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Seung-Gyu Sim, Hsuan-Chih Lin

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Institute of Economics
Academia Sinica
Taipei 115, TAIWAN
http://www.sinica.edu.tw/econ/

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INSTITUTE OF ECONOMICS, ACADEMIA SINICA

TAIWAN

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Abstract

It is well-known that the Pigouvian taxation scheme and emission trading scheme (delegating the emission pricing authority to the market mechanism) offer equivalent incentives to reduce emissions in various autarky settings. In contrast, we demonstrate that in a globalized economy with international trade and cross border pollution, adopting the latter is the strict dominant strategy of each country, and global welfare is maximized when all countries adopt the latter. Adopting the latter incentivizes the other country to tighten its environmental regulation without concern for excessive shrink of domestic production and aggravation of cross border pollution from the adopting country.

Keywords: Emission Trading Scheme, Pigouvian Taxation, International Trade, Cross Border Pollution

JEL Classification: H23, L51, Q56, Q58

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Sim: University of Wisconsin-Madison, 1180 Observatory Drive #7313, Madison, WI 53706. (seunggyusim@wisc.edu, +1-608-571-8883)
Lin (Corresponding Author, +886-2-27822791#207): Institute of Economics, Academia Sinica, 128 Academia Road, Section 2, Nankang, Taipei 115, Taiwan. (linhc@econ.sinica.edu.tw)

1 Introduction

Being aware of the (probably) most serious threat to this planet, Global Warming and Climate Change, many economists and policy makers put enormous efforts in designing and developing public policies to reduce greenhouse gas emissions. Seminal works by Pigou (1920) and Baumol (1972), which argue that a 'Pigouvian tax' effectively internalizes negative externalities from pollution, spawned an extensive literature on emission pricing schemes. In contrast to the traditional taxation approach to environmental market failure, which emphasizes the role of government as benevolent social planner, many countries have begun to delegate emission pricing authority to the market. So called 'emission trading' or 'cap-and-trade' schemes have been widely implemented in the wake of the largest greenhouse gas trading program, the European Union Emission Trading Scheme (EU ETS),[1] although no theoretical studies have provided strong support for the idea of delegating the emission pricing authority to the market mechanism. To close the gap between 'reality' and 'theory,' we reassess those environmental policy instruments, the Pigouvian taxation and emission trading schemes, in terms of domestic and global surplus by extending our scope from an autarky economy to a global economy with international trade and cross border pollution.

Policy makers have debated for the past several decades whether Pigouvian taxation or emission trading is the better environmental policy instrument. Following Weitzman (1974), the debate assesses the relative advantages of price versus quantity control as a policy instrument by comparing an autarky economy that implements cap-and-trade with another autarky economy that implements Pigouvian taxation. Nordhaus (2007) argues that emissions taxes (i) are more efficient in the face of massive uncertainties, (ii) minimize opportunities for corruption and financial finagling, and (iii) incur lower administrative costs of implementation. Keohane (2009) and Murray, Newell, and Pizer (2009) maintain that cap-and-trade with free allowances affords legislators flexibility in balancing distribution and efficiency and, coupled with banking and borrowing allowances, provides intertemporal flexibility with respect to uncertain marginal abatement costs. The latter, in arguing for the superiority of cap-and-trade over taxation based not on its fundamental properties, but on its compatibility with other instruments, paradoxically acknowledge that emission trading cannot strictly dominate Pigouvian taxation by itself. If attention is restricted to an autarky economy, emission trading can be superior to Pigouvian taxation only in the presence of

[1] A plot phase of EU ETS was implemented from 2005, in which year Japan's Voluntary Emissions Trading Scheme (JVETS) was launched, to 2008. The Korea Emission Trading Scheme (KETS) was launched in 2015. In addition, ten north-eastern states in the United States implements the Regional Greenhouse Gas Initiative in 2015. California Greenhouse Gas Solutions Act was signed into law in 2006, and adopted the cap-and-trade program to set the upper limit on statewide greenhouse gas emissions starting 2010. To see more about EU ETS and US ETS, refer to Hintermann (2010) and Stavins (2008b).

government failure or inherent rigidity of the taxation scheme, as summarized in the survey paper by Goulder and Schein (2013).

The present paper expands the scope of analysis from the one-country models that populate the previous literature to a globalized economy in which two countries engage in free international trade and pollutants emitted in one country adversely affect the other's welfare. In this global environment, the Pigouvian taxation scheme no longer solves the (constrained) planner's problem because the respective governments cannot control foreign production and transboundary pollution. When both adopt the Pigouvian taxation scheme, a higher tax rate in one country apparently discourages domestic and encourages foreign production through imperfect international competition (forward damage), and hence aggravates cross border pollution from the other country (backward damage). The negative 'boomerang' effect of domestic environmental regulation renders the respective governments reluctant to impose a higher tax rate than the other countries, which induces 'race to the bottom.' Interestingly, a government that switches to the emission trading scheme explicitly commits to 'quantity control' and hence 'no negative boomerang effect.' The other government realizes that an increase in its own tax rate does not necessarily reduce its domestic production as much as before, and does not aggravate cross border pollution from the neighboring country, because the adopting country's production is controlled independently of its own tax rate. This circumstance constitutes an incentive to the non-adopting government to optimally raise its tax rate without concern for excessive shrink of domestic production and aggravation of cross border pollution. Even though the underlying intuition of the competitive dominance of emission trading in terms of both domestic and global welfare is straightforward, no studies that we are aware of, however, have analyzed the notion of it in a globalized setting.

We also demonstrate in this simple symmetric setting that universally switching to the emission trading scheme would effectively commit both countries to 'no negative boomerang effect' on its neighbor, thereby inducing both to enact stricter environmental regulation. Domestic welfare of each country and global welfare are maximized when it is adopted by all countries. Furthermore, market equilibrium can eventually achieve the constrained planner's outcome by unifying all permit markets into one global market. Our results can be applicable to a multi-sector model, in which each country produces the same amounts of each sectoral products, and continues to hold when each country specializes in a different sector.

The competitive dominance of emission trading over Pigouvian taxation in a globalized economy relies on each country's commitment on 'quantity control,' by which each country can stop 'race to the bottom' in terms of environmental regulation. The key idea is that the emission trading scheme can reduce the amount of pollutants emitted not in the adopting country but in the neighboring country. This finding also provides an optimistic viewpoint not only for subsequent widespread adoption of the emission trading scheme[2] but also for the Paris Agreement. The Paris Agreement, the simultaneous and independent announcement by the political leaders of 195 countries of their respective Intended Nationally Determined Contributions (INDCs), is expected to align incentives to reduce (global) greenhouse gas emissions. It will allow each country to independently implement its own environmental regulation without concerns on the negative boomerang effect, which will be useful in mitigating the 'global warming' issue.

The paper is organized as follows. In Section 2, we describe the model, in Section 3, analyze different equilibria under various environmental policies. Extensions are discussed in Section 4, policy implications presented in Section 5. Section 6 concludes.

2 The Model

The economic model developed in this section retains the feature of the two-country trade model in Bagwell and Staiger (2005) and Suh, Nahm, and Sim (2016). We extend their setting by incorporating the negative externality of cross border pollution, and isolate the differences between the emission trading and Pigouvian taxation schemes by restricting our attention to a simple, symmetric setting with endogenous choice of the environmental policy instrument by each government.

Consider an economy that consists of symmetric home ($j = h$) and foreign ($j = f$) countries. For expositional convenience, we assume each country to have m number of symmetric firms. Firm $i \in \{1, 2, \cdots, m\}$ in country $j \in \{h, f\}$ produces q_{ij} units of final goods, emits γq_{ij} units of carbon dioxide (CO_2), and sells its products in the unified world market. Let $q_j = \sum_{i=1}^{m} q_{ij}$ and $Q = q_h + q_f$. The γq_j units of pollutants reduce country j's domestic welfare by $\eta\gamma q_j$ units and that of country $j'(\neq j)$ by $\theta\eta\gamma q_j$, where preference parameter η captures sensitivity to pollution and θ captures the magnitude of cross border pollution. That θ is assumed to be (strictly) greater than zero but less than or equal to one reflects cross border pollution associated with CO_2 causing 'global warming.'[3] We proceed with a well behaved world demand function

[2] At the time Hahn (1989) wrote "Economic Prescriptions for Environmental Problems: How the Patient Followed the Doctor's Orders," cap-and-trade had not been widely adopted. Its subsequent rise in popularity has been characterized by Keohane (2009) as follows.

> Economists were once frustrated that their prescriptions were not followed by legislators - to use Hahn's (1989) memorable analogy, they worried that the patient was not following the doctor's order. But now that the patient is dutifully taking her medicine, recovering beautifully, and asking for a refill, the doctor wants to abandon the treatment and try an alternative therapy.

[3] Hung and Shaw (2005) point out that categories of pollutants are important when governments imple-

for final goods $P : \mathbb{R}_+ \to \mathbb{R}_{++}$ such that P is (at least) twice differentiable, $P(\cdot) > 0$, $P'(\cdot) < 0$, $P''(\cdot) \geq 0$, and $P''(Q)Q + mP'(Q) < 0$. To make sure the existence of the equilibrium on each subgame later, we assume that $\lim_{Q\to 0} P(Q) > (1+\theta)\eta\gamma$ and $\lim_{Q\to\infty} P(Q) < (1-\theta)\eta\gamma$. For expositional convenience, we sometimes present the underlying intuition with the alternative linear demand function $P(Q) = a - bQ$, where $a > \eta\gamma(1+\theta)$ and $b > 0$. The parametric assumptions are introduced to ensure that $q_{ij} > 0$ for each $j \in \{h, f\}$ in all market equilibria examined in this paper. For simplicity, each firm's marginal cost is assumed to be zero and consumers to be evenly distributed between countries.

We examine the impact of environmental policy reform by analyzing each subtree in which each country implements either Pigouvian taxation or emission trading. The country that adopts Pigouvian taxation sets the per-unit tax rate; the country that adopts emission trading determines the number of tradable permits to be issued. Positing permit price, p_j, to be determined by Walrasian auction, a firm that produces q_{ij} units of final goods and emits γq_{ij} units of pollutants pays $t_j \gamma q_{ij}$ in the Pigouvian taxation country and $p_j \gamma q_{ij}$ in the emission trading country. The time horizon of the game is as follows.

- Each country announces its environmental policy. The country adopting Pigouvian taxation announces the tax rate per unit of pollutant as well, the country adopting emission trading, the number of tradable permits to be issued.
- The firms simultaneously decide their respective output levels, with final goods sold à la Cournot competition in the world market.[4]

We first solve the model backward. Denote by Q_{-ij} the total output by all firms other than firm $i \in \{1, 2, \cdots, m\}$ in country $j \in \{h, f\}$. The environmental policies and rival firms' output plans being given, firm $i \in \{1, 2, \cdots, m\}$ in country $j \in \{h, f\}$ chooses $q_{ij} \in \mathbb{R}_+$ such that

$$q_{ij} = \underset{q \geq 0}{\operatorname{argmax}} \; [P(Q_{-ij} + q) - c_j \gamma] q, \tag{1}$$

where $c_j = t_j$ if country $j \in \{h, f\}$ adopts Pigouvian taxation, or $c_j = p_j$ if it adopts emission trading. Denote by $\hat{q}_{ij}(c_j; Q_{-ij})$ the best response of firm i in country j given

ment environmental policy. Pollutants can be either uniformly- or non-uniformly mixed, ambient concentration depending on the total amount of emissions in uniformly mixed, and on the distribution of various sources in non-uniformly mixed, pollutants. Although this study is focused on uniformly mixed pollutants, parameter θ allows our model to be applied to the case of non-uniformly mixed pollutants.

[4] Sartzetakis (1997a) shows that cap-and-trade system may redistribute production inefficiency among firms if the product market is oligopolistic. In this paper, we show that cap-and-trade system offers different incentives to reduce emissions when the product market is imperfectly competitive.

$(c_j; Q_{-ij})$. For each $i \in \{1, 2, \cdots, m\}$ and $j \in \{h, f\}$,

$$P'(Q_{-ij} + \hat{q}_{ij}(c_j; Q_{-ij}))\hat{q}_{ij}(c_j; Q_{-ij}) + P(Q_{-ij} + \hat{q}_{ij}(c_j; Q_{-ij})) - c_j\gamma = 0. \tag{2}$$

Equation (2) represents the first order condition by each firm, which implicitly determines $\hat{q}_{ij}(c_j; Q_{-ij})$.[5] The second order condition being globally satisfied due to $P'(Q) < 0$ and $P''(Q)Q + P'(Q) < 0$, we do not repeatedly specify it in the proofs presented in the latter part of the paper. Denote by $q_{ij}(c_j, c_{j'})$ and $q_j(c_j, c_{j'})$, respectively, the quantity produced by firm i in country j and the total quantity produced by country j as a result of the mutual best responses. The comparative statics results obtained by summing equations (2) for all $i \in \{1, 2, \cdots, m\}$ in each country and taking the derivative of them with respect to c_h and c_f imply that for each $j \in \{h, f\}$,

$$\frac{\partial q_j}{\partial c_j} = \frac{(P''q_{j'} + (m+1)P')\gamma}{QP'P'' + (2m+1)(P')^2} < 0 \quad \text{and} \quad \frac{\partial q_{j'}}{\partial c_j} = \frac{-(P''q_{j'} + mP')\gamma}{QP'P'' + (2m+1)(P')^2} > 0. \tag{3}$$

Summing equations (3) yields

$$\frac{\partial(q_j(c_j, c_{j'}) + q_{j'}(c_{j'}, c_j))}{\partial c_j} = \frac{m\gamma}{QP'' + (2m+1)P'} < 0. \tag{4}$$

This implies that an increase in tax rate or permit price in country $j \in \{h, f\}$ induces a reduction in total output.[6] It further implies that when $(q_h, q_f) = (q_h(c_h, c_f), q_f(c_f, c_h))$ are given, (c_h, c_f) is uniquely determined.[7]

If country $j \in \{h, f\}$ adopts the emission trading scheme, permit price is determined by the permit market clearing condition given by

$$\sum_{i=1}^{m} \gamma q_{ij}(p_j(n_j, c_{j'}), c_{j'}) = n_j, \tag{5}$$

where n_j is total number of permits initially issued and $c_{j'}$ captures the other country's policy instrument. The total number of permits, n_j, may include free allowances. But free allowances in the emission trading scheme, being just transfer from the government to each firm, does not affect the decision by any economic agent in our model. For fair comparison between Pigouvian taxation and emission trading, we assume that the transfer from the government to the firm is zero regardless of the policy instrument chosen by each government.

[5] Although equation (2) investigates the production decision by each firm, the later analysis will rely more on domestic production q_j.The fact that $q_j = \sum_{i=1}^{m} q_{ij}$ enables us to proceed with q_j only in most cases.

[6] For a detailed derivation of (3) and (4), see Choi (1995).

[7] It is straightforward that two different pairs of (c_h, c_f) cannot solve $(q_h, q_f) = (q_h(c_h, c_f), q_f(c_f, c_h))$ when conditions (3) and (4) are globally satisfied.

When $c_h \in \{p_h, t_h\}$ and $c_f \in \{p_f, t_f\}$ have been determined,[8] consumer surplus (CS_j), producer surplus (PS_j), and government revenue (G_j) for each $j \in \{h, f\}$ can be rewritten as functions of $(q_h(c_h, c_f), q_f(c_f, c_h))$ (or simply (c_h, c_f)). Let $q_h = q_h(c_h, c_f)$ and $q_f = q_f(c_f, c_h)$. We obtain that

$$\begin{aligned} CS_j(q_j, q_{j'}) &= \frac{1}{2}\int_0^{q_h+q_f} [P(Q') - P(q_h + q_f)]dQ', && (6)\\ PS_j(q_j, q_{j'}) &= P(q_h + q_f)q_j - c_j\gamma q_j, \quad \text{and} && (7)\\ G_j(q_j) &= c_j\gamma q_j. && (8) \end{aligned}$$

Subtracting all domestic disutility due to pollution from CS_j yields the total domestic surplus of country $j \in \{h, f\}$ (DS_j). Given $q_h = q_h(c_h, c_f)$ and $q_f = q_f(c_f, c_h)$,

$$DS_j(q_j, q_{j'}) = TS_j(q_j, q_{j'}) - \eta\gamma q_j - \theta\eta\gamma q_{j'}, \tag{9}$$

where $TS_j(q_j, q_{j'}) = CS_j(q_j, q_{j'}) + PS_j(q_j, q_{j'}) + G_j(q_j, q_{j'})$.

At the first stage, country $j \in \{h, f\}$ adopts the Pigouvian taxation scheme and chooses the tax rate, $t_j \in \mathbb{R}_+$, that maximizes $DS_j(q_j(t_j, c_{j'}), q_{j'}(c_{j'}, t_j))$. If country $j \in \{h, f\}$ chooses the emission trading scheme, it determines the number of permits to issue, $n_j \in \mathbb{R}_+$, to maximize $DS_j(q_j(p_j(n_j, c_{j'}), c_{j'}), q_{j'}(c_{j'}, p_j(n_j, c_{j'})))$. Note that if the trading partner of country $j \in \{h, f\}$ adopts the emission trading scheme, $c_{j'} = p_{j'}(n_{j'}, t_j)$.

To see the significance of international competition in the final goods market, we consider first the autarky equilibrium in which, without final goods trade, country $j \in \{h, f\}$ consumes what it produces and country j's production is not affected by the other country's environmental policy. Thus, let us denote by $q_j = q_j(c_j)$ the total quantity produced by country $j \in \{h, f\}$ for a while. If country j adopts the Pigouvian taxation scheme, it chooses the tax rate such that

$$\frac{\partial DS_j(q_j(t_j))}{\partial t_j} = \Big[\frac{\partial TS_j(q_j(t_j))}{\partial q_j} - \eta\gamma\Big]\frac{\partial q_j(t_j)}{\partial t_j} = 0, \text{ where } \frac{\partial q_j(t_j)}{\partial t_j} = \sum_{i=1}^{m}\frac{\partial q_{ij}(t_j)}{\partial t_j}. \tag{10}$$

When country $j \in \{h, f\}$ adopts the emission trading scheme, its permit market clearing condition can be written as $\sum_{i=1}^{m} \gamma q_{ij}(p_j(n_j)) = n_j$. Note that in an autarky setting, the permit price in country j depends only on n_j. Country j then chooses the number of emission permits such that

$$\frac{\partial DS_j(q_j(p_j(n_j)))}{\partial n_j} = \Big[\frac{\partial TS_j(q_j(p_j(n_j)))}{\partial q_j} - \eta\gamma\Big]\frac{\partial q_j(p_j(n_j))}{\partial p_j}\frac{\partial p_j(n_j)}{\partial n_j} = 0. \tag{11}$$

[8] Here, 'p_h' and 'p_f' represent target price in the government plan.

Both first order conditions predict the same outcome. That quantities produced by domestic firms, consumer surplus, and domestic surplus are unchanged whether Pigouvian taxation or emission trading is implemented implies that the emission trading scheme cannot strictly dominate the Pigouvian taxation scheme in terms of domestic welfare in an autarky economy. This result is not a surprising inasmuch as the taxation scheme directly manipulates firms' cost structure to internalize the negative externality of domestic pollution, whereas the emission trading scheme relies partially on the market mechanism. Without additional distortion attached to a particular policy instrument, neither exhibits any differences.

3 Equilibrium Characterization

3.1 The Efficiency Benchmark

Consider as an efficiency benchmark the problem of the benevolent social planner who maximizes global surplus ($GS = DS_h + DS_f$) subject to imperfect competition in the final goods market by imposing the Pigouvian tax in each country.[9] Denote by t_j^* and q_j^*, respectively, the planner's choice of tax rate and implied output in country $j \in \{h, f\}$. The constrained planner chooses (t_h^*, t_f^*) to maximize

$$GS(Q) = \int_0^Q [P(Q') - P(Q)]dQ' + P(Q)Q - \eta\gamma(1+\theta)Q, \tag{12}$$

where $Q = q_h(t_h, t_f) + q_f(t_f, t_h)$. If $Q \geq (q_h^* + q_f^*)$, $GS(Q)$ decreases; otherwise, it increases. Recall for later use that when $Q \geq (q_h^* + q_f^*)$, global surplus improves as Q declines. The first order condition with respect to t_j is given by

$$\frac{\partial GS(q_h + q_f)}{\partial(q_h + q_f)} \frac{\partial(q_h + q_f)}{\partial t_j} = [P(q_h + q_f) - (1+\theta)\eta\gamma] \frac{\partial(q_h + q_f)}{\partial t_j} = 0. \tag{13}$$

Because $P(\cdot)$ strictly decreases, the efficient level of total output is uniquely determined by (13). Although the exact values of q_{ih} and q_{if} are not determined individually, we take the symmetric outcome with $q_{1h}^* = q_{2h}^* = \cdots = q_{mh}^* = q_{1f}^* = q_{2f}^* = \cdots = q_{mf}^*$ as the efficiency benchmark throughout the paper without loss of generality. Note that symmetric pair of (t_h^*, t_f^*), is uniquely determined.

Lemma 1. *Suppose that the constrained social planner implements the symmetric*

[9] This setting is equivalent to the problem of the social planner who chooses (q_{ih}^*, q_{if}^*) directly for each $i \in \{1, 2, \cdots, m\}$. See equation (13).

outcome. The planner will choose (t_h^*, t_f^*) such that

$$t_h^* = t_f^* = \frac{1}{m\gamma}[mP(q_h^* + q_f^*) + P'(q_h^* + q_f^*)q_h^*] \quad \textit{and} \quad P(q_h^* + q_f^*) = (1+\theta)\eta\gamma. \tag{14}$$

3.2 The Market Equilibrium

In this section, we characterize the outcome on each subtree after each country determines its environmental policy independently. The market outcome associated with a particular pair of policy instruments is denoted by superscripts, either PTS or ETS. The payoff matrix in each subtree can be summarized as follows.

		Country f	
		PTS	ETS
Country h	PTS	$(DS_h(q_h^{TT}, q_f^{TT}), DS_f(q_f^{TT}, q_h^{TT}))$	$(DS_h(q_h^{TE}, q_f^{TE}), DS_f(q_f^{TE}, q_h^{TE}))$
	ETS	$(DS_h(q_h^{ET}, q_f^{ET}), DS_f(q_f^{ET}, q_h^{ET}))$	$(DS_h(q_h^{EE}, q_f^{EE}), DS_f(q_f^{EE}, q_h^{EE}))$

Table 1: Payoff Matrix for Each Country

Taxation vs Taxation We first examine the case in which both countries implement the Pigouvian tax scheme (PTS). The outcome associated with 'taxation vs taxation' is designated by superscripts (TT). When both countries implement the Pigouvian tax scheme and choose their tax rates simultaneously, a symmetric equilibrium outcome is achieved, but the domestic surplus is lower compared to the constrained planner's problem.

Lemma 2. *Suppose that each country implements the Pigouvian taxation scheme independently. There exists at least one equilibrium on this subgame. In particular, on any equilibrium candidate, $P(q_h^{TT} + q_f^{TT}) \in ((1-\theta)\eta\gamma, \eta\gamma)$. Both countries impose lower tax rates, produce more, and realize less domestic surplus relative to the constrained planner's problem. (Global surplus in this case is also less than in the planner's problem.)*

If $\theta = 0$, the equilibrium allocation in this case is exactly the same as the symmetric solution of (14), that is, $q_h^{TT} = q_f^{TT} = q_h^* = q_f^*$. This implies that, absent cross border pollution, the Pigouvian tax scheme solves the constrained planner's problem. We subsequently confirm that all outcomes in the different subtrees with different pairs of policy instruments degenerate into the constrained planner's outcome without cross border pollution ($\theta = 0$). Except for the special case with $\theta = 0$, the market equilibrium produces further than the planner does as no government internalizes cross border pollution. Apparently, the negative externality causes efficiency loss in the globalized economy. Moreover, a higher tax rate in one country apparently discourages domestic and encourages foreign production through imperfect international competition (forward damage), and hence aggravates cross border pollution from the other country (backward damage). The negative 'boomerang' effect of domestic environmental regulation renders the respective governments reluctant to impose a higher tax rate than the other countries, which induces 'race to the bottom' maintaining the equilibrium tax rates away from the efficiency benchmark.

Cap-and-trade vs Taxation Consider the case in which the home country adopts the emission trading, and the foreign country the Pigouvian tax, scheme without loss of generality. The market outcome in this subtree is denoted by superscript (ET).

Lemma 3. *Suppose that the home country adopts emission trading while the foreign country retains the Pigouvian tax. There will exist a unique optimal quadlet of* $(n_h^{ET}, t_f^{ET}, q_h^{ET}, q_f^{ET})$ *such that* $q_h^{ET} > q_f^{ET}$ *and* $p_h(n_h^{ET}, t_f^{ET}) < t_f^{ET}$. *Furthermore, switching to the emission trading scheme strictly improves the adopting country's domestic welfare by inducing the other country to reduce its production.*

According to Lemma 3, when the home country implements emission trading, the foreign country raises the tax rate in the presence of cross border pollution.[10] When both adopt the Pigouvian tax scheme, the best response of the foreign government is given by

$$\Big[P'(Q)\Big(\frac{q_f^{TT} - q_h^{TT}}{2}\Big) + P(Q) - \eta\gamma\Big]\frac{\partial q_f}{\partial t_f} + \Big[P'(Q)\Big(\frac{q_f^{TT} - q_h^{TT}}{2}\Big) - \theta\eta\gamma\Big]\frac{\partial q_h}{\partial t_f} = 0, \quad (15)$$

where $Q = q_h^{TT} + q_f^{TT} = \sum_{i=1}^m q_{ih}^{TT} + \sum_{i=1}^m q_{if}^{TT}$. It implies that a unilateral increase in tax rate by the foreign country, because it discourages domestic and encourages home country production, occasions in the country not only loss of producer surplus and government revenue but also aggravation from cross border pollution. When the home country adopts emission trading, however, the home government commits 'quantity control' instead of 'price control.' The best response of the foreign government, by setting $(\partial q_h)/(\partial t_f) = 0$ in (15), is modified as

$$\Big[P'(Q)\Big(\frac{q_f^{ET} - q_h^{ET}}{2}\Big) + P(Q) - \eta\gamma\Big]\frac{\partial q_f}{\partial t_f} = 0, \quad (16)$$

where $Q = q_h^{ET} + q_f^{ET} = \sum_{i=1}^m q_{ih}^{ET} + \sum_{i=1}^m q_{if}^{ET}$. The foreign country, realizing that the negative boomerang effect of raising the tax rate is removed, is motivated to adjust

[10] If we suppose that $\theta = 0$, the solution in Lemma 2 also solves equations (A6) and (A7) without cross border externality issue.

its tax rate optimally. The home country, anticipating an increase in the foreign country's tax rate, can issue a large number, and thereby lower the price, of permits. In other words, the home country, by adopting emission trading, commits to 'no negative boomerang effect' and signals to the foreign government that maintaining a low tax rate no longer reduces the home country's production and cross border pollution.

More detailed intuition accrues to the case with the linear demand structure and one firm in each country. Combining the linear demand equation, $P(q_h+q_f) = a-b(q_h+q_f)$, with (2) and (5) yields that

$$p_h(n_h, t_f) = \frac{1}{2\gamma^2}[-3bn_h + a\gamma + t_f\gamma^2] \iff n_h = \frac{1}{3b}[a\gamma + t_f\gamma^2 - 2\gamma^2 p_h]. \tag{17}$$

The market clearing price of permits falls with the number of permits, but rises with the foreign tax rate. In particular, an increase in the foreign government's tax rate discourages its domestic production and raises the final goods price, thereby stimulating permit demand and raising the permit price in the home country.

In stage 1, the home government chooses $n_h \in \mathbb{R}_+$ and the foreign government $t_f \in \mathbb{R}_+$. The best response of the home government to the foreign government's choice is given by

$$n_h(t_f) = \frac{1}{7b}[5a\gamma - (8-4\theta)\eta\gamma^2 + 3t_f\gamma^2], \tag{18}$$

and the best response by the latter to the former's choice by

$$t_f(n_h) = \frac{1}{3\gamma^2}[4\eta\gamma^2 - a\gamma - bn_h]. \tag{19}$$

Combining (17) and (18), we get the following relationship between p_h and t_f,

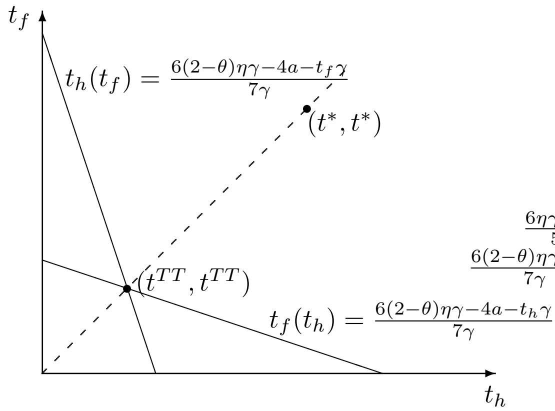
$$p_h = \frac{1}{7\gamma}[6\eta\gamma(2-\theta) - 4a - \gamma t_f], \tag{20}$$

which shows the (intended) target permit price of the home government given t_f. Interestingly, but not surprisingly, (20) is identical to the home country's best response when it adopts the Pigouvian tax scheme because

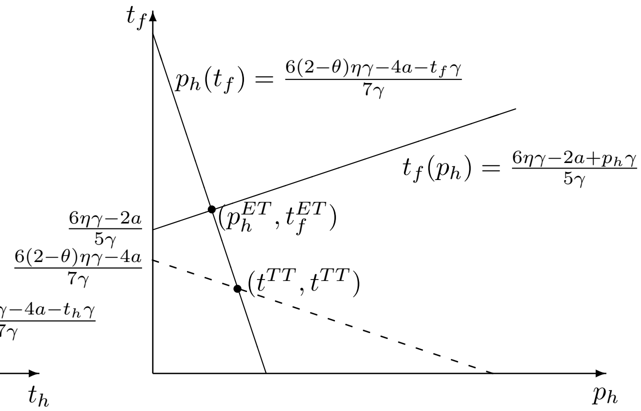
$$\frac{\partial DS_h(p_h(n_h,t_f),t_f)}{\partial n_h} = 0 \iff \frac{\partial DS_h(p_h(n_h,t_f),t_f)}{\partial p_h}\frac{\partial p_h}{\partial n_h} = 0 \iff \frac{\partial DS_h(t_h,t_f)}{\partial t_h} = 0, \tag{21}$$

with small notational abuse of $DS_h(p_h, t_f)$ instead of $DS_h(q_h(p_h,t_f), q_f(t_f,p_h))$. More interestingly, combining (17) and (19) yields

$$t_f = \frac{1}{5\gamma}[6\eta\gamma - 2a + \gamma p_h], \tag{22}$$



(a) Taxation vs. Taxation



(b) Cap-and-trade vs. Taxation

Figure 1: Equilibrium Emission Pricing

which differs from the best response of the foreign country in the previous case. In particular, equation (22) captures the positive relationship between the foreign country's best response to home country's target permit price.[11]

Panel (a) in Figure 1 demonstrates that when both countries adopt Pigouvian taxation schemes, tax rates are lower in the market equilibrium than in the planner's problem. Lowering of the tax rate in each country encourages production by firms in the country, in which case, the other government's best response is to raise its tax rate in response to the expected decrease in final goods price. Knowing this, both governments competitively lower their respective tax rates, which makes the symmetric equilibrium tax rate lie below the efficient level.

Panel (b) describes the case in which the home country adopts the emission trading, but the foreign country retains its Pigouvian tax, scheme. As shown in (20), the home country's target permit prices are exactly same to its best response to the foreign country's tax rate in the case of 'taxation vs taxation.' But it, by switching to the emission trading scheme, commits to making its domestic production independent of the foreign country's regulation, which also incentives the foreign government to strengthen its environmental regulation as discussed earlier. Moreover, given $n_h = q_h/\gamma$, the foreign government takes the remaining market demand, which makes it lower the tax rate as n_h increases.[12] On the other hands, as n_h increases, p_h decreases. These arguments result in the foreign government's tax rate being positively associated with the home government's target permit price, which yields the upward sloping curve in the space of (p_h, t_f).

When $\theta = 0$, equations (20) and (22) intersect at $(p_h^{ET}, t_f^{ET}) = (t_h^{TT}, t_f^{TT})$. The

[11]Since $p_h = p_h(n_h, t_f)$, equation (22) implicitly defines t_f as a function of n_h. But for expositional convenience, we treat t_f as a function of an target price intended by the home government.

[12]Note that $P'(\cdot) = -b < 0$ and $P''(\cdot) = 0$.

market equilibrium outcome is the same whether or not the home country switches to the emission trading scheme. This implies that without cross border pollution, both policy instruments create equivalent incentives. When $\theta > 0$, equations (20) and (22) intersect at $p_h^{ET} < t_h^{TT}$ and $t_f^{ET} > t_f^{TT}$, which implies that the home country, in switching to the emission trading scheme, produces more and realizes a larger domestic surplus. We have already shown that global surplus improves if and only if $q_h^{TT} + q_f^{TT} > q_h^{ET} + q_f^{ET}$.[13] One can see that the necessary and sufficient condition holds in case of the linear demand for final goods. Therefore, when one country switches to the emission trading scheme, global surplus improves as well in this case.

Cap-and-trade vs Cap-and-trade We now consider what happens if both countries switch to the emission trading scheme. The equilibrium outcome in this case is denoted by superscript (EE). When both countries adopt emission trading, we can redefine the permit price in country $j \in \{h, f\}$ as a function of $(n_j, n_{j'})$, that is, $p_j(n_j, n_{j'})$. The permit market clearing condition in country $j \in \{h, f\}$ is given by $\sum_{i=1}^{m} \gamma q_{ij}(p_j(n_j, n_{j'}), p_{j'}(n_{j'}, n_j)) = n_j$.

Lemma 4. *Suppose that the foreign, as well as the home, government adopts the emission trading scheme. There exists a unique equilibrium of this subgame such that $P(q_h^{EE} + q_f^{EE}) = \eta\gamma$. The foreign country in this case realizes a larger domestic surplus than in the previous cases. The global surplus also further improves toward the constrained planner's outcome relative to the previous cases.*

According to Lemma 4, the foreign country will be better off in terms of domestic welfare if it also adopts the emission trading scheme. Additionally, both countries realize a higher surplus in this case than in the case in which both adopt the Pigouvian taxation scheme. The global surplus is also larger in this case than in the previous cases.

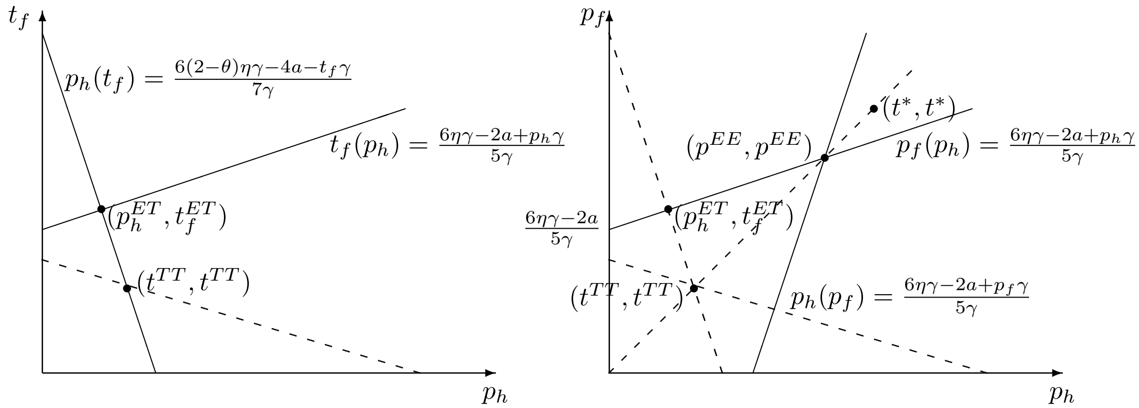
The intuition can be explained using the case of the linear demand curve. Solving the market clearing conditions in both countries and combining them with the first order condition for each government yields

$$p_j = \frac{1}{5\gamma}[6\eta\gamma - 2a + \gamma p_{j'}] \text{ for each } j \in \{h, f\}, \tag{23}$$

which is identical to equation (22) in the case of 'emission trading versus Pigouvian taxation.' But because both countries adopt emission trading, a symmetric equilibrium outcome is obtained in this case.

We borrow Panel (a) in Figure 2 from Panel (b) in Figure 1. Comparing Panels (a) and (b) in Figure 2 reveals that if the foreign government also switches to emission

[13] One can easily show that $q_h^{ET} + q_f^{ET} \geq q_h^* + q_f^*$.



(a) Cap-and-trade vs. Taxation (b) Cap-and-trade vs. Cap-and-trade

Figure 2: The Best Response Functions

trading, the home government's target permit price is positively associated with the foreign government's target permit price. When both countries adopt emission trading, they achieve symmetric equilibrium on the 45 degree line. Apparently, a higher intercept and positive slope coefficient implies (p_h^{EE}, p_f^{EE}) much higher than (t_h^{TT}, t_f^{TT}). More precisely, as shown in Panel (b), $p_h^{EE} > t_h^{TT} > p_h^{ET}$ and $p_f^{EE} > t_f^{ET} > p_f^{TT}$ in the case of the linear demand structure. Global surplus is maximized when all countries adopt the mission trading scheme. As long as the permit markets remain segmented, however, the respective governments intend permit price to be no greater than t^* in the constrained planner's problem.

Equilibrium Characterization The following propositions characterize the equilibrium outcome of the entire game.

Proposition 1. *Adopting emission trading is the strictly dominant strategy in the presence of (imperfect) international competition and cross border pollution.*

Proof. It is straightforward due to Lemmas 2, 3, and 4. □

According to Lemmas 3 and 4, it is optimal for a country to adopt emission trading, whether its neighbor implements Pigouvian taxation or emission trading. We thus conclude that it is a strictly dominant strategy to adopt the emission trading scheme. For example, assuming the linear demand structure, we obtain

$$DS_h^{ET} - DS_h^{TT} = \frac{49\gamma^2\eta^2\theta^2}{144b} > 0, \quad \text{and} \quad DS_f^{EE} - DS_f^{ET} = \frac{5\gamma^2\eta^2\theta^2}{12b} > 0. \tag{24}$$

Interestingly, $DS_h^{EE} - DS_h^{ET} = -\frac{\gamma^2\eta^2\theta^2}{36b} < 0$ in the case of the linear demand structure, implying that if the foreign country switches to emission trading, the domestic welfare of the home country adopting emission trading declines. The following proposition tells us that even in this case, however, global welfare improves.

Proposition 2. *Global welfare is maximized when all countries adopt emission trading. In addition, as more countries adopt emission trading, global welfare gradually improves in case of the linear demand for the final goods.*

Proof. It is straightforward due to Lemmas 2, 3, and 4. □

Proposition 2 is surprising in the sense that without any environmental innovation,[14] we can expect global welfare gains only through regime switch to 'quantity control' by each country.

Permit Market Unification We close this section by showing that the (constrained) planner's outcome can be achieved when permit markets are unified and the number of permits jointly determined. Whereas two policy instruments (t_h, t_f) are available in the planner's problem, with a unified permit market only one, the number of permits, can be adjusted in the market equilibrium. The planner's outcome can nevertheless be achieved in the market equilibrium despite the lack of policy instruments.

Proposition 3. *Should both countries adopt the emission trading scheme and agree to unify their permit markets and jointly determine the number of permits, the outcome of the (constrained) planner's problem described in Lemma 1 is achieved.*

Proof. Denote by n the number of tradable permits in the unified permit market. The first order condition with respect to n is given by

$$\frac{\partial GS(q_h(n) + q_f(n))}{\partial n} = [P(q_h(n) + q_f(n)) - (1+\theta)\eta\gamma] \frac{\partial (q_h(n) + q_f(n))}{\partial n} = 0. \quad (25)$$

Therefore, we get the same symmetric equilibrium outcome as in the constrained planner's problem. □

Although Proposition 3 is considered when there exists only one permit market, same social planner's outcome can be also achieved when there exists a universal carbon tax. In other words, the planner's outcome can be achieved if the markets or taxation ability can be unified without giving the authorities to the individual governments. When the Kyoto protocol turned out to be a failure, Stiglitz (2015) argued that it was time to try an alternative approach: a commitment by each country to raise the

[14]We leave it for future research topic to extend our framework into a dynamic setting with technology innovation. As for the various issues regarding dynamic environment and technology innovation, refer to Biglaiser, Horowitz, and Quiggin (1995), Fischer (2008), Weber and Neuhoff (2010), Kim and Lee (2014), and D'Amato and Dijkstra (2015).

price of emissions (whether through a carbon tax or emissions caps) to a specified level. Nordhaus (2015), meanwhile, pointing out that overcoming the free-riding problem was key to the success of international climate policy, proposed that a so-called 'Climate Club,' with small trade penalties imposed on non-participants, could elicit a large stable coalition and achieve high levels of abatement. One can see that the welfare implication in Proposition 3 is consistent with the proposals by Stiglitz (2015) and Nordhaus (2015).

3.3 More Applications

We address in this subsection whether our results are still applicable to the case with multiple sectors by introducing two sectors, denoted by subscript $k \in \{x, y\}$. Abstracting from the detailed discussion on the proof of the existence, uniqueness, and other characterization of the equilibrium under the generalized setting, we alternatively assume that each sector, consisting of m number of symmetric firms in each country, faces a linear demand structure such as $P(Q_k) = a - bQ_k$, where $Q_k = \sum_i^m q_{ijk}$ for each $j \in \{h, f\}$ and $k \in \{x, y\}$. The two examples based on the linear demand structure still shows that our results are not really limited to the symmetric environment.

With Multiple Sectors Let us assume that all firms in sector y incur a sector-specific production cost $\omega > 0$ regardless of their location. The firm $i \in \{1, 2, \cdots, m\}$ in sector y chooses $q_{ijy} \in \mathbb{R}_+$ such that

$$q_{ijy} = \underset{q}{\operatorname{argmax}} \ (a - b(Q_{-ijy} + q))q - (c_h\gamma + \omega)q, \tag{26}$$

where Q_{-ijy} represents the total quantity produced by all firms in sector y other than firm i in country j. All firms in sector x face a similar decision problem with $\omega = 0$. If country $j \in \{h, f\}$ adopts emission trading and issues n_j permits, the permit price will be determined by the market clearing condition

$$\gamma \sum_{i=1}^{m} q_{ijx} + \gamma \sum_{i=1}^{m} q_{ijy} = n_j. \tag{27}$$

Each country chooses a policy instrument, together with a tax rate or number of permits that maximizes its domestic welfare. The following proposition states that our result is applicable in this multi-sector model.

Proposition 4. *Assume the linear demand and cost structures as above. Propositions 1 and 2 and Lemmas 2-4 are still applicable, which is to say that adopting emission trading is the dominant strategy. One country's switch to emission trading prompts* *the other to implement stricter environmental regulation. As more countries adopt emission trading, global welfare improves.*

Proof. The detailed proof is presented in a separate Online Appendix. □

With Specialized International Trade One may wonder what happens if each country specializes in a different sector. It is a relevant consideration because there is no international trade on the equilibrium of our original model. We thus incorporate on top of the multi-sector model developed in the previous subsection, 'comparative advantage' by assuming the home firms in sector y and foreign firms in sector x to incur marginal production cost $\omega > 0$. The other firms produce their sectoral product at zero production cost. The home (foreign) country thus specializes in sector x (sector y), at least in the case that both countries adopt the same environmental policy. More specifically, the firm $i \in \{1, 2, \cdots, m\}$ in sector y of the home country chooses $q_{iyx} \in \mathbb{R}_+$ such that

$$q_{ihy} = \underset{q}{\operatorname{argmax}} \ (a - b(Q_{-ihy} + q)q - (c_h \gamma + \omega)q, \tag{28}$$

and the firm $i \in \{1, 2, \cdots, m\}$ in sector x of the foreign country $q_{ifx} \in \mathbb{R}_+$ such that

$$q_{ifx} = \underset{q}{\operatorname{argmax}} \ (a - b(Q_{-ifx} + q))q - (c_f \gamma + \omega)q. \tag{29}$$

All the other firms face a similar decision problem with $\omega = 0$. When firms in the same country trade permits domestically and compete with differently comparatively advantaged firms in the other country, we still arrive at the same conclusion as before.

Proposition 5. *Assume the linear demand and cost structures as above. The home (foreign) country specializes in sector x (sector y) regardless of which environmental policy each implements. Propositions 1 and 2 and Lemmas 2-4 continue to hold, which is to say that adopting emission trading is the dominant strategy. A switch by one country to emission trading occasions an increase in the carbon tax by the other. Global welfare is maximized when both countries adopt emission trading.*

Proof. The detailed proof is presented in a separate Online Appendix. □

4 Implication on the Paris Agreement

This section emphasizes that 'global warming' being a global issue, it is important to assess the environmental policy instrument in a globalized setting. In particular, it is nontrivial to examine which instrument provides better incentives in a globalized setting with international trade and cross boarder pollution, because each government, caring about its own domestic surplus only, is reluctant to implement a stronger environmental regulation domestically. Moreover, the lack of international enforcement and punishment mechanism raises skeptical concerns on international cooperation or coordination to reduce the greenhouse gas emissions. Unlike those pessimistic viewpoint, this section based on the previous argument proposes an optimistic viewpoint on the recent international efforts and agreements, especially, the Paris Agreement.

The first international agreement aimed at worldwide emissions reduction, the Kyoto Protocol, despite optimistic expectations, was unable to achieve significant results in part because China and the United States, the two largest greenhouse emission countries, did not participate. Apparently, the top-down approach with targets set by the Kyoto Protocol prevented the Kyoto Protocol itself from getting support from those major countries. The lengthy deadlock associated with the Kyoto Protocol prompted the United Nations Framework Convention on Climate Change (UNFCCC) to initiate a subsequent important agreement designated the Paris Agreement.[15] Unlike the Kyoto Protocol employed a top-down approach, the Paris Agreement solicited Intended Nationally Determined Contributions (INDCs) from 195 countries. With most member countries in UNFCCC agreeing to take action, roughly 90 percent of global emissions are included in the agreement (compared to only 14 percent in the Kyoto Protocol).

Although significant progress has been made under the Paris Agreement, skeptics point out that it incorporates neither enforcement nor punishment mechanisms. According to U.N. assistant secretary-general on climate change János Pásztor, there is only a "name and shame" system, the 'contributions' not being binding as a matter of international law. In a sharp contrast, the current paper provides an optimistic viewpoint. Our results suggest that it is important to close the channel through which domestic environmental regulations discourage domestic, and encourage foreign, production and aggravate cross border pollution. Individual countries' announcements of their INDCs under the Paris Agreement may enable us to achieve a more desirable equilibrium which is similar to the dominant strategy equilibrium in our results, whereby all countries adopt emission trading and simultaneously determine the numbers of tradable permits. Even without specified enforcement or punishment, political leaders' commitments to the independent quantity control are apparently expected to eliminate the negative boomerang effect of domestic environmental regulations and result in a globally enhanced equilibrium by inducing individuals' neighboring countries to strengthen their environmental regulations. Even though the name and shame system does not work well in reducing their own greenhouse gas emissions, it will work well in reducing their neighbors' (and hence their own) emissions.

[15] Please visit http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm for details.

5 Conclusion

This paper is motivated by the fact that 'global warming' is a global issue and the greenhouse gas emission problem requires global cooperation among all countries on this planet. The paper expands the scope of study from an autarky economy, the common choice of the previous literature, to a globalized setting in which multiple countries independently implement environmental policies. We demonstrate that emission trading may outperform Pigouvian taxation in terms not only of the adopting country's domestic surplus, but also of global surplus in the presence of international trade and cross border pollution. The home country's switch to emission trading and announcement of the number of permits to be issued is interpreted as a commitment to its domestic production and cross border pollution. Recognizing that the adverse boomerang effect is removed motivates the neighboring country to adjust its emission price (either tax rate or permit price) upward. This paper emphasizes the advantage of 'quantity control' over 'price control' by highlighting its role as a commitment device in a globalized setting.

One shortcoming of the present research is that its focus on domestic and global welfare gains from a regime switch to emission trading leads to concentration on the symmetric setting without such additional distortions as international bargaining and strategic tariffs between countries. It also neglects the technology and income gaps between developed and developing countries. We recognize that some of the results of our simple experiments depend on the magnitude of embedded heterogeneity and parameter values, but leave it to future quantitative research to determine whether the simplified setting of our paper has led us to overvalue the positive impact of emissions trading.

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Appendices

A Mathematical Appendix

Proof of Lemma 1 The first order condition in (13) implies that $P(q_h^* + q_f^*) = (1+\theta)\eta\gamma$. Since $P(\cdot)$ is continuous, strictly decreasing, and $\lim_{Q\to 0} P(Q) > (1+\theta)\eta\gamma > \lim_{Q\to\infty} P(Q)$, the symmetric pair of (q_h^*, q_f^*) is well defined. Combining it with the first order condition of (1) yields $t_h^* = t_f^* = \frac{1}{m\gamma}[mP(q_h^* + q_f^*) + P'(q_h^* + q_f^*)q_h^*]$. $\square$

Proof of Lemma 2 The first order condition with respect to t_j implies that

$$\Big[-\frac{1}{2}P'(Q)Q+P'(Q)q_j+P(Q)-\eta\gamma\Big]\frac{\partial q_j}{\partial t_j}+\Big[-\frac{1}{2}P'(Q)Q+P'(Q)q_j-\theta\eta\gamma\Big]\frac{\partial q_{j'}}{\partial t_j}=0, \quad \text{(A1)}$$

where $Q = q_h^{TT} + q_f^{TT} = \sum_{i=1}^m q_{ih}^{TT} + \sum_{i=1}^m q_{if}^{TT}$. Note that $(\partial q_j)/(\partial t_j) = \sum_{i=1}^m (\partial q_{ij})/(\partial t_j)$. Due to symmetry, $q_h^{TT} = q_f^{TT}$ so that $P(q_h^{TT} + q_f^{TT}) < \eta\gamma$. If not, the first square bracket is non-negative, while the second square bracket is strictly negative, which makes the whole left hand side of (A1) negative. In addition, since

$-(\partial q_j)/(\partial t_j) > (\partial q_{j'})/(\partial t_j) > 0$, it should be the case that

$$0 > \Big[-\frac{1}{2}P'(Q)Q + P'(Q)q_j + P(Q) - \eta\gamma \Big] > \Big[-\frac{1}{2}P'(Q)Q + P'(Q)q_j - \theta\eta\gamma \Big]. \quad \text{(A2)}$$

It implies that $P(q_h^{TT} + q_f^{TT}) > (1-\theta)\eta\gamma$. Since $P(\cdot)$ is continuous, $P'(\cdot) < 0$, $\lim_{Q\to 0} P(Q) > (1+\theta)\eta\gamma$, and $\lim_{Q\to\infty} P(Q) < (1-\theta)\eta\gamma$, there exists at least one equilibrium outcome (q_h^{TT}, q_f^{TT}) such that

$$P(q_h^{TT} + q_f^{TT}) = \eta\gamma + \theta\eta\gamma \Big[\frac{\partial q_{j'}(q_{j'}^{TT}, q_j^{TT})}{\partial t_j} \Big] \Big[\frac{\partial q_j(q_j^{TT}, q_{j'}^{TT})}{\partial t_j} \Big]^{-1} \in ((1-\theta)\eta\gamma, \eta\gamma). \quad \text{(A3)}$$

We infer that $q_h^{TT} = q_f^{TT} > q_h^* = q_f^*$ and $GS(q_h^{TT} + q_f^{TT}) < GS(q_h^* + q_f^*)$. Also, since domestic surplus is a half of global surplus in any symmetric solution, the domestic surplus of this case is smaller than that of the planner's problem as well.

Given (t_h^{TT}, t_f^{TT}), the mutual best responses, $(\hat{q}_h(t_h^{TT}; q_f^{TT}), \hat{q}_f(t_f^{TT}; q_h^{TT}))$ should satisfy the first order condition (2) for each $i \in \{1, 2, \cdots, m\}$ and $j \in \{h, f\}$. Summing up the first order conditions yields

$$P'(q_h^{TT} + q_f^{TT})(q_h^{TT} + q_f^{TT}) + 2mP(q_h^{TT} + q_f^{TT}) - (t_h^{TT} + t_f^{TT})m\gamma = 0. \quad \text{(A4)}$$

As $Q = (q_h + q_f)$ increases, $P'(Q)Q + 2mP(Q)$ declines, because $P''(Q)Q + (2m+1)P'(Q) < 0$. It implies that $t_h^{TT} = t_f^{TT} < t_h^* = t_f^*$. $\square$

Proof of Lemma 3 The first order condition with respect to n_h is given by

$$\frac{\partial}{\partial p_h} \Big[\frac{1}{2} \int_0^{q_h+q_f} [P(Q') - P(q_h+q_f)]dQ' + P(q_h+q_f)q_h - \eta\gamma q_h - \theta\eta\gamma q_f \Big] \frac{\partial p_h}{\partial n_h} = 0, \quad \text{(A5)}$$

which implies that

$$\Big[P'(Q)\Big(\frac{q_h^{ET} - q_f^{ET}}{2}\Big) + P(Q) - \eta\gamma \Big] \frac{\partial q_h}{\partial p_h} + \Big[P'(Q)\Big(\frac{q_h^{ET} - q_f^{ET}}{2}\Big) - \theta\eta\gamma \Big] \frac{\partial q_f}{\partial p_h} = 0, \quad \text{(A6)}$$

where $Q = q_h^{ET} + q_f^{ET}$. Note that the output level of the home country is fixed at $q_h = n_h^{ET}/\gamma$ under the emission trading scheme. The first order condition with respect to t_f in the foreign country is given by

$$\frac{\partial DS_f}{\partial t_f} = \Big[-\frac{1}{2}P'(q_h+q_f)(q_h+q_f) + P'(q_h+q_f)q_f + P(q_h+q_f) - \eta\gamma \Big] \frac{\partial q_f}{\partial t_f} = 0. \quad \text{(A7)}$$

When $\theta > 0$, no symmetric solution is feasible for equations (A6) and (A7). Equation

(A7) implies that

$$-\frac{1}{2}P'(q_h^{ET}+q_f^{ET})(q_h^{ET}+q_f^{ET})+P'(q_h^{ET}+q_f^{ET})q_f^{ET}+P(q_h^{ET}+q_f^{ET})-\eta\gamma=0. \quad \text{(A8)}$$

Plugging (A8) into (A6) and rewriting yields

$$P'(q_h^{ET}+q_f^{ET})(q_h^{ET}-q_f^{ET})\Big[\frac{\partial q_h}{\partial p_h}+\frac{1}{2}\frac{\partial q_f}{\partial p_h}\Big]-\theta\eta\gamma\frac{\partial q_f}{\partial p_h}=0. \quad \text{(A9)}$$

Since $P(\cdot)$ is strictly decreasing, $P'(q_h^{ET}+q_f^{ET})<0$. The equilibrium property in (3) and (4) implies that the square bracket is negative. Thus, if $q_h^{ET}\le q_f^{ET}$, the left hand side of equation (A9) should be negative, which is contradiction. Consequently, $q_h^{ET}>q_f^{ET}$. Then, the equilibrium property in (3) and (4) jointly implies that $p_h^{ET}<t_f^{ET}$.

Now, we want to show that $q_f^{TT}>q_f^{ET}$. Suppose to the contrary that $q_f^{TT}\le q_f^{ET}$. Consider the case in which the home country switches to emission trading, but issues $n^{TT}(=q_h^{TT}/\gamma)$ number of the tradable permits. The foreign firm optimally chooses $q_f'\in\mathbb{R}_+$ such that

$$P'(q_h^{TT}+q_f')\frac{q_f'-q_h^{TT}}{2}+P(q_h^{TT}+q_f')-\eta\gamma=0. \quad \text{(A10)}$$

Since $P(q_h^{TT}+q_f^{TT})-\eta\gamma<0$, we can infer that $q_f'<q_f^{TT}$. If $q_f'\ge q_f^{TT}$, the left hand side of (A10) should have a negative value. Then, total derivative of the first order condition of the foreign country implies that as long as $q_h\ge q_f$,

$$\frac{dq_f}{dq_h}=-\frac{P''(q_h+q_f)(q_f-q_h)+P'(q_h+q_f)}{P''(q_h+q_f)(q_f-q_h)+3P'(q_h+q_f)}\le 0, \quad \text{(A11)}$$

where $P'(\cdot)<0$ and $P''(\cdot)\ge 0$. Condition (A11) dictates that when either q_h or q_f increases, the other should decrease. Since q_f' is the best response to $q_h=q_h^{TT}$ by construction and $q_f'<q_f^{TT}\le q_f^{ET}$, it should be the case that $q_h^{TT}>q_h^{ET}$. It's contradiction to $q_h^{ET}>q_f^{ET}$, because $q_h^{ET}<q_h^{TT}=q_f^{TT}\le q_f^{ET}$. Therefore, $q_f^{TT}>q_f^{ET}$.

Finally, when $q_f^{TT}>q_f^{ET}$,

$$DS_h(q_h^{TT},q_f^{TT})<DS_h(q_h^{TT},q_f^{ET})\le DS_h(q_h^{ET},q_f^{ET}). \quad \text{(A12)}$$

The first inequality follows from $q_f^{TT}>q_f^{ET}$, and the second inequality from the optimality of $q_h^{ET}\in\mathbb{R}_+$ given q_f^{ET}. □

Proof of Lemma 4 The first order condition with respect to n_j is given by

$$\Big[-\frac{1}{2}P'(q_h+q_f)(q_h+q_f)+P'(q_h+q_f)q_j+P(q_h+q_f)-\eta\gamma\Big]\frac{\partial p_j}{\partial n_j}=0. \quad \text{(A13)}$$

Due to symmetry, the first order condition in (A13) can be rewritten as

$$P(q_h^{EE} + q_f^{EE}) - \eta\gamma = 0. \tag{A14}$$

Since $P'(\cdot) < 0$, $\lim_{Q \to 0} P(Q) > \eta\gamma > \lim_{Q \to \infty} P(Q)$, the continuity of $P(\cdot)$ implies that there exists a unique symmetric pair of (q_h^{EE}, q_f^{EE}).

Suppose to the contrary that $q_h^{EE} + q_f^{EE} \geq q_h^{ET} + q_f^{ET}$. It implies that $P(q_h^{EE} + q_f^{EE}) \leq P(q_h^{ET} + q_f^{ET})$. Then, we get

$$0 = P(q_h^{EE} + q_f^{EE}) - \eta\gamma \leq P(q_h^{ET} + q_f^{ET}) - \eta\gamma = \frac{1}{2} P'(q_h^{ET} + q_f^{ET})(q_h^{ET} - q_f^{ET}). \tag{A15}$$

The first equality comes from (A14) and the last equality comes from (A7). It's contradiction, because the most right hand side of (A15) has a negative value. Therefore, $q_h^{EE} + q_f^{EE} < q_h^{ET} + q_f^{ET}$. When both countries adopt the emission trading scheme, global surplus becomes larger. Then,

$$DS_f(q_f^{ET}, q_h^{ET}) < \frac{1}{2} GS(q_h^{ET} + q_f^{ET}) < \frac{1}{2} GS(q_h^{EE} + q_f^{EE}) = DS_f(q_f^{EE}, q_h^{EE}). \tag{A16}$$

The first inequality comes from $q_f^{ET} < q_h^{ET}$. By switching to the emission trading scheme, the foreign country becomes better off.

Since $P(q_h^{EE} + q_f^{EE}) = \eta\gamma > P(q_h^{TT} + q_f^{TT})$, we can infer that $q_h^{EE} + q_f^{EE} < q_h^{TT} + q_f^{TT}$. It also implies that $p_h^{EE} = p_f^{EE} > t_h^{TT} = t_f^{TT}$. Since $(q_h^{EE} + q_f^{EE}) < (q_h^{TT} + q_f^{TT})$, the global surplus of the market equilibrium with (p_h^{EE}, p_f^{EE}) is larger than that of the outcome associated with (t_h^{TT}, t_f^{TT}). But it is apparently smaller than the global surplus in the (constrained) planner's outcome in (14). Also, since domestic surplus is a half of global surplus in any symmetric solution, the domestic surplus of each country associated with (p_h^{EE}, p_f^{EE}) is larger than the surplus from (t_h^{TT}, t_f^{TT}) as well. Consequently, the foreign country gets a larger domestic surplus in the subtree with (p_h^{EE}, p_f^{EE}) than in the other cases. The global surplus is also maximized in this case. $\square$

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