Optimal Intervention Policies in International Emissions Trading Considering Ancillary Benefits of Carbon Abatement

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Abstract

This paper explores governments' optimal intervention policies under imperfectly competitive international emissions trading (IET) considering ancillary benefits of carbon abatement (i.e., positive externalities). A sequential game is employed to conduct the analyses. It is found optimal for all countries to intervene in IET by imposing an import tariff (or export subsidy) equal to the marginal ancillary benefit of carbon abatement. Accordingly, the magnitude of ancillary benefits will affect the incentive for domestic abatement and the equilibrium of the IET market. Increasing ancillary benefits will enhance the intervention level and leads to a fall in the equilibrium allowance price. However, its impact on the emissions for price-making country and that for price-taking countries are somewhat different. If the price-making country has larger ancillary benefit, she will be willing to abate more carbon emissions. By contrast, an increase in the ancillary benefits of a price-taking country will lead to an ambiguous impact on her abatement level.

Keywords
international emissions trading, optimal intervention policies, ancillary benefits of carbon abatement

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1. INTRODUCTION

In the current literature on global carbon abatement, the cost-effectiveness of international emissions trading (IET) has been widely addressed (e.g., Evans, 2003; Ciorba *et al.*, 2001; Criqui *et al.*, 1999; Kainuma *et al.*, 1999; Weyant, 1999; Rose and Stevens, 1993). To reach the minimum of all trading countries' total compliance cost, each country's marginal abatement cost must equal the equilibrium price of emission allowances, or all countries should have the same marginal abatement cost. This globally cost-effective trading rests on three important premises. The first is a perfectly competitive IET market, in which all traders behave as price-takers. The second is no government's intervention. And the third is neglecting the externalities resulting from the countries' carbon abatements. However, these premises do not fit the real world well because imperfectly competitive market structures, governments' interventions, and the ancillary benefits of carbon abatement are observed frequently.

In contrast with the 1990 baseline emission caps determined by the Kyoto Protocol, most Annex-B countries are predicted to discharge more carbon except for the Former Soviet Union (FSU) nations, primarily Russia and Ukraine. The FSU nations possess excess emission allowances, normally referred to as "hot air," because their actual carbon emissions are much lower than the 1990 baselines during the transition to market economies. Hence, they become major suppliers in the emissions trading market, and the rest Annex-B countries may act like price takers. Many studies thus explore IET under imperfectly competitive market structures (e.g., Persson and Azar, 2003; Sager, 2003; Klepper and Peterson, 2005; Böhringer and Löschel, 2003; Böhringer *et al.*, 2007). The unanimous conclusion is that the exercise of monopoly power would result in higher prices for emission allowances and higher compliance costs for the allowance-importing countries, as compared with the case of perfect competition. Following this literature, obviously, an imperfectly competitive IET structure with one monopolistic player is a plausible assumption.

Next, individual countries usually have different concerns in designing their climate policies aside from global cost minimization. Despite that free trade is indispensable to reach the global cost-effectiveness, individual countries may find strategic interventions in IET more beneficial to themselves. For instance, the market power of the FSU nations would provide a reason for allowance-importing governments to interfere in the IET. Relevant research has paid particular attention to imposing quantitative ceilings on permit imports. Ellerman et al. (1998), for example, show that such import restrictions will result in a fall in demand for emission allowances, which in turn leads to a lower equilibrium allowance price. In practice, price policy instruments (e.g., tariffs or subsidies) are often employed by governments to correct market failures. Because seldom investigated previously, this study will focus on intervention policies using price instruments.

Finally, some research on climate policies indicates that actions to reduce carbon emissions could literally provide ancillary benefits[1] for the whole society through improvement of local air quality and enhancement of human health (e.g., Burtraw et

[1] In the literature, benefits accruing as the side effects of a targeted policy are also called the secondary benefits, co-benefits, or the policy spillover effects.

al., 2003; Barker and Rosendahl, 2000; Burtraw and Toman, 2000; Wang and Smith, 1999; Ekins, 1996a, 1996b). When a nation is framing her climate policies, related costs and benefits should all be evaluated so that the actual (net) social costs of the policies can be reflected. By doing so, sound (or no-regret) policy making can be assured and facilitated (e.g., Dessus and O'Connor, 2003; Markandya et al., 2003). However, the mentioned benefits are rarely counted by the studies on IET. Thus, biased findings may result. To fill this gap, in this paper we deliberate the ancillary benefits of carbon abatement and explore optimal intervention policies in IET.

Specifically, in this paper we account for the ancillary benefits of carbon abatement and explore governments' optimal intervention policies in the imperfectly competitive IET market. A leader-follower sequential game is constructed. The country with market power moves first, i.e., the government decides an optimal tariff (or subsidy) and its firm determines the price of emission allowances sequentially. Then, the rest countries select their optimal strategies, i.e., these governments select their optimal tariffs (or subsidies) and then their firms choose optimal carbon emission levels. The timing of the game is designed to reflect that the dominant country and its firm have the exclusive power to determine the equilibrium allowance prices. This setup is consistent with the current situation in the IET market.[2]

Our result suggests that it is optimal for all countries to intervene in IET when the ancillary benefits of carbon abatement are considered. Each country's optimal import tariff (or export subsidy) will equal its marginal ancillary benefit of carbon abatement. Accordingly, the magnitude of ancillary benefits will affect the incentive for domestic abatement and the equilibrium of the IET market. If the price-making country has larger ancillary benefit, she will be willing to abate more carbon emissions. By contrast, an increase in the ancillary benefits of a price-taking country will affect her abatement level through the intervention effect of increasing domestic abatement and price effect that lowers equilibrium allowance price and domestic abatement. Consequently the impact on her abatement level is ambiguous. In both of the cases of price-making and price-taking countries, increasing ancillary benefits leads to a fall in the equilibrium allowance price.

Our imperfectly competitive IET structure is similar to Hahn's (1984), except that Hahn (1984) does not consider governments and the externalities of emission abatements. Ellerman et al. (1998) conduct numerical simulations by setting exogenous import ceilings of emission allowances and considering no externalities. Unlike Ellerman et al.'s (1998) setup, we explore governments' optimal intervention in the IET market by endogenously determined optimal tariffs or subsidies. Finally, Lutter and Shogren (2002) analyze governments' optimal intervention policies under consideration of the ancillary benefits of carbon abatement as well. However, their model has only one country and one firm, which differs from the more general setup of ours with $N(\geq 2)$ countries and $N(\geq 2)$ firms.

The rest of this paper is organized as follows. The model is introduced in Section 2. Derived equilibrium is presented in Section 3. Section 4 discusses the equilibrium

[2] Lee et al. (2013) develop a somewhat different sequential game, in which all governments move together first, then the price-influencing firms act, and price-taking firms undertake actions finally. Under the circumstance, different optimal intervention polices are acquired.

and comparative static results using specific functional forms. Finally, the conclusions are drawn in Section 5.

2. The Model

There are $N(\geq 2)$ countries, indexed by $i = 1,2,\ldots,N$, and each country has a representative firm. Assume that the maximum emission amounts for all individual countries are limited. Denote $\overline{w}_i$ the exogenous emission cap of country i. Firm i's actual emission level is denoted by e_i. Let $AC_i(e_i)$ be firm i's abatement cost at emission level e_i with $AC_i'(e_i) < 0, AC_i''(e_i) > 0$ for all $e_i \geq 0, i = 1,2,\ldots,N$. As pointed out in Burtraw et al. (2003), some ancillary benefits will accrue when countries undertake actions to mitigate carbon emissions. Denote $AB_i(e_i)$ the ancillary benefit of firm i's carbon abatement with $AB_i'(e_i) < 0, AB_i''(e_i) \leq 0$ for all $e_i \geq 0, i = 1,2,\ldots,N$.

In addition to abating carbon emissions domestically, countries can meet their emission caps by purchasing or selling emission allowances under market price p. In reality, the FSU nations have the dominant allowance supply position due to "hot air." Thus, as in Hahn (1984), we presume that firm 1 has market power, and the other $(N-1)$ firms act as price takers. When firm i trades emission allowances internationally, its government can intervene. Let variable t_i characterizes government i's intervention policy. If firm i imports emission allowances, then $t_i > (<) 0$ means that its government imposes a tariff (subsidy) on the import. In contrast, if firm i exports emission allowances, $t_i > (<) 0$ implies that its government puts a subsidy (tariff) on the export. Finally, $t_i = 0$ suggests no government's intervention.

Next, we introduce the objective functions for firms and countries. Firm i's compliance cost consists of its abatement cost and its allowance-trading expenditure (or revenue). That is,

$$FC_i(e_i) = AC_i(e_i) + (p + t_i)(e_i - \overline{w}_i), i = 1,2,\ldots,N. \quad (1)$$

If $e_i > (<) \overline{w}_i$, firm i will import (export) emission allowances, and $(p + t_i)(e_i - \overline{w}_i)$ is its trading expenditure (revenue). Note that the sign of $(e_i - \overline{w}_i)$, i.e., the status of firm i's buying or selling permits, is endogenously determined. If a firm has higher demand for emission allowances (e_i) or lower emission allowances ($\overline{w}_i$), it is more likely to be a permit buyer. In what follows, we will show that higher demand for emission allowances could be attributed to less efficient abatement technology and higher intervention in the IET market. Countries' emission allowances are usually the results of international negotiation, which are beyond the scope of this paper.

Under the circumstance, country i's social cost equals firm i's compliance cost subtracting the tariff (or subsidy) and the ancillary benefit of carbon abatement because the tariff or subsidy is a transfer payment between a government and its firm. Hence government i's social cost can be written as

$$SC_i(t_i) \equiv AC_i(e_i) + p(e_i - \overline{w}_i) - AB_i(e_i), i = 1,2,\ldots,N. \quad (2)$$

Based on the above settings, we construct a leader-follower sequential game, in which government 1 and firm 1 move first and the rest price-taking governments and firms take actions afterward. Precisely, the model proceeds as follows. First, government 1 chooses t_1^* to minimize its social cost. Second, given t_1^*, firm 1 selects optimal emission allowance price p^* to minimize its compliance cost. Third, given p^*, government i chooses t_i^* to minimize its social cost for $i = 2, \ldots, N$. Finally, given t_i^* and p^*, firm i selects optimal emission level e_i^* to minimize its compliance cost for $i = 2, \ldots, N$. Thus, $\{\{t_i^*\}_{i=1}^N, \{e_i^*\}_{i=1}^N, p^*\}$ constitutes a subgame perfect equilibrium (hereafter SPE) of the sequential game.

3. THE EQUILIBRIUM

In this section, we derive SPE by the backward induction method. First, given tariff (or subsidy) t_i and allowance price p, price-taking firm i chooses e_i^* to solve the problem of

$$\min FC_i(e_i) = AC_i(e_i) + (p + t_i)(e_i - \overline{w}_i), i = 2, \ldots, N. \tag{3}$$

The first-order condition for an interior solution is

$$-AC_i'(e_i) = p + t_i, i = 2, \ldots, N. \tag{4}$$

The second-order condition holds since $\frac{d^2FC_i}{de_i^2} = AC_i''(e_i) > 0$. Equation (4) means that price-taking firms will adjust their emission levels until the marginal cost of abatement ($-AC_i'(e_i)$) equals the marginal saving of abatement $(p + t_i)$. By (4), e_i^* is affected by both the allowance price and the tariff (or subsidy), i.e., $e_i^* = e_i^*(p, t_i)$ with $\frac{\partial e_i^*}{\partial t_i} = -\frac{1}{AC_i''(e_i^*)} < 0$ and $\frac{\partial e_i^*}{\partial p} = -\frac{1}{AC_i''(e_i^*)} < 0, i = 2, \ldots, N$.

Second, given firm i's optimal emissions e_i^* in (4) and emission allowance price p, government i chooses t_i^* to solve the problem of

$$\min SC_i(t_i) = AC_i(e_i^*) + p(e_i^* - \overline{w}_i) - AB_i(e_i^*), i = 2, \ldots, N. \tag{5}$$

The associated first-order condition for an interior solution is

$$-AC_i'(e_i^*) = p - AB_i'(e_i^*), i = 2, \ldots, N. \tag{6}$$

Based on (4) and (6), we get

$$t_i^* = -AB_i'(e_i^*) > 0, i = 2, \ldots, N. \tag{7}$$

This means that all governments without market power will set the optimal import tariff (or export subsidy) equal to the marginal ancillary benefit of carbon abatement.

Third, given price-taking firms' optimal emissions $\{e_i^*\}_{i=2}^N$ in (4), price-taking governments' optimal tariffs $\{t_i^*\}_{i=2}^N$ in (7), and government 1's tariff (or subsidy) t_1, firm 1 will choose allowance price p^* to minimize its compliance cost subject to the market-clearing condition. In other words, p^* is the solution of the following problem.

$$\min FC_1(e_1) = AC_1(e_1) + (p + t_1)(e_1 - \bar{w}_1), \tag{8}$$

$$\text{s.t. } e_1 = \sum_{i=1}^{N} \bar{w}_i - \sum_{i=2}^{N} e_i^*. \tag{9}$$

Substituting $e_i^* = e_i^*(p, t_i^*)$ into (9), we can express e_1 as a function of allowance price p, i.e., $e_1 = \sum_{i=1}^{N} \bar{w}_i - \sum_{i=2}^{N} e_i^*(p, t_i^*)$ with $\frac{\partial e_1}{\partial p} = -\sum_{i=2}^{N} \frac{\partial e_i^*}{\partial p} > 0$. Substituting $e_1 = \sum_{i=1}^{N} \bar{w}_i - \sum_{i=2}^{N} e_i^*(p, t_i^*)$ into (8) and differentiating FC_1 with respect to p yields

$$-AC_1'(e_1) = (e_1 - \bar{w}_1)\left(\frac{\partial e_1}{\partial p}\right)^{-1} + p + t_1. \tag{10}$$

Under the circumstance, p^* exists and firm 1's optimal emission amount equals

$$e_1^* = \sum_{i=1}^{N} \bar{w}_i - \sum_{i=2}^{N} e_i^*(p^*, t_i^*). \tag{11}$$

Finally, given firms' optimal emission levels $\{e_i^*\}_{i=1}^{N}$ in (4) and (11), optimal tariffs (or subsidies) of countries with price-taking firms $\{t_i^*\}_{i=2}^{N}$ in (7), and equilibrium allowance price p^* in (10), government 1 chooses t_1^* to solve the problem of

$$\min SC_1(t_1) = AC_1(e_1^*) + p^*(e_1^* - \bar{w}_1) - AB_1(e_1^*). \tag{12}$$

The associated first-order condition for an interior solution is

$$-AC_1'(e_1^*) = (e_1^* - \bar{w}_1)\left(\frac{\partial e_1^*}{\partial p^*}\right)^{-1} + p^* - AB_1'(e_1^*). \tag{13}$$

Combining (10) and (13), we obtain

$$t_1^* = -AB_1'(e_1^*). \tag{14}$$

Equation (14) implies that government 1 will also set its optimal import tariff (or export subsidy) equal to the marginal ancillary benefit of firm 1's carbon abatement.

Based on the above, we have the following theorem.

Theorem 1. *In an imperfectly competitive IET market with one price-influencing country, it is optimal for all governments to intervene in the IET market if the ancillary benefit of carbon abatement is taken into consideration. Each country's optimal policy is to set the import tariff or export subsidy equal to the marginal ancillary benefit of firm's carbon abatement.*

The intuition of Theorem 1 is illustrated as follows. For individual country i, increasing import tariff (t_i) will raise firms' marginal savings of abatement, hence firms will abate more and have a higher abatement cost, which results in a higher social cost. At the same time, due to an increase in domestic abatement, the ancillary benefits of carbon abatement rises, leading to a lower social cost. Since country i will adjust its optimal tariff until the marginal social cost of tariff equals the marginal social benefit of tariff, the country will set the optimal tariff equal to its firm's marginal ancillary benefit of carbon abatement.

4. THE CASE OF SPECIFIC FUNCTIONAL FORMS

In this section, we will use specific functional forms of firms' abatement costs and ancillary benefits of carbon abatement to derive the SPE solution for a deeper and more intuitive discussion.

Let $\bar{b}_i$ be the carbon emissions firm i discharges under no abatement, i.e., the so-called business-as-usual (BAU) emission level. Hence, firm i's abatement level is $(\bar{b}_i - e_i)$, which costs the firm

$$AC_i(e_i) = \frac{1}{2}\alpha_i(\bar{b}_i - e_i)^2, \tag{15}$$

where $\alpha_i > 0$ is the technological parameter. Bigger α_i indicates that firm i's abatement effort is less efficient.

Following Tol (1997), we assume that the ancillary benefit of carbon abatement for country i, AB_i, is a linear function of its abatement level. That is,

$$AB_i(e_i) = \gamma_i(\bar{b}_i - e_i), \tag{16}$$

where $\gamma_i > 0$ represents the marginal ancillary benefit of domestic abatement for country i.

Given the above settings, we derive SPEs by the backward induction method. First, given tariff (or subsidy) t_i and allowance price p, price-taking firm i chooses e_i^* to solve the problem of

$$\min FC_i(e_i) = \frac{1}{2}\alpha_i(\bar{b}_i - e_i)^2 + (p + t_i)(e_i - \bar{w}_i), i = 2, \dots, N. \tag{17}$$

The first-order condition for an interior solution is

$$\alpha_i(\bar{b}_i - e_i) = p + t_i, i = 2, \dots, N. \tag{18}$$

The second-order condition holds because $\frac{d^2 FC_i}{de_i^2} = \alpha_i > 0$. Rearranging (18) yields firm i's demand for emission allowances

$$e_i^* = \bar{b}_i - \frac{p + t_i}{\alpha_i}, i = 2, \dots, N. \tag{19}$$

Second, given firm i's optimal emission e_i^* in (19) and emission allowance price p, government i ($i = 2, \dots, N$) chooses t_i^* to solve the problem of

$$\min SC_i(t_i) = \frac{1}{2}\alpha_i(\bar{b}_i - e_i^*)^2 + p(e_i^* - \bar{w}_i) - \gamma_i(\bar{b}_i - e_i^*). \tag{20}$$

The associated first-order condition for an interior solution suggests that

$$t_i^* = \gamma_i, i = 2, \dots, N. \quad (21)$$

Third, given price-taking firms' optimal emissions $\{e_i^*\}_{i=2}^N$ in (19), price-taking governments' optimal tariffs $\{t_i^*\}_{i=2}^N$ in (21), and government 1's tariff (or subsidy) t_1, firm 1 would choose allowance price p^* to minimize its compliance cost subject to the market-clearing condition. In other words, p^* is the solution of the following problem.

$$\min FC_1(e_1) = \frac{1}{2}\alpha_1(\bar{b}_1 - e_1)^2 + (p + t_1)(e_1 - \bar{w}_1). \quad (22)$$

$$\text{s.t. } e_1 = \sum_{i=1}^N \bar{w}_i - \sum_{i=2}^N e_i^*. \quad (23)$$

To solve this problem, we first substitute (19) and (21) into constraint (23) and rearrange it as

$$e_1 = \frac{p}{A} - \left[\left(\sum_{i=2}^N \left(\bar{b}_i - \frac{\gamma_i}{\alpha_i}\right)\right) - \left(\sum_{i=1}^N \bar{w}_i\right)\right], \quad (24)$$

where $A = \left[\sum_{i=2}^N \left(\frac{1}{\alpha_i}\right)\right]^{-1} > 0$. Then, substituting (24) into objective function (22) and differentiating the function with respect to p yields

$$p^* = A\left[\frac{(\alpha_1\bar{b}_1 + A\bar{w}_1 - AK - t_1)}{(\alpha_1 + 2A)} + K\right], \quad (25)$$

where $K = \sum_{i=2}^N \left(\bar{b}_i - \frac{\gamma_i}{\alpha_i}\right) - \sum_{i=1}^N \bar{w}_i$. Since the second-order condition holds given that $\frac{d^2FC_1}{dp^2} = \frac{\alpha_1 + 2A}{A^2} > 0$ for all p, equilibrium price p^* in (25) is an optimal interior solution. Consequently, firm 1's optimal emission level equals

$$e_1^* = \frac{\alpha_1\bar{b}_1 + A\bar{w}_1 - AK}{\alpha_1 + 2A} - \frac{t_1}{\alpha_1 + 2A}. \quad (26)$$

To make firms' optimal emission levels and equilibrium allowance prices positive, the following assumption is needed.

Assumption A1: $\bar{b}_i$ is large enough for $i = 1, 2, \dots, N$.

Finally, given firms' optimal emission levels $\{e_i^*\}_{i=1}^N$ in (19) and (26), optimal tariffs (or subsidies) of countries with price-taking firms $\{t_i^*\}_{i=2}^N$ in (21), and equilibrium allowance price p^* in (25), government 1 would choose t_1^* to solve the problem of

$$\min SC_1(t_1) = \frac{1}{2}\alpha_1(\bar{b}_1 - e_1^*)^2 + p^*(e_1^* - \bar{w}_1) - \gamma_1(\bar{b}_1 - e_1^*). \quad (27)$$

The associated first-order condition for an interior solution suggests that

$$t_1^* = \gamma_1 > 0. \tag{28}$$

By (15)-(28), the SPE using specific functional forms is summarized as follows.

Corollary 1. *Suppose that Assumption A1 holds. Then, SPE* $\{\{t_i^*\}_{i=1}^N, \{e_i^*\}_{i=1}^N, p^*\}$ *exists with*

(i) $t_i^* = \gamma_i > 0$ *for* $i = 1,2, \dots, N$,

(ii) $e_1^* = \frac{\alpha_1 \bar{b}_1 + A\bar{w}_1 - AK}{\alpha_1 + 2A} - \frac{t_1^*}{\alpha_1 + 2A}$,

(iii) $e_i^* = \bar{b}_i - \frac{p^* + t_i^*}{\alpha_i}$ *for* $i = 2, \dots, N$, *and*

(iv) $p^* = A\left[\frac{(\alpha_1 \bar{b}_1 + A\bar{w}_1 - AK - t_1^*)}{(\alpha_1 + 2A)} + K\right]$,

where $K = \sum_{i=2}^N \left(\bar{b}_i - \frac{\gamma_i}{\alpha_i}\right) - \sum_{i=1}^N \bar{w}_i > 0$ *based on Assumption A1.*

Corollary 1 demonstrates that firms' optimal emissions and equilibrium allowance price depend on marginal ancillary benefit, abatement technology parameter, and required emission cap. Their relations are summarized below.

Proposition 1. *Suppose that assumption A1 holds. Given the SPEs in Corollary 1,* $\{\{t_i^*\}_{i=1}^N, \{e_i^*\}_{i=1}^N, p^*\}$, *we have the followings.*

(i) $\frac{\partial e_1^*}{\partial \gamma_1} < 0$, $\frac{\partial p^*}{\partial \gamma_1} < 0$, *and* $\frac{\partial e_i^*}{\partial \gamma_1} > 0$ *for* $i = 2, \dots, N$.

(ii) $\frac{\partial e_i^*}{\partial \gamma_i} \overset{>}{\underset{<}{=}} 0$ *iff* $\frac{\partial p^*}{\partial \gamma_i} \overset{<}{\underset{>}{=}} -1$, $\frac{\partial p^*}{\partial \gamma_i} < 0$, $\frac{\partial e_1^*}{\partial \gamma_i} > 0$, *and* $\frac{\partial e_i^*}{\partial \gamma_j} > 0$ *for* $i, j \in \{2, \dots, N \mid i \neq j\}$.

(iii) $\frac{\partial e_1^*}{\partial \alpha_1} > 0$, $\frac{\partial p^*}{\partial \alpha_1} > 0$, *and* $\frac{\partial e_i^*}{\partial \alpha_1} < 0$ *for* $i = 2, \dots, N$.

(iv) $\frac{\partial e_i^*}{\partial \alpha_i} \overset{>}{\underset{<}{=}} 0$ *iff* $\frac{p^* + \gamma_i}{\alpha_i} \overset{>}{\underset{<}{=}} \frac{\partial p^*}{\partial \alpha_i}$, $\frac{\partial p^*}{\partial \alpha_i} > 0$, $\frac{\partial e_1^*}{\partial \alpha_i} < 0$, *and* $\frac{\partial e_i^*}{\partial \alpha_j} < 0$ *for* $i, j \in \{2, \dots, N \mid i \neq j\}$.

(v) $\frac{\partial e_i^*}{\partial \bar{w}_i} > 0$ *and* $\frac{\partial p^*}{\partial \bar{w}_i} < 0$ *for* $i = 1,2, \dots, N$.

Proof. See the Appendix.

Proposition 1(i) shows that country 1 will be willing to abate more carbon emissions domestically if she has larger marginal ancillary benefit of carbon abatement. There is thus an increase in the level of the emission allowances available to the price-taking countries, which in turn leads to a fall in the equilibrium allowance price. Due to a lower allowance price level, the marginal saving of domestic abatement for the price-taking firms decreases. Therefore, the price-taking countries have lower levels of carbon abatement.

The intuition of Proposition 1(ii) is provided as follows. For price-taking country i, the effect of an increase in marginal ancillary benefit of carbon abatement (γ_i) on firm i's optimal emissions (e_i^*) can be decomposed into two parts: the intervention effect and the price effect. An increase in γ_i will lead to a higher level of tariff (subsidy) on the import (export) of emission allowances, consequently enhancing the marginal saving of domestic abatement. Accordingly, firm i will abate more emissions domestically. This is the intervention effect of an increase in γ_i on e_i^*. On the other hand, tariff intervention reduces firm i's demand for emission allowances, which in turn leads to a lower level of equilibrium allowance price. And lower equilibrium allowance price increases firm i's allowance purchase, hence firm i's emissions will increase. This is the price effect of an increase in γ_i on e_i^*. If the intervention effect dominates the price effect, firm i's optimal emissions will decrease as γ_i increases, and vice versa. If both effects are equal, firm i's optimal emissions are unaffected by γ_i. As mentioned above, increasing γ_i will make firm i buy fewer emission allowances given the emission allowance price unchanged. It will then lead to excess supply of the emission allowance in emission trading market. Accordingly, price-making firm 1 will increase its emissions to clear the market. An increase in γ_i has also an impact on the other price-taking firms' emission levels through the price effect. As noted before, a higher value of γ_i will lead to a lower level of the equilibrium allowance price, which implies a lower level of the marginal saving of carbon abatement. As a result, the other price-taking firms will all have lower levels of abatement, or equivalently, higher levels of emissions.

Proposition 1(iii) indicates how firm 1's abatement technology affects all firms' optimal levels of emissions and equilibrium allowance price. Given other things the same, the larger the value of firm 1's technological parameter (α_1) is, the higher firm 1's marginal cost of abatement is, hence the more emissions firm 1 will discharge. As a result, there is a lower level of emission allowances available to the other price-taking firms, and the equilibrium allowance price thus increases. For the price-taking firms, a higher price level of emission allowances implies a higher level of marginal saving of domestic abatement. It is therefore that the price-taking firms increase the levels of domestic abatement.

Similarly, higher value of price-taking firm i's technological parameter (α_i) implies higher marginal cost of abatement. Thus, firm i will discharge more emissions (e_i^*), which is referred to as the technological effect of increasing α_i on e_i^*. As a result, firm i has higher demand for emission allowances, consequently leading to an increase in the equilibrium allowance price. However, a higher equilibrium allowance price will in turn increase firm i's marginal saving of abatement, and firm i will thus lower its emissions. This is referred to as the price effect of increasing α_i on e_i^*. Given the fact that the technological effect is positive and the price effect is negative, the total effect of increasing α_i on e_i^* is ambiguous. If the technological effect dominates, firm i's optimal emissions will increase as α_i increases, and vice versa. If both effects are equal, firm i's optimal emissions are unaffected by α_i. As mentioned before, increasing α_i will let firm i buy more emission allowances given the emission allowance price unchanged. It will then result in excess demand of emission allowances in the trading market. Accordingly, price-making firm 1 will decrease its emissions to clear the market. On the other hand, increasing α_i will also has an impact on the other price-taking firms' optimal emissions through the price effect. Other price-taking firms will abate more emissions because of the higher equilibrium emission allowance prices caused by higher α_i. That is what Proposition 1(iv) says.

Finally, Proposition 1(v) shows that the larger emission cap each country faces, the fewer emissions each country needs to abate. Then, fewer emission allowances are demanded. Thus, equilibrium allowance price will decrease.

5. Conclusions

This paper analyzes governments' optimal intervention policies and firms' optimal emissions under imperfectly competitive IET considering the ancillary benefits of carbon abatement. Our result suggests that it is optimal for countries to intervene in the IET market by imposing import tariffs or export subsidies when the ancillary benefits are considered, and the optimal tariff or subsidy equals the marginal ancillary benefit of carbon abatement for all countries. Accordingly, the magnitude of ancillary benefits will affect the incentive for domestic abatement and the equilibrium of the IET market. Increasing ancillary benefits will enhance the intervention level and leads to a fall in the equilibrium allowance price. However, its impact on the emissions for price-making country and that for price-taking countries are somewhat different. If the price-making country has larger ancillary benefit, she will be willing to abate more carbon emissions. By contrast, an increase in the ancillary benefits of a price-taking country will affect her abatement level through the intervention effect (increasing the intervention level and domestic abatement) and price effect (higher intervention lowers equilibrium allowance price and domestic abatement), consequently leading to an ambiguous impact on her abatement level.

To learn more policy implications in designing IET systems for the post-Kyoto period, this work can be extended in several directions in the future. For instance, countries' emission caps might be endogenously determined through international negotiation mechanism or based on individual countries' self-interests. As such, the environmental efficiency of IET can be further explored. One may also consider more generalized market structures of imperfectly competitive IET by allowing for several dominant players in the setup, and analyze how the optimal intervention policies change with the number of the dominant players.

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Appendix

Proof of Proposition 1:

(i) By differentiating (26) with respect to γ_1, we get $\frac{\partial e_1^*}{\partial \gamma_1} = \frac{-1}{\alpha_1 + 2A} < 0$.
Differentiating (25) with respect to γ_1 yields $\frac{\partial p^*}{\partial \gamma_1} = A\left(\frac{\partial e_1^*}{\partial \gamma_1}\right) < 0$.
Finally, differentiating (19) with respect to γ_1 yields $\frac{\partial e_i^*}{\partial \gamma_1} = \left(\frac{-1}{\alpha_i}\right)\left(\frac{\partial p^*}{\partial \gamma_1}\right) > 0$ for $i = 2, \dots, N$.

(ii) Differentiating (26) with respect to γ_i gives $\frac{\partial e_1^*}{\partial \gamma_i} = \frac{A}{\alpha_i(\alpha_1 + 2A)} > 0$ for $i = 2, \dots, N$.

Differentiating (25) with respect to γ_i gives $\frac{\partial p^*}{\partial \gamma_i} = \left(\frac{-A}{\alpha_i}\right)\left(\frac{\alpha_1 + A}{\alpha_1 + 2A}\right) < 0$ for $i = 2, \dots, N$.

Finally, differentiating (19) with respect to γ_i gives $\frac{\partial e_i^*}{\partial \gamma_i} = \left(\frac{-1}{\alpha_i}\right)\left(\frac{\partial p^*}{\partial \gamma_i} + 1\right) \overset{>}{\underset{<}{=}} 0$ iff $\frac{\partial p^*}{\partial \gamma_i} \overset{<}{\underset{>}{=}} -1$ for $i = 2, \dots, N$.

Differentiating (19) with respect to $\gamma_j, j \in \{2, \dots, N | j \neq i\}$ yields $\frac{\partial e_i^*}{\partial \gamma_j} = \left(\frac{-1}{\alpha_i}\right)\left(\frac{\partial p^*}{\partial \gamma_j}\right) > 0$.

(iii) Differentiating (26) with respect to α_1 yields
$\frac{\partial e_1^*}{\partial \alpha_1} = \frac{(\alpha_1+2A)[\bar{b}_1-(\alpha_1\bar{b}_1+A\bar{w}_1-AK-\gamma_1)/(\alpha_1+2A)]}{(\alpha_1+2A)^2} = \frac{\bar{b}_1-e_1^*}{\alpha_1+2A} > 0$
by assumption A1.
Differentiating (25) with respect to α_1 yields $\frac{\partial p^*}{\partial \alpha_1} = A\left(\frac{\partial e_1^*}{\partial \alpha_1}\right) > 0$.
Finally, differentiating (19) with respect to α_1 yields $\frac{\partial e_i^*}{\partial \alpha_1} = \left(-\frac{1}{\alpha_i}\right)\left(\frac{\partial p^*}{\partial \alpha_1}\right) < 0$ for $i = 2, \dots, N$.

(iv) Differentiating (26) with respect to α_i yields

$$\frac{\partial e_1^*}{\partial \alpha_i} = \frac{(A/\alpha_i^2)(A\bar{w}_1-AK-\gamma_i-2Ae_1^*)}{\alpha_1+2A} = \frac{(A/\alpha_i^2)(\alpha_1 e_1^*-\alpha_1\bar{b}_1+\gamma_1-\gamma_i)}{\alpha_1+2A}$$

by $A\bar{w}_1 - AK = (\alpha_1 + 2A)e_1^* - \alpha_1\bar{b}_1 + \gamma_1$. Thus, we have $\frac{\partial e_1^*}{\partial \alpha_i}$<0 because of large enough $\bar{b}_1$ by assumption A1 for $i = 2, \dots, N$.

Differentiating (25) with respect to α_i gives

$$\frac{\partial p^*}{\partial \alpha_i} = \frac{A}{\alpha_i^2(\alpha_1+2A)}[\alpha_1 p^* + (\alpha_1 + A)\gamma_i + A^2(K + \bar{w}_1)] > 0$$

by $K > 0$ for $i = 2, \dots, N$.
Finally, differentiating (19) with respect to α_i yields

$$\frac{\partial e_i^*}{\partial \alpha_i} = \left(\frac{1}{\alpha_i^2}\right)\left[-\alpha_i\left(\frac{\partial p^*}{\partial \alpha_i}\right) + (p^* + \gamma_i)\right] \begin{matrix} > \\ = \\ < \end{matrix} 0 \text{ iff } \frac{p^*+\gamma_i}{\alpha_i} \begin{matrix} > \\ = \\ < \end{matrix} \frac{\partial p^*}{\partial \alpha_i} \text{ for } i = 2, \dots, N.$$

Differentiating (19) with respect to $\alpha_j, j \in \{2, \dots, N | j \neq i\}$ yields $\frac{\partial e_i^*}{\partial \alpha_j} = \left(\frac{-1}{\alpha_i}\right)\left(\frac{\partial p^*}{\partial \alpha_j}\right) < 0$.

(v) By differentiating (25) with respect to $\bar{w}_1$ and $\bar{w}_i, i \neq 1$, respectively, we get

$$\frac{\partial p^*}{\partial \bar{w}_1} = \frac{-\alpha_1 A}{\alpha_1+2A} < 0 \text{ and } \frac{\partial p^*}{\partial \bar{w}_i} = \frac{-A(\alpha_1+A)}{\alpha_1+2A} < 0 \text{ for } i = 2, \dots, N.$$

Next, differentiating (26) and (19) with respect to $\bar{w}_1$ and $\bar{w}_i, i \neq 1$, respectively, yields $\frac{\partial e_1^*}{\partial \bar{w}_1} = \frac{2A}{\alpha_1+A} > 0$ and $\frac{\partial e_i^*}{\partial \bar{w}_i} = \left(\frac{-1}{\alpha_i}\right)\left(\frac{\partial p^*}{\partial \bar{w}_i}\right) > 0$ for $i = 2, \dots, N$.