement costs. Simpson (1995) looks at Cournot competition between two polluting firms with production cost asymmetry and finds that the socially optimal tax rate may be higher than the environmental marginal 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. Helfand (1999) identifies conditions under which the two pollution control instruments have the same welfare effects. Specifically, she indicates that if polluting firms are symmetric, then uniform taxes and absolute standards are equally efficient in reducing emissions and maximizing social welfare. Lahiri and Ono (2007) consider an imperfectly competitive market with a fixed number of firms and find that the welfare effect is stronger with standards than with taxes under the same pollution emissions. Nevertheless, allowing for an identical welfare effect, emission taxes are more efficient in reducing pollution than absolute standards. When firms can freely enter and exit the market, the opposite results emerge for a concave demand function. Heuson (2010) analyzes emission taxes versus absolute standards with uncertain abatement costs in the presence of imperfect competition. The researcher shows that taxes have a comparative advantage over standards. Moner-Colonques and Rubio (2016) show that under regulatory commitment, both taxes and standards as policy instruments for protecting the environmental quality (measured in terms of emissions) are equivalent as they yield the same welfare level. Bárcena-Ruiz and Campo (2017) show that emission taxes and absolute standards are equivalent in welfare effect when polluting firms operate independently without engaging cross-shareholdings. When one firm unilaterally holds a share of another firm's equity, emission taxes generate higher welfare than absolute standards if the equity share is sufficiently low. By contrast, if the equity share is significantly high, emission taxes result in lower welfare than absolute standards. The reason is that unilateral partial ownership reduces the competitiveness of the market, causing the non-equivalence between taxes and standards. Dong and Chang (2020) show the equivalence of emission taxes and emission standards when polluting firms engage in symmetric partial ownership arrangements. Bárcena-Ruiz and Garzón (2022) find that the ownership structure of firms that compete in international markets affects the design of environmental policies by governments (taxes vs. standards). Chang and Sellak (2023) show that the equivalence of taxes and standards may cease to hold when the government sets an equity share limit and the firms' products are substitutes.

The studies mentioned above investigate issues on the equivalence/non-equivalence between emission taxes and absolute standards for closed economies. To focus on environmental regulation in open economies,[2] Ulph (1992, 1996a, 1996b) compares taxes and standards within a strategic environmental policy framework with two polluting firms located separately in two countries. Ulph (1992) finds that, contingent upon production technologies; environmental standards may have stronger welfare effects than emission taxes. Ulph (1996a) further indicates that for some generalized production technologies, the welfare comparisons between emission taxes and standards are generally indeterminate depending on whether governments act strategically to determine the emission tax and the absolute standard.

In the present paper, we consider an importing-country framework and focus our analysis on downstream pollution in a vertically related market with an upstream foreign monopolist selling a specific input to two polluting firms located downstream in the domestic country. Explicitly, we extend the model of Sugeta and

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[2] For contributions that examine the welfare effects of strategic environmental policies under transboundary pollution, see, e.g. Kennedy (1994), Tanguay (2001), and Fujiwara (2012).

Matsumoto (2007) by assuming that the upstream monopolist is a foreign firm. This extension permits us to evaluate the performance of emission taxes and standards in regulating downstream pollution in an open economy. We show that domestic welfare is higher by imposing taxes on downstream emissions than by setting standards. In the analysis, we adopt a three-stage game to analyze environmental regulation in a vertical market with a downstream polluting firm requiring the use of a specific input from an upstream monopolist. At stage one, the domestic government imposes an emission tax or an absolute standard to regulate downstream pollution. At stage two, taking the policy as given, the upstream foreign monopolist sets an input price to maximize profit. At stage three, the downstream multiproduct firms independently make their output and abatement decisions to maximize respective profit.

We summarize the main findings as follows. (i) Input price is lower, and the upstream foreign monopoly profit is higher under an emission tax than an absolute standard. (ii) The downstream polluting firms' output levels and profits are relatively higher under an emission tax. (iii) A more stringent environmental regulation with an emission tax or an absolute standard policy can reduce pollution, but the environmental quality is relatively higher (due to lower emissions) under the latter policy. (iv) In analyzing downstream pollution by domestic multiproduct firms that generate pollution in a product line while the other production line is pollution-free, we show that an optimal emission tax policy requires the domestic government to set the tax *higher* than the marginal environmental damage whereas an optimal emission standard policy requires the government to set the standard *lower* than the marginal environmental damage. (v) Remarkably, consumer surplus, the domestic multiproduct firms' profits, and domestic welfare are at relatively higher levels under an emission tax. These results show the *non-equivalence* of taxes and standards in regulating downstream pollution. Furthermore, the tax equilibrium leads to a win–win–win situation compared to the standard equilibrium. The findings of this paper have significant implications for the pollution tax policy's economic and political feasibility relative to an absolute standard policy.

An interesting study by Shapiro and Walker (2018) empirically documents that air pollution emissions from US manufacturing firms dropped by 60 percent between 1990 and 2008, even as real US manufacturing output grew substantially. Shapiro and Walker (2018) indicate that the significant drop in emissions of air pollutants was due mainly to changes in environmental regulation during the 1990–2008 period, having the pollution tax doubled. In essence, environmental taxes are costly to polluting firms and hence work as economic incentives for encouraging them to abate more pollutants or produce less. This explains the economic benefit of implementing environmental taxes (Requate 2005b). Our theoretical result that increasing emission tax as an economically and politically feasible policy appears to be consistent with the empirical finding.

The rest of the paper proceeds as follows. Section 2 presents an analytical framework and derives the equilibrium outcome for each policy option (an emission tax or an absolute standard). Section 3 presents the differences in welfare implications between the two environmental policies. Section 4 concludes.

2 The Model of Downstream Pollution in a Vertical Market

2.1 Basic Assumptions

We consider a vertical market structure in an open economy in which an upstream foreign monopolist exports a specific input to an importing country, where there are two downstream multiproduct firms (1 and 2) compete in producing differentiated goods (A and B) for domestic consumption.[3] Denote q_{Ai} and q_{Bi} as the quantities of goods A and B produced by the domestic firm $i(i = 1, 2)$. The total amount of good A served by the two downstream multiproduct (DMP) firms is $Q_A = q_{A1} + q_{A2}$. Likewise, that of good B served by the DMP firms is $Q_B = q_{B1} + q_{B2}$.

We follow Dixit (1979) and Singh and Vives (1984) by assuming that the preference function of a representative consumer over the differentiated goods A and B is:

$$U(Q_A,\ Q_B) = \alpha(Q_A +\ Q_B) - \frac{1}{2}\left(Q_A^2 + 2\beta Q_A Q_B + Q_B^2\right) + m, \tag{1}$$

where the parameter β stands for the degree of product differentiation, and m is the quantity of a numeraire good. The two goods are imperfect substitutes for $0 < \beta < 1$. Corresponding to the preference structure in (1), we have the following system of linear (inverse) demand functions for goods A and B:

$$p_A = \alpha - (q_{A1} + q_{A2}) - \beta(q_{B1} + q_{B2}), \tag{2a}$$

$$p_B = \alpha - (q_{B1} + q_{B2}) - \beta(q_{A1} + q_{A2}). \tag{2b}$$

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[3] Our setup of downstream multiproduct firms in a vertical market is closely related to the model of Arya and Mittendorf (2010). The authors pay attention to input price discrimination in multiple markets without pollution, while we consider uniform input price in analyzing issues on regulating downstream pollution. For studies on multiproduct firms in the absence of environmental externalities, see, e.g. Bailey and Friedlaender (1982), van Witteloostuijn and van Wegberg (1992), Eckel and Neary (2010), Bernard et al. (2010), and Kopel, Löffler, and Pfeiffer (2016).

The preference function in (1) and the demand system in (2) imply that consumer surplus (CS) in the domestic market is given as $\mathrm{CS} = \left(Q_A^2 + Q_B^2 + 2\beta Q_A Q_B\right)/2$.

We consider that the downstream multiproduct firms generate pollution in the production of good A.[4] To reduce pollution emissions, each DMP firm incurs a cost to abate its pollutant emissions in producing good A. We postulate that one unit of good A produced by each DMP firm generates one unit of pollutant emission. The amount of emissions is then given as $e_{Ai} = q_{Ai} - a_{Ai}$, where a_{Ai} is the level of abatement by the ith DMP firm for $i = 1, 2$. The total cost of abating emissions to each DMP firm is taken to be a quadratic function: $k(a_{Ai})^2$, where $k(> 0)$ represents the cost-effectiveness of the abatement technology.

In the open economy, the government's objective is to choose a policy mix that combines (i) an optimal tariff, denoted by τ, on each unit of the specific input imported from the upstream foreign monopolist, and (ii) an optimal pollution control measure to maximize social welfare. To concentrate our study on comparing the choice of environmental policy regulations, we consider two policy options. The first policy option is a uniform tax, denoted by t, for each unit of polluting emission. In this case, the amount of emission taxes (ET) collected from the two polluting firms is $\mathrm{ET} = t[(q_{A1} - a_{A1}) + (q_{A2} - a_{A2})]$. Other things being equal, an increase in the emission tax (t) makes pollution more costly to the DMP firms. The second policy option is an absolute standard, denoted by s, for limiting the level of pollution emissions. With the emission limit, the level of abatement by each of the polluting firms is then given as $a_{Ai} = q_{Ai} - s$. Other things being equal, a *decrease* in the emission standard or permissible limit (i.e. a lower level for s) increases the abatement level, making pollution more costly to the DMP firms.

Denote w as the input price that the DMP firms pay in purchasing the specific input from its exclusive upstream foreign supplier. Under an emission tax, the aggregate profit function of the DMP firm i (for $i = 1, 2$) from selling the two differentiated products is $\pi_i^T = \pi_{Ai}^T + \pi_{Bi}^T$, where

$$\pi_{Ai}^T = \left[(p_A - w)\, q_{Ai} - t(q_{Ai} - a_{Ai}) - k a_{Ai}^2\right] \text{ and } \pi_{Bi}^T = (p_B - w) q_{Bi}. \tag{3}$$

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[4] There are some interesting examples of multiproduct firms. For example, *Unilever*, a European company, produces consumer goods, including food and beverages. While some of its products generate emissions during the production process, the firm also produces non-emission products such as plant-based foods and sustainable cleaning products. (See https://www.unilever.com/planet-and-society/positive-nutrition/plant-based-foods/). Another example is *Nestle*, a food and beverage company, that generates zero emissions while producing its organic and non-GMO products but generates emissions while producing its non-organic and GMO products. (See https://www.nestle.com/sites/default/files/2022-03/2021-annual-review-en.pdf, Page 11).

Under an absolute standard, the aggregate profit function of the DMP firm *i* is $\pi_i^S = \pi_{Ai}^S + \pi_{Bi}^S$, where

$$\pi_{Ai}^S = \left[(p_A - w)q_{Ai} - k(q_{Ai} - s)^2\right] \text{ and } \pi_{Bi}^S = (p_B - w)q_{Bi}. \tag{4}$$

Depending on the government's choice of a regulation policy (denoted as superscript *j* for $j = T, S$), which may affect input price differently, the upstream foreign monopolist's profit is:

$$\pi_U^j = (w^j - \tau)(q_{A1} + q_{A2} + q_{B1} + q_{B2}). \tag{5}$$

We assume that the marginal cost of production for the upstream foreign monopolist is zero for simplicity and without loss of generality.[5] The total amount of producer surplus (PS) for the DMP firms in the domestic market is the sum of their profits:

$$\text{PS}^j = \left(\pi_{A1}^j + \pi_{B1}^j\right) + \left(\pi_{A2}^j + \pi_{B2}^j\right) \text{ for } j = T, S. \tag{6}$$

Define λ as the parameter representing the extent to which the environment deteriorates due to pollutant emissions. Total environmental damage (ED) generated by the downstream polluting firms is taken to be a convex quadratic function of emissions:

$$\text{ED}^j = \lambda(e_{A1} + e_{A2})^2. \tag{7a}$$

It follows that the marginal environmental damage (MED) under either the emission tax policy ($j = T$) or the absolute standard policy ($j = S$) is given as

$$\text{MED}^j = 2\lambda(e_{A1} + e_{A2}). \tag{7b}$$

As in the literature, social welfare is taken as the sum of consumer surplus, producer surplus, and government revenues (GR) from two sources: (i) a specific tariff on the imported input and (ii) the emission tax, net of the total environmental damage. The social welfare equation is:

$$\text{SW}^j = \text{CS}^j + \text{PS}^j + \text{GR}^j - \text{ED}^j \text{ for } j = T, S, \tag{8}$$

where $\text{CS} = \left(Q_A^2 + Q_B^2 + 2\beta Q_A Q_B\right)/2$ as mentioned earlier, PS^j and ED^j are given in (6) and (7), and GR^j depends on whether there is an emission tax or an absolute standard. They are:

$$\text{GR}^T = \tau(Q_A + Q_B) + t[(q_{A1} - a_{A1}) + (q_{A2} - a_{A2})] \text{ under an emission tax policy:} \tag{9a}$$

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[5] The paper's main findings remain the same for a positive marginal cost of production for the foreign monopolist.

$$\mathrm{GR}^S = \tau(Q_A + Q_B) \text{ under an absolute standard policy.} \tag{9b}$$

In the analysis, we adopt a three-stage game to analyze an importing country government's tariff and environmental policies in a vertical market with downstream polluting firms requiring the use of a specific input from an upstream foreign monopolist. At stage one, the government imposes a specific tariff on imports and an environmental regulation (either an emission tax or an absolute standard) over the downstream pollution. At stage two, taking the policies as given, the upstream foreign monopolist sets an input price to maximize profit. At stage three, the two downstream multiproduct firms simultaneously and non-cooperatively make their output and abatement decisions to maximize their respective profits. We solve the three-stage game by backward induction for each environmental policy to obtain a subgame-perfect Nash equilibrium. Throughout the analysis, we follow the studies by Bárcena-Ruiz and Campo (2017) and Dong and Chang (2020) and assume that $k = \lambda = 1/3$.

2.2 Emission Tax

We first examine an emission tax policy on the downstream polluting firms. At the third and last stage of the three-stage game, each DMP firm maximizes its total profit by determining output levels for products A and B, $\{q_{Ai}, q_{Bi}\}$,and the abatement level,$\{a_i\}$. Using the DMP firms' profit functions in (3), we calculate the first-order conditions (FOCs) for profit maximization. The FOCs for the ith DMP firm are:

$$\frac{\partial \pi_i^T}{\partial q_{Ai}} = \alpha - w - t - 2(q_{Ai} + \beta q_{Bi}) - (q_{Ak} + \beta q_{Bk}) = 0,$$

$$\frac{\partial \pi_i^T}{\partial q_{Bi}} = \alpha - w - 2(q_{Bi} + 2\beta q_{Ai}) - (q_{Bk} + \beta q_{Ak}) = 0,$$

$$\frac{\partial \pi_i^T}{\partial a_i} = t - \frac{2}{3}a_i = 0,$$

where π_i^T is the ith firm's profit under emission for $i, k = 1, 2$ and $i \neq k$. Using these FOCs, we solve for the optimal levels of outputs and abatement for the DMP firms yields

$$q_{A1} = q_{A2} = \frac{(1-\beta)(\alpha - w)\ - t}{3\,(1-\beta)(1+\beta)},\ q_{B1} = q_{B2} = \frac{(1-\beta)(\alpha - w) + t\beta}{3(1-\beta)(1+\beta)},\ \text{and}$$
$$a_{A1} = a_{A2} = \frac{3t}{2}. \tag{10}$$

At stage two, the upstream foreign monopolist sets an input price that maximizes its profit function in (5), taking into account the downstream firms' demand for the input. That is, the monopolist maximizes $\pi_U = (w - \tau)[(q_{A1} + q_{A2}) + (q_{B1} + q_{B2})]$, where the DMP firms' outputs are given in (10). The FOC for the upstream foreign monopolist is:

$$\frac{\partial \pi_U^T}{\partial w} = \frac{2}{3(1+\beta)}(t + 4w - 2\alpha - 2\tau) = 0.$$

Solving for the optimal input price, we have:

$$w = \frac{2\alpha + 2\tau - t}{4}. \tag{11}$$

It follows from (11) that input price increases with the tariff rate but decreases with the emission tax rate. That is,

$$\frac{\partial w}{\partial \tau} > 0 \text{ and } \frac{\partial w}{\partial t} < 0. \tag{12}$$

The economic intuitions behind the results in (12) are as follows. A higher tariff rate makes it more costly for the upstream foreign monopolist to export the input. In response, the foreign monopolist charges a higher price for the input to maximize profit. As for more stringent environmental regulation due to a higher emission tax on the downstream polluting firms, the upstream foreign monopolist finds it profitable to lower the input price.

Substituting the input price w from (11) back into (10), we have the optimal levels of outputs produced by the DMP firms:

$$\begin{aligned} q_{A1} = q_{A2} &= \frac{2(1-\beta)(\alpha - \tau) - t(3+\beta)}{12(1-\beta)(1+\beta)} \text{ and} \\ q_{B1} = q_{B2} &= \frac{2(1-\beta)(\alpha - \tau) + (1+3\beta)t}{12(1-\beta)(1+\beta)}. \end{aligned} \tag{13}$$

We have from (13) the following comparative-static derivatives:

$$\frac{\partial q_{Ai}}{\partial t} < 0 \text{ and } \frac{\partial q_{Bi}}{\partial t} > 0. \tag{14}$$

A stringent regulation with a higher emission tax affects the output composition of the downstream multiproduct firms differently. It lowers the output level of good *A* produced by each DMP firm since its production generates pollution, and raises the output of good *B* as its production is emission-free.[6] The economic explanations are as follows. An increase in emission tax has two adverse effects on the DMP firms. One is associated with the higher abatement costs to the polluting firms.

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[6] In our analysis, good *B* can be treated as an environmentally friendly product.

The other is an "output-reducing effect" of an emission tax, causing the production of good *A* to decline. To mitigate the losses resulting from these two perverse effects, the DMP firms find it profitable to produce more of good *B*.

We proceed to the first stage of the three-stage game, at which the government determines an optimal rates on tariff and emission tax to maximize social welfare. Making use of Equations (3) and (6a)–(9a), the government solves the following welfare maximization problem:

$$\underset{\{\tau,t\}}{\text{Max}}\, \text{SW}^T = \text{CS}^T + \text{PS}^T + \text{GR}^T - \text{ED}^T$$

where $\text{GR}^T = \tau(q_{A1} + q_{B1} + q_{A2} + q_{B2}) + t[(q_{A1} - a_{A1}) + (q_{A2} - a_{A2})]$, which is the sum of tariff revenues and emission taxes. To find the solution, we first use the DMP firms' output levels as solved in (13) to compute consumer surplus and producer surplus in (6), tariff revenue, emission taxes, and the environmental damage in (7a). We then use the resulting welfare function to calculate the FOCs for the government. Solving the FOCs yields the optimal values of import tariff and emission tax, denoted as τ^T and t^*, respectively. Plugging τ^T and t^* back into the relevant equations under the emission tax policy, we have their equilibrium values as summarized in the first lemma (see the detailed analysis in Appendix A 1).

In our examination of downstream pollution in an open economy, it is necessary to compare the optimal emission tax (t^*) to the marginal environmental damage (MED^T). Comparison the two reveal the following inequality:

$$t^* - \text{MED}^T = \frac{2\alpha(1-\beta)}{1177 - 1020\beta - 1113\beta^2 + 972\beta^3} > 0, \tag{15a}$$

which implies that

$$t^* > \text{MED}^T. \tag{15b}$$

The economic justifications for this outcome are as follows. When determining an optimal pollution tax to impose, the government takes into account three major effects. First, since an emission tax makes it more costly for downstream firms to emit pollutants, it has a positive welfare effect on lowering pollution. That is, $\partial \text{ED}^T/\partial t < 0$. The resulting decrease in emissions lowers the marginal environmental damage such that $\partial \text{MED}^T/\partial t < 0$. Second, the emission tax causes a reduction in good A's output, which has a negative impact on welfare. This output-reducing effect implies that $\partial q_{Ai}/\partial t < 0$. Third, the emission tax has a positive effect on welfare since it increases the output of good B, whose production is free of pollution. For the case that downstream firms generate pollution in producing good *A*, the third effect is zero ($\partial q_{Bi}/\partial t = 0$), and the first and second effects work against each other. To compensate for the output-reducing effect, the emission tax is set at a level lower than the marginal environmental damage for the conventional case of single-product polluting firms.[7] When the downstream multiproduct firms start to produce good B whose production is pollution-free, there is a positive welfare effect. As such, the government finds it beneficial to set an optimal emission tax *higher* than the marginal environmental damage. This is because an emission tax's pollution-reducing effect more than offsets its output-reducing effect.

Our finding that $t^* > \text{MED}^T$ in (15b) is consistent with the result in Katsoulacos and Xepapadeas (1995). The authors show the interesting case that the optimal emission tax may well be *higher* than the marginal environmental damage under an oligopoly.

2.3 Absolute Standard

Next, we turn to an alternative environmental regulation by setting an absolute standard on emission. At the third and last stage of the game, the DMP firms determine output levels for goods A and B to maximize their respective profit functions in (4). The FOCs for the ith DMP firm are:

$$\frac{\partial \pi_i^S}{\partial q_{Ai}} = \frac{2}{3}s - w + \alpha - \left(\frac{8}{3}q_{Ai} + 2\beta q_{Bi}\right) - (q_{Ak} + \beta q_{Bk}) = 0, \tag{16}$$

$$\frac{\partial \pi_i^S}{\partial q_{Bi}} = \alpha - w - 2(q_{Bi} + \beta q_{Ai}) - (q_{Bk} + \beta q_{Ak}) = 0, \tag{17}$$

where π_i^T is the ith firm profit under emission standard for $i, k = 1, 2$ and $i \neq k$. Using the FOCs in (16) and (17), we solve for the optimal levels of outputs and abatement for the DMP firms:

$$q_{A1} = q_{A2} = \frac{3(1-\beta)(\alpha - w) + 2s}{11 - 9\beta^2} \text{ and } q_{B1} = q_{B2} = \frac{(11 - 9\beta)(\alpha - w) - 6\beta s}{33 - 27\beta^2}. \tag{18}$$

At stage two, the upstream foreign monopolist sets an input price that maximizes its profit function in (5), taking into account the DMP firms' demands for the input. That is, the monopolist maximizes $\pi_U = (w - \tau)[(q_{A1} + q_{A2}) + (q_{B1} + q_{B2})]$, where the downstream firms' outputs are given in (18). The upstream foreign monopolist's FOC is:

$$\frac{\partial \pi_U^S}{\partial w} = \frac{4[(\alpha + \tau)(10 - 9\beta) + 3(1-\beta)s - (20 - 18\beta)w]}{33 - 27\beta^2} = 0.$$

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[7] See Buchanan (1969), Barnett (1980), and Levin (1985) for the traditional case in which polluting firms produce a single product and the optimal tax rate is strictly *lower* than the marginal environmental damage.

Solving for the optimal input price yields

$$w = \frac{(\alpha + \tau)(10 - 9\beta) + 3(1 - \beta)s}{20 - 18\beta}. \tag{19}$$

We have from w in (19) the following comparative-static derivatives:

$$\frac{\partial w}{\partial \tau} > 0 \text{ and } \frac{\partial w}{\partial s} > 0. \tag{20}$$

It comes as no surprise that a *ceteris paribus* increase in the specific tariff on the upstream foreign monopolist's input raises its cost of exporting, causing the input price to go up. This tariff effect on input price resembles the case under an emission tax. We therefore have $\partial w/\partial \tau > 0$. Next, we see that a stringent environmental regulation through a decrease in the permissible emission standard increases the abatement level, making pollution more costly to the downstream firms. In this case, the downstream firms' production is affected negatively, causing the quantity of the input demanded to go down. In response, the upstream foreign monopolist finds it profitable to lower its price. This explains the result that $\partial w/\partial s > 0$.

Substituting the input price w from (19) back into (18) yields the optimal levels of outputs by the DMP firms:

$$q_{A1} = q_{A2} = \frac{3(1 - \beta)(10 - 9\beta)(\alpha - \tau) + s(31 - 18\beta - 9\beta^2)}{2(10 - 9\beta)(11 - 9\beta^2)},$$

$$q_{B1} = q_{B2} = \frac{(\alpha - \tau)(10 - 9\beta)(11 - 9\beta) - 3s(11 + 20\beta - 27\beta^2)}{6(10 - 9\beta)(11 - 9\beta^2)}. \tag{21}$$

We have from (21) the following comparative-static derivatives:

$$\frac{\partial q_{Ai}}{\partial s} > 0 \text{ and } \frac{\partial q_{Bi}}{\partial s} < 0. \tag{22}$$

Other things being equal, a more stringent regulation through a lowering of emission standards lead the downstream polluting firms' abatement costs to go up. Accordingly, the DMP firms then find it profitable to produce less of good A and more of good B.

The results of the above analyses permit us to establish the first proposition:

Proposition 1. *In a vertical market with an upstream foreign monopolist selling a specific input to downstream domestic multiproduct firms that pollute in producing one of their products, the upstream foreign monopolist lowers the input price when the domestic government adopts more stringent environmental regulation with a lower permissible level of pollution emissions.*

Proposition 1 indicates that the marginal effects of emission tax and absolute standard policies on the upstream input price are identical. That is, more stringent environmental regulation by increasing an emission tax or reducing an emission standard leads the foreign monopolist to lower the input price.

We proceed to the first stage of the three-stage game, where the government determines an optimal tariff rate on the imported input and an optimal level of emission standard. Making use of Equations (4) and (6b)–(9b), the government solves the welfare maximization problem:

$$\underset{\{\tau,s\}}{\text{Max}}\ \text{SW}^S = \text{CS}^S + \text{PS}^S + \text{GR}^S - \text{ED}^S,$$

where $\text{GR}^S[= \tau(q_{A1} + q_{A2} + q_{B1} + q_{B2})]$ is the amount of tariff revenues collected by the government, and q_{Ai} and q_{Bi} for $i = 1, 2$ are given in (21). To find the solution for the government, we first use the DMP firms' output levels in (21) to calculate consumer surplus and producer surplus in (6), tariff revenue, and the environmental damage in (7a). We then use the resulting welfare function to calculate the FOCs for the government. Solving the FOCs yields the optimal values of import tariff and absolute standard, denoted as τ^S and s^*, respectively. Plugging τ^S and s^* back into the equations under the absolute standard policy, we have their equilibrium values as summarized in the second lemma (see the detailed analysis in Appendix A.2).

It is instructive to note that the socially optimal level of permissible emission standard, s^*, is a function of market size (α) and the degree of product substitutability (β) between goods A and B. The greater the market size (or demand) for the consumption goods, the higher the socially permissible level of emission. That is, $\partial s^*/\partial\alpha > 0$. The economic implication of this comparative-static derivative is that, other things being equal, the government's environmental regulation becomes less stringent when market size is greater. Next, it is easy to verify that $\partial s^*/\partial\beta < 0$. For the case where the degree of product substitutability is lower (due to a higher β for $0 < \beta < 1$), the government finds it optimal to set a more stringent environmental policy by reducing the permissible emission standard. In reaction to the policy, the DMP firms reduce their emissions by decreasing the output of good A whose production generates pollution. As a result, we have $\partial\left(q_{A1}^S + q_{A2}^S\right)/\partial\beta < 0$. In the meanwhile, the DMP firms react by increasing the output of good B whose production is pollution-free. That is, $\partial\left(q_{B1}^S + q_{B2}^S\right)/\partial\beta > 0$.

3 Non-Equivalence Between Taxes and Standards[8]

This section compares the equilibrium outcomes between the tax and standard policies and discusses differences in their welfare implications. First, we look at the effects on input price charged by the upstream foreign monopolist and the resulting impacts on outputs of the downstream multiproduct firms in the importing country. According to the equilibrium results Lemmas 1 and 2 (see A.1 and A.2 in the appendix), we have the following proposition:[9]

Proposition 2. *In a vertical market with an upstream foreign monopolist selling a specific input to downstream domestic multiproduct firms that generate pollution in a product line, the input price is lower and the quantities of the final products are higher under an emission tax than under an absolute standard. That is,*

$$w^T < w^S, q^T_{Ai} > q^S_{Ai}, \quad \mathit{and} \quad q^T_{Bi} > q^S_{Bi}.$$

The optimal input price set by the upstream foreign monopolist depends on the importing country government's choice of an environmental policy. Under an absolute standard, the upstream foreign monopoly charges a higher input price than that under an emission tax. Moreover, the DMP firms' output levels are lower under an absolute standard. The economic explanations are as follows. Since the input price is lower under an emission tax than an absolute standard, the DMP firms purchase more input, and hence produce relatively higher levels of their products under an emission tax policy.

Next, we look at the DMP firms' profits and the resulting environmental damage. We have from Lemmas 1 and 2 (see A.1 and A.2 in the appendix), the following:

Proposition 3. *In a vertical market with an upstream foreign monopolist selling a specific input to downstream domestic multiproduct firms that generate pollution in a product line, the equilibrium outcomes for the firms' profits and the levels of environmental damage under taxes and standards imply that*

$$\pi^T_i > \pi^S_i, \pi^T_U > \pi^S_U, ED^T > ED^S, \quad \mathit{and} \quad MED^T > MED^S.$$

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[8] It is instructive to mention that the paper's main findings in Propositions 1-5 remain the same for the case of one downstream domestic monopolist purchasing a key input from an upstream foreign monopolist. Thus, the non-equivalence of emission taxes and absolute standards holds in vertical markets whether there is a monopoly or differentiated duopoly at the downstream level.

[9] Detailed comparisons for the equilibrium outcomes between the two policy instruments can be found in Appendix A.3.

The upstream foreign monopoly and the downstream domestic firms make higher profits under an emission tax than an absolute standard. Since the input price is lower under an emission tax (See Proposition 3), a greater amount of the input will be sold to the DMP firms by the upstream foreign monopolist for more profits. Meanwhile, the DMP firms make higher profits as the marginal benefit of increasing production outweighs the marginal cost when there is a switch in policy from the absolute standard to the emission tax. Moreover, Proposition 3 indicates that the total environmental damage is relatively higher under an emission tax policy as environmental damage depends exclusively on the output of good A that the DMP firms produce. As a consequence, the marginal environmental damage under an emission tax is higher than that under absolute standard, i.e. $\mathrm{MED}^T > \mathrm{MED}^S$.

Finally, we look at differences in implications for consumer surplus and social welfare. We have from the equilibrium outcomes in Appendix A.1 and A.2 the following:

Proposition 4. *In a vertical market with an upstream foreign monopolist selling a specific input to downstream domestic multiproduct firms that generate pollution in a product line, emission taxes result in higher levels of consumer surplus and domestic welfare than absolute standards. This indicates the non-equivalence of taxes and standards in regulating downstream pollution since*

$$CS^T > CS^S \quad and \quad SW^T > SW^S.$$

Although environmental quality is higher under an absolute standard (see Proposition 3), consumer surplus, firms' profits, and overall welfare are higher under an emission tax (as shown in Propositions 3 and 4). Given that consumer surplus depends on the quantities of differentiated products served by the DMP firms, a higher level of consumer surplus is obtained when the government sets an emission tax policy. Furthermore, higher social welfare under an emission tax policy is explained by the higher levels of consumer surplus, the total tariff, the emission tax collected, and the downstream firms' profits, which more than offset the resulting damage to the environment.

Propositions 3 and 4 have significant implications for the choice of environmental regulation policies. We find that an emission tax policy generates higher welfare than an absolute standard, despite that there is cost symmetry for the downstream domestic polluting firms and that there is no uncertainty.[10] This finding adds to the existing literature, as mentioned in the introduction, which contends that

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[10] We thank an anonymous referee for suggesting that we stress the non-equivalence of taxes and standards in a proposition.

emission taxes dominate absolute standards in terms of social welfare when polluting firms are different. Our analysis has further demonstrated the non-equivalence of emission taxes and absolute standards in vertically related markets with symmetric multiproduct firms producing downstream.

4 Concluding Remarks

This paper examines differences in welfare implications between emission taxes and absolute standards to control pollution generated by downstream multiproduct firms in a vertical market when the firms purchase specific input from an upstream foreign monopolist. We show that different policy instruments lead to different input prices, affecting the abatement level and the output decisions of downstream polluting firms in the domestic product markets. Our analysis demonstrates the non-equivalence of emission taxes and absolute standards. Unsurprisingly, environmental quality is relatively higher under an absolute standard policy. Nevertheless, there are win–win–win outcomes under an emission tax policy since consumer surplus, firms' profits, and social welfare are all relatively higher. In other words, domestic consumers and firms are all better off under the tax than the standard. The analytical results suggest that pollution tax is an economically and politically feasible policy.

Despite that our results provide policy implications for the choice of pollution taxes over absolute standards, the limitations of the present analysis and hence possibly interesting extensions of the model should be mentioned. Requate (2005b) indicates that, among all the environmental regulation instruments, pollution taxes generally generate the highest incentives for firms to adopt cleaner technology. Our simple analysis does not consider the adoption of a cleaner technology by downstream polluting firms through emission-reducing R&D activities. Moreover, our analysis of an open economy abstracts from the possibility of factor price negotiations between the upstream foreign input supplier and the downstream domestic multiproduct firms. In addition, our analysis does not consider cost asymmetry at the downstream level and input price discrimination by the upstream foreign monopolist. These are important topics for future research.

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Appendix A

A.1 Welfare Maximization Problem under an Emission Tax Policy

Under an emission tax policy, the government determines optimal rates on tariff and emission tax to maximize social welfare. Making use of Equations (3) and (4) and (6)a)–a(9a), the government solves the following welfare maximization problem:

$$\underset{\{\tau,t\}}{\text{Max}}\, \text{SW}^T = \text{CS}^T + \left(\pi_1^T + \pi_2^T\right) + \text{GR}^T - \text{ED}^T$$

where $\text{GR}^T = \tau(q_{A1} + q_{B1} + q_{A2} + q_{B2}) + t[(q_{A1} - a_{A1}) + (q_{A2} - a_{A2})]$, which is the sum of tariff revenues and emission taxes.

To find the solution, we first use the DMP firms' output levels in (12) to calculate consumer surplus, the firms' profits in (3), tariff revenue, emission taxes, and the environmental damage in (5). We record the results as follows:

$$\text{CS}^T = \frac{4(1-\beta)(\alpha-\tau)(\alpha-\tau-t) + t^2(3\beta+5)}{36(1-\beta)(1+\beta)},$$

$$\pi_1^T = \pi_2^T = \frac{4(1-\beta)(\alpha-\tau)(\alpha-\tau-t) + (59+3\beta-54\beta^2)t^2}{72(1-\beta)(1+\beta)},$$

$$\text{GR}^T = \frac{(1-\beta)[4\tau(\alpha-\tau) + 2t(\alpha-2\tau)] - t^2(3+\beta)}{6(1-\beta)(1+\beta)},$$

$$\text{ED}^T = \lambda\left(e_{A1}^2 + e_{A2}^2\right) = \frac{[2(1-\beta)(\alpha-\tau) - t(21+\beta-18\beta^2)]^2}{108(1-\beta)^2(1+\beta)^2},$$

We then use the welfare function to calculate the FOCs for the government.

$$\frac{\partial \text{SW}^T}{\partial t} = \frac{\begin{matrix}\big(303t - 48\alpha + 66\tau + 42t\beta + 46\alpha\beta - 64\beta\tau - 455t\beta^2 \\ -36t\beta^3 + 162t\beta^4 + 44\alpha\beta^2 - 42\alpha\beta^3 - 62\beta^2\tau + 60\beta^3\tau\big)\end{matrix}}{54(1-\beta^2)^2} = 0$$

$$\frac{\partial \text{SW}^T}{\partial \tau} = \frac{(33t - 8\alpha + 26\tau + t\beta + 2\alpha\beta - 2\beta\tau - 30t\beta^2 + 6\alpha\beta^2 - 24\beta^2\tau)}{27(1-\beta)(1+\beta)^2} = 0$$

Solving the FOCs for the optimal tariff and emission tax yields

$$\tau^T = \frac{\alpha(286 - 240\beta - 285\beta^2 + 243\beta^3)}{1177 - 1020\beta - 1113\beta^2 + 972\beta^3} > 0 \text{ and}$$

$$t^* = \frac{6\alpha(1-\beta)(10-9\beta)}{1177 - 1020\beta - 1113\beta^2 + 972\beta^3} > 0.$$

Plugging τ^T and t^* back into the relevant equations under the emission tax policy, we have their equilibrium values as summarized in the first lemma (see Appendix A.1).

Lemma 1. *In a vertical market where domestic polluting firms produce downstream and rely on an intermediate input imported from an upstream foreign monopolist, imposing an emission tax to regulate downstream pollution leads to the following equilibrium results:*

$$w^T = \frac{\alpha(1433 - 1203\beta - 1425\beta^2 + 1215\beta^3)}{2(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)},$$

$$q_{A1}^T = q_{A2}^T = \frac{3\alpha(1-\beta)(89-81\beta)}{2(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)},$$

$$q_{B1}^T = q_{B2}^T = \frac{\alpha(307 - 546\beta + 243\beta^2)}{2(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)},$$

$$CS^T = \frac{\alpha^2(82\,769 - 221\,823\beta + 116\,238\beta^2 + 161\,334\beta^3 - 197\,559\beta^4 + 59\,049\beta^5)}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2},$$

$$\pi_1^T = \pi_2^T = \frac{\alpha^2\big(88\,169 - 242\,343\beta + 145\,452\beta^2 + 142\,866\beta^3 - 193\,185\beta^4 + 59\,049\beta^5\big)}{2(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2},$$

$$\pi_U^T = \frac{3\alpha^2(1+\beta)(287 - 528\beta + 243\beta^2)^2}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2},$$

$$GR^T = \frac{2\alpha^2(84\,692 - 229\,887\beta + 128\,778\beta^2 + 152\,748\beta^3 - 195\,372\beta^4 + 59\,049\beta^5)}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2},$$

$$ED^T = \frac{3\alpha^2(1-\beta)^2(27-29\beta)^2}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2},$$

$$MED^T = \frac{2\alpha(1-\beta)(29-27\beta)}{1177 - 1020\beta - 1113\beta^2 + 972\beta^3},$$

$$SW^T = \frac{\alpha^2(287 - 528\beta + 243\beta^2)}{1177 - 1020\beta - 1113\beta^2 + 972\beta^3}.$$

A.2 Welfare Maximization Problem under an Absolute Standard Policy

Under an absolute standard, the government solves the following welfare maximization problem:

$$\underset{\{\tau,s\}}{\text{Max}}\,\text{SW}^S = \text{CS}^S + \left(\pi_1^S + \pi_2^S\right) + \text{GR}^S - \text{ED}^S$$

where $\text{GR}^S = \tau(q_{A1} + q_{A2} + q_{B1} + q_{B2})$, which is the amount of tariff revenues collected by the government. To find the solution, we first use the DMP firms' output levels in (15) to calculate consumer surplus, the DMP firms' profits in (4), tariff revenue, and the environmental damage in (5). We note the terms of the welfare functions as follows:

$$\text{CS}^S = \frac{1}{2}\left(Q_A^2 + 2Q_AQ_B + Q_B^2\right)$$

where $Q_A = q_{A1} + q_{A2}$ and $Q_B = q_{B1} + q_{B2}$ with the output levels of the products by the DMP firms as given (20),

$$\pi_1^S + \pi_2^S = \frac{\begin{array}{c}110\alpha - 33s - 110\tau - 60s\beta - 189\alpha\beta + 189\beta\tau \\ +81s\beta^2 + 81\alpha\beta^2 - 81\beta^2\tau\end{array}}{6(11 - 9\beta^2)(10 - 9\beta)},$$

$$\text{GR}^S = \frac{2\tau[3(1-\beta)s + (\alpha - \tau)(10 - 9\beta)]}{3(11 - 9\beta^2)} \text{ and } \text{ED}^S = \frac{1}{3}(2s)^2.$$

We then use the welfare function to calculate the FOCs for the government.

$$\frac{\partial \text{SW}^S}{\partial \tau} = \frac{\partial \text{CS}^S}{\partial \tau} + \frac{\partial\left(\pi_{D_1}^S + \pi_{D_2}^S\right)}{\partial \tau} + \frac{\partial \text{GR}^S}{\partial \tau} - \frac{\partial \text{ED}^S}{\partial \tau} = 0,$$

$$\frac{\partial \text{SW}^S}{\partial s} = \frac{\partial \text{CS}^S}{\partial s} + \frac{\partial\left(\pi_{D_1}^S + \pi_{D_2}^S\right)}{\partial s} + \frac{\partial \text{GR}^S}{\partial s} - \frac{\partial \text{ED}^S}{\partial s} = 0.$$

Solving the FOCs for the optimal levels of import tariff and emission standard yields

$$\tau^S = \frac{\alpha(6581 - 12\,393\beta + 933\beta^2 + 9261\beta^3 - 4374\beta^4)}{25\,262 - 46\,476\beta + 726\beta^2 + 38\,016\beta^3 - 17\,496\beta^4}$$

and

$$s^* = \frac{3\alpha(1-\beta)(10 - 9\beta)(29 - 27\beta)}{2(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)}.$$

Plugging τ^S and s^* back into the equations under the absolute standard policy, we have the second lemma:

Lemma 2. *The imposition of an emission standard policy to control downstream pollution leads to the following equilibrium results:*

$$w^S = \frac{\alpha(16\,052 - 29\,817\beta + 1203\beta^2 + 23\,517\beta^3 - 10\,935\beta^4)}{2(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)},$$

$$q_{A1}^S = q_{A2}^S = \frac{3\alpha(1-\beta)(10-9\beta)(89-81\beta)}{2(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)},$$

$$q_{B1}^S = q_{B2}^S = \frac{\alpha(10-9\beta)(307-546\beta+243\beta^2)}{2(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)},$$

$$CS^S = \frac{\alpha^2(10-9\beta)^2\left(82\,769 - 221\,823\beta + 116\,238\beta^2 + 161\,334\beta^3 - 197\,559\beta^4 + 59\,049\beta^5\right)}{(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)^2},$$

$$\pi_1^S = \pi_2^S = \frac{\alpha^2(10-9\beta)^2\left(93\,389 - 262\,341\beta + 174\,162\beta^2 + 124\,560\beta^3 - 188\,811\beta^4 + 59\,049\beta^5\right)}{2(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)^2},$$

$$\pi_U^S = \frac{3\alpha^2(10-9\beta)(11-9\beta^2)(287-528\beta+243\beta^2)^2}{(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)^2},$$

$$GR^S = \frac{\alpha^2(10-9\beta)(287-528\beta+243\beta^2)\Big(6581 - 12\,393\beta + 933\beta^2 + 9261\beta^3 - 4374\beta^4\Big)}{(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)^2},$$

$$ED^S = \frac{3\alpha^2(1-\beta)^2(10-9\beta)^2(29-27\beta)^2}{(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)^2},$$

$$MED^S = \frac{2\alpha(1-\beta)(10-9\beta)(29-27\beta)}{12631 - 8748\beta^4 + 19\,008\beta^3 + 363\beta^2 - 23\,238\beta},$$

$$SW^S = \frac{\alpha^2(10-9\beta)(287-528\beta+243\beta^2)}{12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4}.$$

A.3 A Comparison in Equilibrium Outcomes Between Taxes and Standards

A.3.1 Tariff Rates

$$\begin{aligned}\tau^T - \tau^S &= \frac{\alpha(-240\beta - 285\beta^2 + 243\beta^3 + 286)}{-1020\beta - 1113\beta^2 + 972\beta^3 + 1177}\\ &\quad - \frac{\alpha(6581 - 12\,393\beta + 933\beta^2 + 9261\beta^3 - 4374\beta^4)}{25\,262 - 46\,476\beta + 726\beta^2 + 38\,016\beta^3 - 17\,496\beta^4}\\ &= -\frac{3\alpha(1-\beta)(287 - 528\beta + 243\beta^2)(605 - 540\beta - 543\beta^2 + 486\beta^3)}{2(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)} < 0\\ &\qquad (-12\,631 + 123\,238\beta - 363\beta^2 - 19\,008\beta^3 + 8748\beta^4)\end{aligned}$$

Thus, we have $\tau^S > \tau^T$. Tariff rate is relatively lower under an emission tax policy.

A.3.2 Input Price

$$\begin{aligned}w^T - w^S &= \frac{\alpha(1433 - 1203\beta - 1425\beta^2 + 1215\beta^3)}{2(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)}\\ &\quad - \frac{\alpha(16\,052 - 29\,817\beta + 1203\beta^2 + 23\,517\beta^3 - 10\,935\beta^4)}{2(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)}\\ &= \frac{9\alpha(1-\beta)(287 - 528\beta + 243\beta^2)(307 - 279\beta - 267\beta^2 + 243\beta^3)}{2(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)} < 0\\ &\qquad (-12\,631 + 23\,238\beta - 363\beta^2 - 19\,008\beta^3 + 8748\beta^4)\end{aligned}$$

This result implies that $w^T < w^S$. Input price is relatively lower under an emission tax policy.

A.3.3 Downstream Production

$$\begin{aligned}q_{Ai}^T - q_{Ai}^S &= \frac{3\alpha(81\beta - 89)(\beta - 1)}{2(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)}\\ &\quad - \frac{3\alpha(1-\beta)(89 - 81\beta)(10 - 9\beta)}{2(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)}\\ &= \frac{9\alpha(\beta - 1)^2(287 - 528\beta + 243\beta^2)(81\beta - 89)}{2(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)} > 0\\ &\qquad (-12\,631 + 23\,238\beta - 363\beta^2 - 19\,008\beta^3 + 8748\beta^4)\end{aligned}$$

This result indicates that $q_{Ai}^{T} > q_{Ai}^{S}$. The quantity of product A is relatively higher under an emission tax policy.

$$q_{Bi}^{T} - q_{Bi}^{S} = \frac{\alpha(307 - 546\beta + 243\beta^{2})}{2(1177 - 1020\beta - 1113\beta^{2} + 972\beta^{3})} - \frac{\alpha(10 - 9\beta)(307 - 546\beta + 243\beta^{2})}{2(12\,631 - 23\,238\beta + 363\beta^{2} + 19\,008\beta^{3} - 8748\beta^{4})}$$

$$= \frac{3\alpha(\beta - 1)(287 - 528\beta + 243\beta^{2})(307 - 546\beta + 243\beta^{2})}{2(1177 - 1020\beta - 1113\beta^{2} + 972\beta^{3})} > 0$$

$$(-12\,631 + 23\,238\beta - 363\beta^{2} - 19\,008\beta^{3} + 8748\beta^{4})$$

This result indicates that $q_{Bi}^{T} > q_{Bi}^{S}$. The quantity of product B is relatively higher under an emission tax policy. Thus, we have $Q^{T} > Q^{S}$, implying that total industry output is relatively higher under an emission tax policy.

A.3.4 Upstream Foreign Monopolist's Profit

$$\pi_{U}^{T} - \pi_{U}^{S} = \frac{3\alpha^{2}(\beta + 1)(287 - 528\beta + 243\beta^{2})^{2}}{(1177 - 1020\beta - 1113\beta^{2} + 972\beta^{3})^{2}} - \frac{3\alpha^{2}(10 - 9\beta)(287 - 528\beta + 243\beta^{2})^{2}(11 - 9\beta^{2})}{(12\,631 - 23\,238\beta + 363\beta^{2} + 19\,008\beta^{3} - 8748\beta^{4})^{2}}$$

$$= \frac{3\alpha^{2}(\beta - 1)(287 - 528\beta + 243\beta^{2})^{2}\begin{pmatrix} 19\,073\,853\beta - 3791\,451\beta^{2} - 30\,139\,182\beta^{3} + 25\,349\,823\beta^{4} \\ +6694\,569\beta^{5} - 14\,283\,297\beta^{6} + 4251\,528\beta^{7} - 7155\,971 \end{pmatrix}}{(1177 - 1020\beta - 1113\beta^{2} + 972\beta^{3})^{2}(-12\,631 + 23\,238\beta - 363\beta^{2} - 19\,008\beta^{3} + 8748\beta^{4})^{2}} > 0$$

We thus have $\pi_{U}^{T} > \pi_{U}^{S}$, which implies that foreign input monopolist makes a relatively higher profit under an emission tax policy.

A.3.5 Downstream Multiproduct Firms' Profits

$$\pi_{i}^{T} - \pi_{i}^{S}$$

$$= \frac{\alpha^{2}(88\,169 - 242\,343\beta + 145\,452\beta^{2} + 142\,866\beta^{3} - 193\,185\beta^{4} + 59\,049\beta^{5})}{2(1177 - 1020\beta - 1113\beta^{2} + 972\beta^{3})^{2}} - \frac{\alpha^{2}(10 - 9\beta)^{2}\left(93\,389 - 262\,341\beta + 174\,162\beta^{2} + 124\,560\beta^{3} - 188\,811\beta^{4} + 59\,049\beta^{5}\right)}{2(12\,631 - 23\,238\beta + 363\beta^{2} + 19\,008\beta^{3} - 8748\beta^{4})^{2}}$$

$$= \frac{3\alpha^2(\beta-1)\begin{pmatrix} 2413\,191\,070\,266\beta - 6008\,899\,915\,917\beta^2 + 6132\,067\,557\,768\beta^3 \\ +1446\,864\,157\,548\beta^4 - 10\,034\,124\,430\,212\beta^5 + 9311\,501\,435\,688\beta^6 \\ -1365\,695\,378\,856\beta^7 - 3733\,856\,734\,725\beta^8 \\ +3139\,788\,503\,106\beta^9 - 1063\,899\,709\,515\beta^{10} + 139\,471\,376\,040\beta^{11} \\ -376\,407\,931\,703 \end{pmatrix}}{2(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2(-12\,631 + 23\,238\beta - 363\beta^2 - 19\,008\beta^3 + 8748\beta^4)^2} > 0$$

Thus, $\pi_i^T > \pi_i^S$, implying that each DMP firm's profit is relatively higher under an emission tax policy.

A.3.6 Environmental Damage

$$ED^T - ED^S = \frac{3\alpha^2(27\beta-29)^2(\beta-1)^2}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2} - \frac{3\alpha^2(1-\beta)^2(10-9\beta)^2(29-27\beta)^2}{(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)^2}$$

$$9\alpha^2(1-\beta)^3(29-27\beta)^2(287-528\beta+243\beta^2)$$

$$= \frac{(24\,401 - 44\,031\beta - 1587\beta^2 + 38\,745\beta^3 - 17\,496\beta^4)}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2} > 0$$

$$(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)^2$$

$$\mathrm{MED}^T - \mathrm{MED}^S = \frac{2\alpha(1-\beta)(29-27\beta)}{1177 - 1020\beta - 1113\beta^2 + 972\beta^3} - \frac{2\alpha(1-\beta)(10-9\beta)(29-27\beta)}{12631 - 8748\beta^4 + 19\,008\beta^3 + 363\beta^2 - 23\,238\beta}$$

$$= \frac{6\alpha(1-\beta)^2(8323 - 6561\beta^3 + 21\,303\beta^2 - 23\,061\beta)}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2} > 0$$

$$(23\,238\beta - 363\beta^2 - 19\,008\beta^3 + 8748\beta^4 - 12\,631)^2$$

These results indicate that $\mathrm{ED}^T > \mathrm{ED}^S$ and $\mathrm{MED}^T > \mathrm{MED}^S$. Thus, total (or marginal) environmental damage is relatively higher under an emission tax policy.

A.3.7 Consumer Surplus

$$\mathrm{CS}^T - \mathrm{CS}^S$$

$$= \frac{\alpha^2(-221\,823\beta + 116\,238\beta^2 + 161\,334\beta^3 - 197\,559\beta^4 + 59\,049\beta^5 + 82\,769)}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2} - \frac{\alpha^2\left(82\,769 - 221\,823\beta + 116\,238\beta^2 + 161\,334\beta^3 - 197\,559\beta^4 + 59\,049\beta^5\right)(10 - 9\beta)^2}{(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)^2}$$

$$= \frac{\left[3\alpha^2(\beta - 1)(287 - 528\beta + 243\beta^2)(44\,031\beta + 1587\beta^2 - 38\,745\beta^3 + 17\,496\beta^4 - 24\,401)(82\,769 - 221\,823\beta + 116\,238\beta^2 + 161\,334\beta^3 - 197\,559\beta^4 + 59\,049\beta^5)\right]}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)^2 (23\,238\beta - 363\beta^2 - 19\,008\beta^3 + 8748\beta^4 - 12\,631)^2} > 0$$

Thus, $\mathrm{CS}^T > \mathrm{CS}^S$, implying that consumer surplus is relatively higher under an emission tax policy.

A.3.8 Domestic Welfare

$$\mathrm{SW}^T - \mathrm{SW}^S = \frac{\alpha^2(287 - 528\beta + 243\beta^2)}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)} - \frac{\alpha^2(10 - 9\beta)(287 - 528\beta + 243\beta^2)}{(12\,631 - 23\,238\beta + 363\beta^2 + 19\,008\beta^3 - 8748\beta^4)}$$

$$= \frac{3\alpha^2(1 - \beta)(287 - 528\beta + 243\beta^2)^2}{(1177 - 1020\beta - 1113\beta^2 + 972\beta^3)\left(23\,238\beta - 363\beta^2 - 19\,008\beta^3 + 8748\beta^4 - 12\,631\right)} > 0$$

Thus, $\mathrm{SW}^T > \mathrm{SW}^S$, implying that domestic welfare is relatively higher under an emission tax policy.

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