Environmental Management Policy under International Carbon Leakage[*]

Kazuharu Kiyono[†] Jota Ishikawa[‡]

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Abstract

This paper studies environmental management policy when two fossil-fuel-consuming countries non-cooperatively regulate greenhouse-gas emissions through emission taxes or quotas. The presence of carbon leakage caused by fuel-price changes affects the tax-quota equivalence. We explore each country's incentive to choose a policy instrument in a two-stage policy choice game and find subgame-perfect Nash equilibria. This sheds new light on the questions of which policy instrument is more stringent and of why adopted instruments could be different among countries. In particular, our result suggests a reason why developing countries tend to employ emission taxes, while developed countries tend to adopt emission quotas.

Keywords: global warming, carbon leakage, emission tax, emission quota, tax-quota equivalence
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[†] Waseda University

[‡] Hitotsubashi University and RIETI; Faculty of Economics, Hitotsubashi University, Kunitachi, Tokyo 186-8601, Japan; E-mail: jota@econ.hit-u.ac.jp

1 Introduction

To tackle the issue of global warming, the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change has been meeting annually since 1995. In 1997, the third meeting, the COP 3, adopted the Kyoto Protocol, in which the developed countries, called Annex I Parties to the Convention, made a commitment to decrease their greenhouse-gas (GHG) emissions to 5.2% below their 1990 baseline levels over the 2008–2012 period. However, Non-Annex I Parties have no obligation to the reductions. Governments of Annex I Parties have gradually adopted measures to reduce GHG emissions. For example, emissions trading has been implemented by EU and New Zealand. Emission taxes have been introduced in Australia.[1]

Since the Kyoto Protocol expires at the end of 2012, the post-Kyoto Protocol deals have been negotiated. The COP 17 held in Durban, South Africa in 2011 agreed to the Durban Platform that a legally binding deal comprising all countries is prepared by 2015 to put it into effect in 2020. Therefore, not only developed countries but also developing countries have to adopt some measures to control GHG emissions. In fact, India and South Africa have already introduced an emission tax. China has also announced that it will implement an emission tax by 2015.

A major element of measures to control GHG emissions adopted by many countries is the introduction of emission taxes and quotas (including the creation of markets to trade emission permits). Previous studies on environmental regulation suggest that, within a closed economy, emission taxes and quotas are essentially equivalent instruments. In an open-economy framework, however, this is usually not the case. In particular, carbon leakage across countries could arise and affect the equivalence.

An important point in an open-economy framework is that the toughness of each country's anti-global warming policies is affected by the policy choices of other countries, in turn affecting global environmental quality. For example, the emission regulations adopted by one country do not affect GHG emissions of other countries if these countries employ emission quotas which are binding. That is, international carbon leakage does not occur once other countries directly control their GHG emissions. As Kiyono and Ishikawa (2003) pointed out, emission taxes and quotas are unilaterally equivalent for each country given the policy decisions of other countries (unilateral equivalence). However, they are not unilaterally equivalent once each country understands that the policy instrument choices of other countries may be affected by its own choice under strategic interdependence among countries subject to the carbon-leakage effect (strategic non-equivalence).[2]

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[1] In Australia, emission taxes will be replaced by emissions trading in 2015. The US, which is a signatory to the protocol, has not ratified the protocol.

[2] The issue of unilateral equivalence and strategic non-equivalence between tariffs and quotas was discussed in Kiyono (1985).

In this paper, we first demonstrate unilateral equivalence and strategic non-equivalence more rigorously in the presence of international carbon leakage.[3] We should mention that in our study, the term "tax-quota equivalence" is understood to mean that subject to the objective of national welfare maximization, the government can achieve the same resource allocation through either an emission tax or an emission quota. However, the term has several different meanings in the previous literature. In particular, when the replacement of an emission tax with a quota that is set to equal emission levels under the tax-ridden equilibrium gives rise to the same resource allocation across the economy. Within a partial equilibrium framework in the absence of uncertainty and incomplete information, such equivalence holds in a perfectly competitive market (see Xepapadeas, 1997) as well as in an imperfectly competitive market without strategic abatement investment by firms before the government policy decision (see Ulph, 1996). However, the equivalence breaks down in a general equilibrium model, as shown in Ishikawa and Kiyono (2000,2006) and Ishikawa and Okubo (2008).[4] This is mainly because an emission quota puts a cap on a country's total greenhouse gas emissions whereas the emissions are endogenously determined under emission tax policy.

When the equivalence does not hold, interesting research questions are i) which policy instrument is more stringent and ii) why some countries adopt emission taxes while others adopt emission quotas. We then address these questions. We explore each country's incentive to choose an environment regulation instrument within a framework of a two-stage policy choice game and find subgame-perfect Nash equilibria.

Carbon leakage across countries plays a crucial role in our analysis. There are three main channels through which international carbon leakage can arise. The first channel is changes in a country's industrial structure as discussed in Copeland and Taylor (2005) and Ishikawa et al. (2012). When a country adopts emission regulations, the comparative advantage of the emission-intensive industry could shift abroad. The second channel is the relocation of plants in response to emission regulations, particularly in emission-intensive industries (see Markusen et al., 1993; Markusen et al., 1995; Ulph and Valentini, 2001; and Ishikawa and Okubo, 2008, for example). The third channel, finally, is changes in the price of fossil fuels (See, for example, Bohm, 1993; Felder and Rutherford, 1993; Burniaux and Martins,

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[3] In Kiyono and Ishikawa (2003), we discussed the issue of unilateral equivalence and strategic non-equivalence. However, the analysis there was conducted in a much simpler framework using partial equilibrium analysis. In addition to providing a general equilibrium analysis, the present study analyzes the game of policy instrument choices.

[4] Even in the absence of carbon leakage, the tax-quota equivalence may break down. Whereas a difference in pollution intensities across industries plays a crucial role in Ishikawa and Kiyono (2000,2006), firm relocation (i.e., foreign direct investment) is crucial in Ishikawa and Okubo (2008).

2000; Kiyono and Ishikawa, 2003; Hoel, 2005; and Böringer et al., 2010). A decrease in fossil fuel demand caused by emission regulations in one country lowers the global price of fossil fuels, boosting fossil fuel demand and hence GHG emissions in other countries.

In our analysis, we focus on the last channel, because Felder and Rutherford (1993) and Böringer et al. (2010) argue that the changes in fuel price dominate in the source of international carbon leakage. We build a model with one fuel-producing (or fuel-exporting) country and two fuel-consuming (or fuel-importing) countries. In the fuel-consuming countries, the non-tradable sector emits GHG and causes global warming.[5] We consider a two-stage policy choice game in which both fuel-consuming countries independently choose their emission regulation instrument, either emission taxes or emission quotas, and then, in the second stage, after observing which emission regulation instrument the other country has chosen, determine the specific level of the policy instrument chosen in the first stage.

Depending on the instrument choices, different policy game equilibria emerge. When both countries choose emission taxes (emission quotas), the second-stage subgame is the tax-tax policy game (the quota-quota policy game). When one country chooses emission taxes and the other emission quotas, the resulting second-stage game is the tax-quota policy game. We examine which combination of instruments emerges as a subgame perfect Nash equilibrium for our full game and obtain three possible pure-strategy equilibria: (i) both countries always choose emission quotas; (ii) one country always chooses emission quotas and, given this, the other chooses emission taxes; (iii) neither country has fixed preferences for policy instruments, but each wants to choose the different instruments from the other's choice.

Our policy choice game captures an important aspect of the current situation of climate policy in the world, i.e., the Durban Platform. Under the platform, all major GHG emitters are required to prepare some measures to control emissions. However, the target levels are still highly controversial and hence governments have non-corporatively determined what kinds and levels of measures they employ.[6] Our analysis yields interesting arguments as to why adopted policy instruments could be different among countries. In particular, our result suggests a reason why developing countries such as China and India tend to employ emission taxes, while developed countries such as EU tend to adopt emission quotas.[7]

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[5] Power generation and heat supply is the major source of GHG emissions. According to the International Energy Agency (IEA), the shares of world CO_2 emissions from fuel combustion for electricity and heat, transport, and industry are, respectively, 41%, 23%, and 20% in 2007. Thus, the GHG-emission share of the non-tradable is fairly high.

[6] Moreover, the Kyoto Protocol was provisionally extended in COP 17. Canada and Japan were against the extension and announced their secession from the protocol.

[7] China and India are also large emitters. China is the largest CO_2 emitter in 2011. Its share in the world is 27.1%. The second and the third largest emitters (as a single country) are the US (15.9%) and India (5.5%).

There are many papers that compare various environmental policies including emission taxes and quotas (see, for example, Ulph, 1996; Xepapadeas, 1997; Ishikawa and Kiyono, 2006; Lahiri and Ono, 2007; and Ishikawa and Okubo, 2008). Some of them argue what policy instruments should be used. To our knowledge, however, no study has rigorously examined the endogenous environmental-policy choices as a result of a policy game between countries. We explore the subgame perfect equilibrium when the countries commit to either taxes or quotas before determining specific instrument levels.

The rest of the paper is organized as follows. In Section 2, we construct a model of two fuel-consuming countries emitting GHG and one fuel-producing country, and show that the relative difference in the emission coefficient, that is the GHG emission per unit of fossil fuel, between the fuel-consuming countries determines the size of the carbon-leakage effect. We discuss the properties of the equilibria when the two fuel-consuming countries choose emission taxes in Section 3 and those when the two fuel-consuming countries choose emission quotas in Section 4. In Section 5, we discuss the unilateral equivalence between emission taxes and quotas, and then the strategic non-equivalence between emission taxes and quotas. In Section 6, we explore each country's incentive to choose an environment regulation instrument within a framework of a two-stage policy choice game and find subgame-perfect Nash equilibria. Section 7 concludes.

2 Model

Consider a world consisting of three countries, with countries 1 and 2 both consuming the fossil fuel supplied by the third country, s. The economy of each country is characterized by perfect competition. Each of the fuel-consuming countries produces two goods: a homogeneous tradable commodity (other than the fossil fuel) produced only by labor, and a non-tradable produced by labor, fossil fuel, and environment resources. Production of each good is subject to constant returns to scale, and the non-tradable sector requires the use of a certain combination of fossil fuel and the environment. The use of fossil fuel results in GHG emissions, which degrade global environmental quality.

In this paper, the volume of the GHG emissions is represented by the environment as an input factor. Thus, the tradable good is what we may call a "clean" good and the non-tradable good a "dirty" one. We refer to either of the fuel-consuming countries by superscripts $i, j, k \in \{1, 2\}$ where i and $j(\neq i)$ represent the different countries and k represents either one. The third country, s, a single country supplying the fossil fuel, produces the fossil fuel and the homogeneous tradable commodity.

Thus, each of the fuel-consuming countries produces and exports the tradable commodity to the fuel-supplying country and imports fossil fuel to produce the non-tradable good.[8] The government of neither of the three countries directly intervenes in the trade in the commodity or the fossil fuel. Hereafter, we use the non-fuel tradable good as the numeraire. The constant-returns-to-scale production technology used to produce it means that we can choose the units of output and input so that one unit of the tradable needs one unit of labor. This means that the wage rate should be equal to unity across the world.

As our benchmark, we construct a model in which both fuel-consuming countries regulate their GHG emissions by means of emission taxes.

2.1 Fuel-Consuming Country

Supply-side We start with the supply side. In a fossil-fuel-consuming country, production of the dirty non-tradable good emits GHG and worsens the quality of the global environment hurting the welfare of households across the world. According to Meade (1952), the emitted GHG is an "unpaid factor of production", pricing of which is made by the government in the country having the dirty industry. The specific emission tax rate on GHG serves as the factor price of the environmental resource for firms in the dirty non-tradable sector.[9]

Next, let r denote the world price of the fossil fuel, t_i, the emission tax rate set by the government in fuel-consuming country $i \in \{1,2\}$, and $c^i(r,t_i)$ the unit cost function for the dirty non-tradable sector in country $i \in \{1,2\}$. We should note that the wage rage, being always unity, is suppressed in the unit cost function. The assumption of perfect competition subject to constant returns to scale means that the equilibrium holds only when the price of the non-tradable denoted by p_i is equal to the unit cost, i.e.,

$$p_i = c^i(r,t_i).$$

Hereafter, we assume that the unit cost function $c^i(r,t_i)$ satisfies all the standard assumptions except perfect complementarity between the fuel and the GHG emissions in the sense that there exists a certain value $e_i(>0)$ such that

$$c^i_t(r,t_i) = e_i c^i_r(r,t_i) \tag{1}$$

for $\forall(r,t_i)$, where $c^i_t(r,t_i) \overset{\text{def}}{=} \partial c^i(r,t_i)/\partial t_i$ and $c^i_r(r,t_i) \overset{\text{def}}{=} \partial c^i(r,t_i)/\partial r$. We call this e_i the <u>emission coefficient</u> of country $i \in \{1,2\}$.

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[8] The tradable-commodity may be a composite good. If this is the case, the fossil-fuel-consuming countries may trade with each other. This would not affect our analysis at all.

[9] See also Copeland and Taylor (1994). Only one country may levy an emission tax (i.e. $t_i > 0$ and $t_j = 0$ ($i \in \{1,2\}$ and $i \neq j$)). In this case, we can simply set $t_j = 0$ in the following analysis of this section.

One should also note that, by virtue of Shephard's lemma, $c_r^i(r, t_i)$ gives the input of fossil fuel required per unit of the non-tradable good and $c_t^i(r, t_i)$ is the counterpart for the GHG emissions in the dirty non-tradable sector. Note that this assumption of complementarity (1) leads to

$$c_{tt}^i = e_i c_{rt}^i < 0,$$

where use was made of the strict concavity of the unit cost function with respect to the fuel price.

Next, let x_i represent the output of the non-tradable. Then, we may express the fossil fuel demand denoted by f_i and the GHG emissions denoted by z_i as follows:

$$\begin{aligned} f_i &= c_r^i(r, t_i)x_i, \\ z_i &= c_t^i(r, t_i)x_i = e_i f_i. \end{aligned}$$

Demand-side Let us now consider the demand side. The utility of a representative consumer is given by

$$u^i(x_i^c) + y_i^c - \theta_i D(z_W),$$

where x_i^c denotes the consumption of the non-tradable, y_i^c the consumption of the tradable, $z_W \overset{\text{def}}{=} \sum_k z_k$ world total GHG emissions, $D(z_W)$ the world damage from global warming in terms of the numeraire good, and $\theta_i (> 0)$ what extent country i perceives this damage to be a damage to its own environment. We assume $D'(z_W) > 0$ and $D''(z_W) > 0$. We also assume that the labor endowment is sufficiently large and hence $y_i^c > 0$ holds in equilibrium.

The consumer maximizes the above utility given world total GHG emissions subject to the budget constraint

$$m_i = p_i x_i^c + y_i^c,$$

where m_i denotes the national income and p_i the domestic price of the non-tradable good in country $i \in \{1, 2\}$. Since there arise no excess profits in either sector, the national income is the sum of labor income and emission tax revenue, i.e.,

$$m_i = L_i + t_i z_i,$$

where L_i denotes the labor endowment of country i and use was made of the wage rate being equal to unity.

Further, assume that the utility function $u^i(x_i^c)$ satisfies all the standard assumptions as well as

$$\lim_{x \to 0} u_x^i(x) = +\infty, \text{ and } \lim_{x \to +\infty} u_x^i(x) = 0,$$

which assures production of the non-tradable good to be always strictly positive in each country.

Then, one may define the indirect utility function as follows:

$$v^i(p_i) + L_i + t_i z_i - \theta_i D\left(\sum_k z_k\right),$$

where $v^i(p_i) \overset{\text{def}}{=} \max_x \left\{u^i(x) - p_i x_i\right\}$. In the analysis that follows, we also make use of the relation $x^i(p_i) \overset{\text{def}}{=} \arg\max_x \left\{u^i(x) - p_i x_i\right\}$. Finally, it should be noted that $v^{i\prime}(p_i) = -x^i(p_i)$ holds by Roy's identity.

National welfare To sum up, suppressing the labor endowment term, which is constant, in the above equation, we employ the following expression for the welfare of country i.

$$\tilde{w}^i(r, t_i) \overset{\text{def}}{=} v^i(p_i) + t_i z_i - \theta_i D\left(\sum_k z_k\right) \tag{2}$$

subject to

$$\begin{aligned} v^{i\prime}(p_i) &= -x^i(p_i), &(3)\\ p_i &= c^i(r, t_i), &(4)\\ f_i = f^i(r, t_i) &\overset{\text{def}}{=} c^i_r(r, t_i) x^i\left(c^i(r, t_i)\right), &(5)\\ z_i = z^i(r, t_i) &\overset{\text{def}}{=} c^i_t(r, t_i) x^i\left(c^i(r, t_i)\right) = e_i f^i(r, t_i). &(6) \end{aligned}$$

Differentiation of (2) yields:

$$\begin{aligned} \partial\tilde{w}^i/\partial t_i &= (t_i - \theta_i D')z^i_t,\\ \partial\tilde{w}^i/\partial r &= (t_i - \theta_i D')z^i_r - (f_i + \theta_i D' z^j_r),\\ \partial\tilde{w}^i/\partial t_j &= -\theta_i D' z^j_t. \end{aligned} \tag{7}$$

One should also note the following relations for the succeeding discussion:

$$\begin{aligned} f^i_r \overset{\text{def}}{=} \partial f^i/\partial r &= c^i_{rr} x_i + (c^i_r)^2 x^i_p < 0, & f^i_t \overset{\text{def}}{=} \partial f^i/\partial t_i &= e_i f^i_r,\\ z^i_r \overset{\text{def}}{=} \partial z^i/\partial r &= e_i f^i_r < 0, & z^i_t \overset{\text{def}}{=} \partial z^i/\partial t_i &= e_i f^i_t = e_i z^i_r < 0, \end{aligned} \tag{8}$$

by virtue of the technological complementarity between fossil fuel and GHG. As the third and fourth equations of (8) show, each country's GHG emissions decrease as the fuel price or the emission tax rate increases, which is the source of carbon leakage considered in our analysis.

2.2 Fuel-Supplying Country

As in the fuel-consuming countries, the wage rate in the fuel-supplying country is equal to unity. For the purpose of focusing on the effects of fossil fuel trade and carbon leakage, we assume that production of fossil fuel is subject to decreasing returns to scale though the other commodities are subject to constant returns to scale. By letting $\Phi(r)$ represent the maximum profit function of the fossil-fuel sector, Hotelling's lemma implies that $\Phi'(r)$ gives the supply function of the fossil fuel, which we represent by $s(r)$.

2.3 World Trade Equilibrium

To express the equilibrium, it suffices to write down the world fossil-fuel market clearing condition, i.e.,

$$s(r) - \sum_j f^j(r, t_i) = 0. \tag{9}$$

Given the emission tax policies of the fuel-consuming countries $\boldsymbol{t} \overset{\text{def}}{=} (t_1, t_2)$, the world fuel price is determined via (9), the relation of which we express by $\hat{r}(\boldsymbol{t})$. When either fuel-consuming country raises the emission tax rate, this dampens its fuel demand, thus leading to a decline in the equilibrium fuel price. To show this effect on the price, we define the following:

$$\Delta_r \overset{\text{def}}{=} s'(r) - \sum_k f_r^k (> 0), \tag{10}$$

$$\zeta_\ell \overset{\text{def}}{=} \begin{cases} -f_r^i/\Delta_r & \text{for } \ell \in \{1,2\} \\ s'(r)/\Delta_r & \text{for } \ell = s \end{cases} . \tag{11}$$

Here, ζ_i represent the <u>relative price sensitivity of fuel-demand</u> by country $i \in \{1, 2\}$ and ζ_s the <u>relative price sensitivity of fuel-supply</u> by the fuel-supplying country. By definition, the following holds:

$$\zeta_\ell \in (0,1), \quad \sum_\ell \zeta_\ell = 1 \ \text{ for } \ell \in \{1, 2, s\} \tag{12}$$

In terms of these relative price sensitivities, one can express the effect of an increase in fuel-country i's emission tax rate on the fuel price as follows:

$$\hat{r}_i(\boldsymbol{t}) \overset{\text{def}}{=} \partial \hat{r}/\partial t_i = -e_i \zeta_i < 0, \tag{13}$$

where use was made of (8). The following lemma is straightforward from (13).

Lemma 1 *(i) The world fuel price always declines as one of the fuel-consuming countries raises its emission tax rate. (ii) The decrease in the world fuel price caused by an increase in a fuel-consuming country's emission tax rate becomes greater as its emission coefficient and relative price sensitivity of fuel demand increase.*

Note that, with fuel-consuming countries facing an upward-sloping fuel-supply function $s'(r) > 0$, the above lemma critically depends on the market power of each fuel-consuming country. If country i is small with no market power in the world fuel market, then it cannot affect the world fuel price.

2.4 Emission Taxes and GHG Emissions

Before investigating each country's strategic incentive for environment regulation, let us look into the effects of emission tax increases on GHG emissions, which are the key to the following analysis.

For this purpose, we first redefine the demand for fuel and GHG emissions as a function of the emission tax rates of the two countries, i.e., the emission-tax profile $\boldsymbol{t} = (t_1, t_2)$.

$$\hat{f}^i(\boldsymbol{t}) \overset{\text{def}}{=} f^i\left(\hat{r}(\boldsymbol{t}), t_i\right), \hat{z}^i(\boldsymbol{t}) \overset{\text{def}}{=} z^i\left(\hat{r}(\boldsymbol{t}), t_i\right). \tag{14}$$

These input demand functions satisfy

$$\begin{aligned}
\hat{f}^i_i \overset{\text{def}}{=} \partial \hat{f}^i(\boldsymbol{t})/\partial t_i &= f^i_t + f^i_r \hat{r}_i = -\Delta_r e_i(1-\zeta_i)\zeta_i < 0 \\
\hat{f}^i_j \overset{\text{def}}{=} \partial \hat{f}^i(\boldsymbol{t})/\partial t_j &= f^i_r \hat{r}_j = \Delta_r e_j \zeta_i \zeta_j > 0 \\
\hat{z}^i_i \overset{\text{def}}{=} \partial \hat{z}^i(\boldsymbol{t})/\partial t_i &= e_i \hat{f}^i_i = -\Delta_r e_i^2 \zeta_i(1-\zeta_i) < 0 \\
\hat{z}^i_j \overset{\text{def}}{=} \partial \hat{z}^i(\boldsymbol{t})/\partial t_j &= e_i \hat{f}^i_j = \Delta_r e_i e_j \zeta_j \zeta_i = \hat{z}^j_i > 0
\end{aligned} \tag{15}$$

where use was made of (8). The above equations show that an increase in the emission tax rate by a fuel-consuming country decreases its own fuel demand as well as its own GHG emissions, while it increases those of the other fuel-consuming country (only when there is a decrease in the world fuel price).

An increase in the emission-tax by one country lowers the fuel price, leading to an increase in the fuel-demand of the other country and hence an increase in its GHG emissions. This is the basic mechanism of carbon leakage via trade in fuel considered in this study. This carbon-leakage effect involves the possibility of an increase in world total GHG emissions even with an increase in the emission tax rate of one of the countries.

To show this possibility of an increase in world total GHG emissions, let

$$\hat{z}^W(\boldsymbol{t}) \overset{\text{def}}{=} \sum_k \hat{z}^k(\boldsymbol{t}), \hat{f}^W(\boldsymbol{t}) \overset{\text{def}}{=} \sum_k \hat{f}^k(\boldsymbol{t}),$$

respectively represent world total GHG emissions and fuel demand as a function of the tax profile. Using (13) and (15), the effect of an increase in $t_i (i = 1, 2)$ on world total GHG emissions and fuel demand can be represented as:

$$\begin{aligned}
\hat{f}^W_i \overset{\text{def}}{=} \partial \hat{f}^W(\boldsymbol{t})/\partial t_i &= s'(r)\hat{r}_i = -s'(r) e_i \zeta_i < 0, \qquad (16) \\
\hat{z}^W_i \overset{\text{def}}{=} \partial \hat{z}^W(\boldsymbol{t})/\partial t_i &= \Delta_r e_i \zeta_i \{e_j \zeta_j - e_i(1-\zeta_i)\},
\end{aligned}$$

the latter of which can also be rewritten as:

$$\hat{z}_i^W = \Delta_r e_i e_j (1-\zeta_i)\zeta_i \left\{ \frac{\zeta_j}{1-\zeta_i} - \frac{e_i}{e_j} \right\}. \tag{17}$$

Thus, an increase in the emission tax by either of the two countries unambiguously reduces the world fuel-demand (see (16)), but, as (17) shows, it may increase world total GHG emissions.

Proposition 1 *Suppose that country $i \in \{1,2\}$ raises its emission tax rate. Then, world total GHG emissions decrease if and only if $e_i/e_j > \zeta_j/(1-\zeta_i)$.*

Hereafter, without loss of generality, we assume that the emission coefficient is not larger in country 1 than in country 2, i.e., $e_1 \leq e_2$.[10] Then, there are two possible cases when discussing the change in world total GHG emissions through an increase in either country's emission tax rate. They are illustrated in Figure 1.

When the emission coefficients of the two fuel-consuming countries do not differ to a great extent and hence the relative emission coefficient e_1/e_2 is in *Region N* (i.e., $\zeta_2/(1-\zeta_1) < e_1/e_2 \leq 1$), an increase in either country's emission tax rate decreases world total GHG emissions.[11] If the emission coefficients differ a lot and hence e_1/e_2 is in *Region A* (i.e., $0 < e_1/e_2 < \zeta_2/(1-\zeta_1)$), however, an increase in the emission tax rate by country 1 increases world total GHG emissions. This is because, provided the emission coefficient of country 1 is sufficiently smaller than that of country 2, such a tax increase lowers the fuel demand and thus GHG emission by country 1 with the smaller emission coefficient but the resulting decrease in the fuel price boosts the fuel demand by country 2 with the larger emission coefficient, leading to a large increase in GHG emissions.

Given ζ_s, a decrease in ζ_1 (a relative price sensitivity of fuel-demand by country 1) which is equivalent to an increase in ζ_2 (see (12)), expands *Region A*. A small ζ_1 or, a large ζ_2 implies that a change in country 1's fuel demand caused by a given price change is small and a change in country 2's fuel demand caused by a given price change is large. For example, this is likely to be the case when country 1 is relatively small and/or has a

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[10] $e_1 < e_2$ could stem from differences in artificial carbon sinks between countries. Artificial carbon sinks called "carbon capture and storage (CCS)" mitigate the carbon dioxide release into the atmosphere from fossil fuel use. According to the IEA, CCS is the only technology available to mitigate GHG emissions from large-scale fossil fuel usage. In IEA's scenario, CCS will contribute to 20% reductions of GHG emissions in 2050. Since developed countries such as Japan and Germany have been developing CCS technologies, the emission coefficient is expected to be lower in developed countries than in developing countries.

[11] If countries 1 and 2 are symmetric and hence $e_1 = e_2$ and $\zeta_1 = \zeta_2$ hold, then we have $\zeta_2/(1-\zeta_1) < e_1/e_2 = 1$ because $\zeta_1 = \zeta_2 < 1/2$ holds from (12).

relatively small price elasticity of demand.[12] As ζ_1 becomes smaller, the above-mentioned carbon leakage effect is magnified and hence world total GHG emissions are more likely to increase.

As already mentioned, the possibility of an increase in world GHG emissions as a result of an increase in the emission tax in a country depends on the country's market power in the world fuel market. In fact, when the fuel price is constant, the increase in a country's emission tax rate only affects its own GHG emissions, so that in this case world total GHG emissions always decrease.

We should mention that the $\hat{z}_1^W + \hat{z}_2^W < 0$ holds.[13] Therefore, even when an increase in the emission tax by country 1 with the smaller emission coefficient increases world total GHG emissions, the following lemma is established.

Lemma 2 *When both fuel-consuming country simultaneously raise their emission tax rates by the same amount, there must be a decrease in world total GHG emissions.*

3 The Individually Optimal Emission Tax

Our next task is to explore the properties of the equilibria when the two fuel-consuming countries non-cooperatively choose optimal emission taxes and/or quotas. In this section, we look at the case in which each fuel-consuming country sets its emission tax rate knowing the other country also employs emission taxes, which we call the tax-tax policy equilibrium. Since the optimal tax rate should maximize each country's national welfare given the other's tax rate, we refer to it as the individually optimal emission tax rate in the following discussion.

3.1 Determinants of the Optimal Emission Tax

In this subsection, we point out that there are three determinants of the individually optimal emission tax rate. For this, we obtain the individually optimal emission tax rate. Inserting the equilibrium fuel-price function into (2), we can express each country's welfare as the following function of the tax profile:

$$\hat{w}^{iT}(\boldsymbol{t}) \overset{\text{def}}{=} \tilde{w}^i\left(t_i, \hat{r}(\boldsymbol{t})\right). \tag{18}$$

We assume that the above welfare function is strictly concave in the country's own emission tax rate.

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[12] If the two countries have the identical price elasticity of demand, $\zeta_1 < \zeta_2$ implies that country 1 is smaller than country 2. If the country sizes are identical, on the other hand, $\zeta_1 < \zeta_2$ implies that country 1 has a smaller price elasticity of demand than country 2.

[13] The proof is provided in Appendix A.

Since the optimal tax rate is chosen non-cooperatively, it should satisfy the following first-order condition for welfare maximization:

$$\begin{aligned} 0 = \tfrac{\partial \hat{w}^{iT}}{\partial t_i} &= \tfrac{\partial \tilde{w}^i}{\partial t_i} + \tfrac{\partial \tilde{w}^i}{\partial r} \hat{r}_i \\ &= (t_i - \theta_i D') z_t^i + \left\{ (t_i - \theta_i D') z_r^i - (f_i + \theta_i D' z_r^j) \right\} \hat{r}_i \qquad (19) \\ &= (t_i - \theta_i D') \hat{z}_i^i - f_i \hat{r}_i - \theta_i D' z_r^j \hat{r}_i, \end{aligned}$$

where use was made of (7). Letting t_i^T represent the solution of the above first-order condition for welfare maximization, i.e., country i's emission tax rate at the non-cooperative tax-tax policy game equilibrium, we have

$$t_i^T = \theta_i D' + f_i \left(\frac{\hat{r}_i}{\hat{z}_i^i} \right) + \theta_i D' \left(\frac{\hat{z}_i^j}{\hat{z}_i^i} \right), \qquad (20)$$

or alternatively,

$$\begin{aligned} t_i^T &= f_i \left(\frac{\hat{r}_i}{\hat{z}_i^i} \right) + \theta_i D' \left(\frac{\hat{z}_i^W}{\hat{z}_i^i} \right) \qquad (21) \\ &= \frac{f_i}{\Delta_r e_i (1 - \zeta_i)} + \left(1 - \frac{e_j \zeta_j}{e_i (1 - \zeta_i)} \right) \theta_i D', \qquad (22) \end{aligned}$$

where use was made of (13) and (15).

In (20), each term represents different determinant of emission tax.[14] The first term represents the well-known basic motive for internalizing negative externalities caused by emissions. This term is obviously positive. The second term is related to the terms of trade (TOT) for fuel. As a result of an emission tax, the fuel-consuming country can improve the TOT for fuel and hence welfare. This effect works to raise the emission tax rate. Finally, the last term arises because of carbon leakage. Since an increase in the emission tax rate lowers the fuel price, the other fuel-consuming country's demand for the fossil fuel is boosted, which worsens the global environment quality through an increase in GHG emissions. This carbon-leakage effect works to reduce the emission tax rate. If this carbon-leakage effect is sufficiently large, then the optimal policy would in fact be to impose a negative, rather than a positive, emission tax rate. This case occurs only when an increase in the emission tax rate increases world total GHG emissions (i.e., $\hat{z}_i^W > 0$), as is shown in (21). Since $\hat{z}_2^W < 0$ always holds with $e_1 \leq e_2$, the optimal emission tax could be negative only in country 1.

Therefore, we obtain the following proposition.

Proposition 2 *1. Given the emission tax rate of the other country, the TOT effect makes the optimal emission tax rate for a fuel-consuming country higher but the carbon-leakage effect makes it lower.*

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[14] This decomposition is similar to that in Markusen (1975) who investigates tariffs, consumption taxes and production taxes in the presence of international externalities in a two-country model.

2. *Given the emission tax rate of the other country, each fuel-consuming country sets a strictly positive rate of emission tax if an increase in its own emission tax rate decreases world total GHG emissions. A negative emission tax rate is optimal only in country 1. This is the case only if an increase in country 1's emission tax rate increases world total GHG emissions.*

Note that the carbon-leakage effect vanishes when a fuel-consuming country is a price-taker in the world fuel market, so that its optimal emission tax rate is given by

$$t_i^T = \theta_i D' \left(\sum_k z_k \right). \tag{23}$$

The emission tax rate should be set equal to the perceived marginal environment damage. This result is the same with the standard result obtained in a closed-economy model where neither the TOT effect nor the carbon-leakage effect exists.

We should mention that the effect of an increase in the emission coefficient on the optimal emission tax rate is ambiguous. It increases the marginal environment damage, D'. It is straightforward from (23) that an increase in D' induces the country to raise the optimal emission tax rate without carbon leakage. However, this is not necessary the case with carbon leakage (see (21)). That is, an increase in country i's emission coefficient raises country i's optimal emission tax rate without carbon leakage, but may lower it with carbon leakage.

3.2 Shapes of the Reaction Curves

When we solve (19) for the own emission tax rate, the solution gives country i's reaction function, which we denote by $R^{iT}(t_j)$. In this subsection, we discuss its shape.

As has been made clear in the previous literature, when each fuel-consuming country is a price-taker in the world fuel market, the optimal emission tax rate formula (23) implies that the optimal emission tax of one country decreases as that of the other country increases. This is because an emission tax increase by the other country decreases the own GHG emissions as well as the world total, which decreases the marginal environment damage. This leads the first country to lower its emission tax rate. For this reason, each country's reaction curve is downward-sloping in the tax-tax policy game in the absence of the carbon-leakage effect.

However, as is implied by (20), once the carbon-leakage effect occurs, the shape of the reaction function may change and it is possible that it becomes upward-sloping.

Lemma 3 *In the presence of carbon leakage through fuel trade, each country's emission tax rate is not necessarily a strategic substitute to the other's tax rate in the tax-tax policy game.*

3.3 Changes in the marginal environment consciousness

It may be of interest to examine how each country's optimal emission tax rate changes along with the marginal environment consciousness, θ_i. We can easily find the effect of a change in the marginal environment consciousness, because it does not affect the fuel demand or the GHG emissions of either country. Partial differentiation of (19) yields:

$$\frac{\partial^2 \hat{w}^{iT}}{\partial \theta_i \partial t_i} = -D' \hat{z}_i^W,$$

where use was made of the envelope theorem, $\hat{z}_i^W = \hat{z}_i^i + \hat{z}_i^j$ and $\hat{z}_i^j = z_r^j \hat{r}_i$.

Thus, we establish the following proposition.

Proposition 3 *When country $i \in \{1, 2\}$ becomes more environment conscious in the sense that θ_i increases, its optimal emission tax rate increases if and only if an increase in country i's emission tax rate decreases world total GHG emissions.*

In view of Proposition 1, an increase in θ_2 necessarily raises country 2's optimal emission tax rate, while an increase in θ_1 may lower country 1's optimal emission tax rate. As is clear from (23), an increase in θ_i necessarily raises country *i*'s optimal emission tax rate without carbon leakage. This relationship holds even with carbon leakage, however, as long as the leakage is not strong enough.

3.4 A Tax Increase by the Other Country

We next consider whether a fuel-consuming country gains or loses if the other fuel-consuming country raises its emission tax rate. Specifically, we evaluate this effect when the country initially employs the optimal-response emission tax rate.

It is proved in Appendix B that even in the presence of carbon leakage, one finds that a tax increase by either fuel-consuming country benefits the other country. That is, $\partial \hat{w}^{iT} / \partial t_j > 0$ holds.

Proposition 4 *Given the individually optimal emission tax rate, the welfare of either of the fuel-consuming countries improves as the other country increases the emission tax rate.*

Thus, as in the standard literature, emission taxation by a fuel-consuming country gives rise to pecuniary external economies to the other fuel-consuming country. Using this result, it is straightforward to depict each country's iso-welfare contour at the non-cooperative equilibrium, as shown in Figure 2. In the figure, point T_1 is the non-cooperative equilibrium. Country i's iso-welfare contour is given by w_i^T. Thus, the two fuel-consuming countries are better off by raising their tax rates above those at the non-cooperative equilibrium. Note that this result holds regardless of whether the emission tax rates are strategic substitutes or complements.

4 The Individually Optimal Emission Quota

In this section, we examine the case in which both fuel-consuming countries employ emission quotas. By emission quota, we mean a country-wide cap of total GHG emissions. We assume that the government issues a certain number of GHG emission permits and establishes a perfectly competitive market for the domestic trade in such permits.

4.1 The Optimal Emission Quota

Consider a policy game in which both fuel-consuming countries employ emission quotas. We call this the quota-quota policy game. Let q_i denote country i's quota and $\boldsymbol{q} \overset{\text{def}}{=} (q_1, q_2)$ the quota profile. In view of (2)-(6), each fuel-consuming country's welfare is now described by

$$\widetilde{w}^{iQ}(t_i, r) \overset{\text{def}}{=} v^i(p_i) + t_i q_i - \theta_i D\left(\sum_k q_k\right) \tag{24}$$

subject to

$$v^{i\prime}(p_i) = -x^i(p_i) \tag{3}$$

$$p_i = c^i(r, t_i) \tag{4}$$

$$f_i = f^i(r, t_i) \tag{5}$$

$$q_i = z^i(r, t_i) = e_i f^i(r, t_i) \tag{25}$$

$$s(r) = \sum_k \frac{q_i}{e_i} \tag{26}$$

where t_i now represents the price of the tradable emission permit in country i. The last equation (26) determines the equilibrium fuel price as a function of the quota profile, which we express by $\widehat{r}^Q(\boldsymbol{q})$. Simple calculation yields

$$\frac{\partial \widehat{r}^Q(\boldsymbol{q})}{\partial q_i} = \frac{1}{e_i s'(r)} > 0,$$

which implies:

Lemma 4 *The world fuel price always declines as one of the fuel-consuming countries decreases the level of its emission quota.*

We insert $\widehat{r}^Q(\boldsymbol{q})$ into (25), and solve for t_i. We then obtain the price of the tradable permit as a function of the quota profile, which we express by $\widehat{t^i}(\boldsymbol{q})$. From $\widehat{r}^Q(\boldsymbol{q})$ and $\widehat{t^i}(\boldsymbol{q})$, the country's welfare is represented as a function of the quota profile:

$$\widehat{w}^{iQ}(\boldsymbol{q}) \overset{\text{def}}{=} \widetilde{w}^{iQ}(t^i(\boldsymbol{q}), r^Q(\boldsymbol{q})).$$

In the quota-quota policy game, each country sets the quota so as to maximize its welfare given by (24), so that the following first-order condition holds:

$$\begin{aligned} 0 = \tfrac{\partial \widehat{w}^{iQ}}{\partial q_i} &= \left(-x_i c_t^i + q_i\right) \tfrac{\partial \widehat{t^i}(\boldsymbol{q})}{\partial q_i} + (-x_i c_r^i) \tfrac{\partial \widehat{r}^Q(\boldsymbol{q})}{\partial q_i} + (t_i - \theta_i D') \\ &= -\tfrac{f_i}{e_i s'(r)} + (t_i - \theta_i D'), \end{aligned} \tag{27}$$

where use was made of (25) and $f_i = c_r^i x_i$.

Solving the above equation for the permit price, we obtain

$$t_i^Q = \theta_i D' + \frac{f_i}{e_i s'(r)}, \tag{28}$$

which, compared with (20), shows that there are no carbon-leakage effects. This means that each fuel-consuming country has an incentive to strengthen its environmental regulation by setting a higher price for emission permits.

The following proposition is established.

Proposition 5 *If both fuel-consuming countries employ emission quotas, then there are no carbon-leakage effects, and hence each country has an incentive to strengthen its environmental regulation compared with the case of emission taxes.*

4.2 Reaction Curves in the Quota-Quota Policy Game

In this subsection, we explore reaction curves in the quota-quota policy game. In general, the shape of the associated reaction curve is ambiguous. In the absence of fuel trade, (28) is rewritten as $t_i^Q = \theta_i D'$. Since the domestic permit price is independent of the other country's quota, it is straightforward to see that each country's emission quota is a strategic substitute to the other's. In the presence of fuel trade, however, this is not necessarily the case.

Let us now examine the relationship between the original reaction functions in terms of emission quota levels and the corresponding reaction curve in terms of the price of the tradable emission permit. The transformed reaction curves below allow us to make comparisons among the equilibria in different games.

Let $\Gamma^i(q_j) \stackrel{\text{def}}{=} \arg\max_{q_i} \widehat{w}^{iQ}(\boldsymbol{q})$. Since $q_k = \hat{z}^k(\boldsymbol{t})$ holds for $k \in \{1,2\}$, the reaction function in terms of the permit price, $t_i = R^{iQ}(t_j)$, should satisfy

$$\hat{z}^i(\boldsymbol{t}) = \Gamma^i\left(\hat{z}^j(\boldsymbol{t})\right).$$

Thus, the transformed reaction function, $R^{iQ}(t_j)$, should satisfy:

$$\frac{dR^{iQ}(t_j)}{dt_j} = \frac{\frac{d\Gamma^i(q_j)}{dq_j}\hat{z}^j_j - \hat{z}^i_j}{\hat{z}^i_i - \frac{d\Gamma^i(q_j)}{dq_j}\hat{z}^j_i}.$$

Since

$$\frac{\hat{z}^i_i}{\hat{z}^j_i} = -\frac{e_j(1-\zeta_i)}{e_i\zeta_j} \tag{29}$$

holds by virtue of (15), we can rewrite the slope of the transformed reaction function as follows:

$$\frac{dR^{iQ}(t_j)}{dt_j} = -\frac{\hat{z}^j_j}{\hat{z}^j_i}\frac{\frac{d\Gamma^i(q_j)}{dq_j} + \frac{e_j(1-\zeta_j)}{e_i\zeta_i}}{\frac{d\Gamma^i(q_j)}{dq_j} + \frac{e_j\zeta_j}{e_i(1-\zeta_i)}}.$$

Since $e_j\zeta_j/e_i(1-\zeta_i) < e_j(1-\zeta_j)/e_i\zeta_i$ always holds, it is straightforward to obtain the following lemma from the above equation:

Lemma 5

$$\frac{dR^{iQ}(t_j)}{dt_j} < 0 \iff \begin{cases} (i) & \frac{d\Gamma^i(q_j)}{dq_j} < 0 \\ (ii) & \frac{e_j\zeta_j}{e_i(1-\zeta_i)} < \left|\frac{d\Gamma^i(q_j)}{dq_j}\right| < \frac{e_j(1-\zeta_j)}{e_i\zeta_i} \end{cases}$$

As the above lemma shows, under the quota-quota policy game, the reaction curve in terms of the price of the tradable emission permit becomes upward-sloping even when the corresponding reaction curve in terms of emission quota levels is downward-sloping. When the original reaction curve in the quota-quota policy game over the quota-quota space is upward-sloping, the corresponding transformed reaction curve should always be upward-sloping.

4.3 A Quota Decrease by the Other Country

What if the other country reduces its emission quota level in the quota-quota policy game? The following shows that if a country optimizes its emission quota in response to the quota set by the other country, such a decrease in the other country's quote unambiguously improves the welfare of the first country:

$$\begin{aligned} \frac{d\widehat{w}^{iQ}\left(\Gamma^i(q_j), q_j\right)}{dq_j} &= \frac{\partial\widehat{w}^{iQ}\left(\Gamma^i(q_j), q_j\right)}{\partial q_j} \text{ (by virtue of the envelope theorem)} \\ &= -\theta_i D' - f_i\widehat{r}^Q_j < 0. \end{aligned} \tag{30}$$

Thus, in the quota-quota policy game, each country's choice of the emission quota level generates external diseconomies for the other country. This means that the incentive for each country to reduce GHG emissions through quotas is not enough from the viewpoint of the joint welfare of both fuel-consuming countries.

Thus, we have established:

Proposition 6 *If both fuel-consuming countries further reduce their GHG emissions through quotas, then both can be better off than at the non-cooperative quota-quota policy game equilibrium.*

5 The Equivalence between Taxes and Quotas

Depending on the instrument choices, different policy game equilibria emerge. When both countries choose emission taxes (emission quotas), the second-stage subgame is the tax-tax policy game (the quota-quota policy game). When one country chooses emission taxes and the other emission quotas, the resulting second-stage game is the tax-quota policy game. We compare the equilibria with the aid of reaction curves depicted over the t_1-t_2 space. Both unilateral equivalence and strategic non-equivalence below are useful when investigating reaction curves.

5.1 Unilateral Equivalence

From the viewpoint of an individual country, taxes and quotas, given the policy instrument of the other country, can be shown to be equivalent in the sense that they achieve the same world resource allocation. We call this result unilateral equivalence between emission taxes and quotas.[15]

First, suppose that country j employs emission taxes. Then in view of (14), given country i's emission quota q_i, the equilibrium permit price t_i should satisfy

$$q_i = \hat{z}^i(t_i, t_j).$$

Thus, given country j's emission tax rate, there is a one-to-one relationship between the emission quota q_i and the emission tax rate or permit price t_i. This establishes that emission taxes and quotas are equivalent for country i given country j's emission tax rate.

Next consider the case in which country j sets the emission quota q_j. Then, given q_j, when country i chooses the emission quota q_i, the resulting permit prices, t_i and t_j, should satisfy

$$q_i = \hat{z}^i(t_i, t_j), q_j = \hat{z}^j(t_j, t_i).$$

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[15] This is similar to the well-known tax-quota equivalence in a closed economy.

Since

$$\Delta_z \overset{\text{def}}{=} \hat{z}_1^1 \hat{z}_2^2 - \hat{z}_2^1 \hat{z}_1^2 > 0 \tag{31}$$

holds,[16] the implicit function theorem can be applied to ensure a one-to-one relationship between the permit-price profile $\boldsymbol{t}$ and the emission-quota profile $\boldsymbol{q} \overset{\text{def}}{=} (q_1, q_2)$. This implies that emission taxes and quotas are equivalent for country i given country j's emission quota.[17]

The above discussion leads to the following unilateral equivalence result.

Proposition 7 *Given the environmental policy instrument of the other fuel-consuming country, emission taxes and quotas are equivalent for each individual country.*

This proposition implies the following lemma.

Lemma 6 *Given the other country's environmental policy instrument, a country's reaction curves are the same regardless of its choice between taxes and quotas once they are transformed and depicted over the* t_1*-*t_2 *space.*

In Figure 3, R^{iT} is country i's reaction curve given that country j employs emission tax. t_i is the tax rate (the permit price) in country i when country i employs emission tax (quota). Similarly, R^{iQ} is country i's reaction curve given that country j employs emission quota.[18]

5.2 Strategic Non-equivalence

Even when emission taxes and quotas are equivalent given the other country's environmental policy instrument, they are no longer equivalent once the other country changes its policy instrument. In fact, once the other country switches from emission taxes to quotas, each country has an incentive to strengthen its own environmental regulation. Let us demonstrate this result, which we call the strategic non-equivalence result.

We assume that the two countries initially employ emission taxes. In Figure 2, the equilibrium is given by point T_1 where the reaction curves (which are not shown in the figure to avoid it getting too complex) intersect with each other. Now suppose that country 2 switches from emission taxes to quotas. Given the associated tax profile, draw a curve showing the tax pairs keeping country 2's GHG emissions constant. This iso-GHG-emissions

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[16] This result is obtained as follows:

$$\begin{aligned}\Delta_z &= (z_t^1 + z_r^1 \hat{r}_1)(z_t^2 + z_r^2 \hat{r}_2) - z_r^1 z_r^2 \hat{r}_1 \hat{r}_2 = z_t^1 z_t^2 + z_t^1 z_r^2 \hat{r}_2 + z_r^1 z_t^2 \hat{r}_1 \\ &= e_1 e_2 (f_t^1 f_t^2 + f_t^1 f_r^2 \hat{r}_2 + f_r^1 f_t^2 \hat{r}_1) = e_1^2 e_2^2 f_r^1 f_r^2 \zeta_s > 0.\end{aligned}$$

[17] A more rigorous proof is provided in Appendix C.

[18] As shown in Lemma 7 below, R^{iQ} is located outside of R^{iT}.

curve is given by $z_2^T z_2^{T'}$. In view of (15), such a curve should be upward-sloping. Then, since country 1's iso-welfare contours are U-shaped as shown in Figure 2 and its welfare improves in the higher country 2's emission tax rate, country 1 becomes better off by choosing point Q_1 along the iso-GHG-emissions curve $z_2^T z_2^{T'}$.

The result is that country 1's emission tax rate becomes higher as well as country 2's. The reason is as follows. Since country 2's GHG emissions are held constant, its fuel demand is also kept constant under the emission quota. This implies that country 1's tax increase results in no carbon leakage, leading to an increase in the emission tax rate.

How do the GHG emissions by country 1 change after such a change in the emission tax policy? The figure also shows the iso-GHG-emissions curves for country 1, $z_1^T z_1^{T'}$ and $z_1^Q z_1^{Q'}$. They are also upward-sloping and their slopes are greater than country 2's by virtue of the following relation:

$$\left.\frac{dt_2}{dt_1}\right|_{z_1=const} - \left.\frac{dt_2}{dt_1}\right|_{z_2=const} = \frac{\hat{z}_1^2}{\hat{z}_2^2} - \frac{\hat{z}_1^1}{\hat{z}_2^1} = \frac{1}{\hat{z}_2^2 \hat{z}_2^1}\left(\hat{z}_2^1 \hat{z}_1^2 - \hat{z}_1^1 \hat{z}_2^2\right) > 0,$$

where use was made of (31).

Since $\hat{z}_1^1 < 0$, GHG emissions on the iso-GHG-emissions curve $z_1^Q z_1^{Q'}$ are smaller than those on the curve $z_1^T z_1^{T'}$. This is consistent with the result for the case above when country 1 employs more stringent environmental regulations.

Thus, we obtain:

Proposition 8 *If a country switches from an emission tax to an individually equivalent emission quota, then the other country has an incentive to raise its emission tax rate or to reduce its emission quota level.*

Thus, environmental quotas are a more stringent policy instrument than environmental taxes in the sense that environmental quotas lead the other country to strengthen environmental regulations in the other country in the presence of carbon leakage. The above proposition also implies that when one country switches from an emission tax to a quota, the other country's reaction curve (which is not shown in Figure 2 but in Figure 3) shifts outside on the t_1-t_2 plane.[19] That is,

Lemma 7 *Country i's reaction curve given that country j employs emission quota is located outside of country i's reaction curve given that country j employs emission tax.*

We should mention that below (above) the iso-GHG-emissions curve $z_2^T z_2^{T'}$, country 2's GHG emissions are larger (smaller) than at T_1. Similarly,

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[19] The resulting new reaction curve does not necessarily have the same shape as the original curve.

above (below) the iso-GHG-emissions curve $z_1^T z_1^{T'}$, country 1's GHG emissions are larger (smaller) than at T_1. Thus, the world iso-GHG-emissions curve which keeps world total GHG emissions at the level of T_1 goes through the regions $z_1^T T_1 z_2^{T'}$ and $z_1^{T'} T_1 z_2^T$. The world iso-GHG-emissions curve is downward-sloping in Case N of $\hat{z}_1^W < 0$ and $\hat{z}_2^W < 0$ (i.e., when e_1/e_2 lies in *Region N* in Figure 1) but is upward-sloping in Case A of $\hat{z}_1^W > 0$ and $\hat{z}_2^W < 0$ (i.e., when e_1/e_2 lies in *Region A* in Figure 1).[20] Therefore, we obtain

Proposition 9 *When both* t_1 *and* t_2 *increase, total world GHG emissions necessarily decrease if* $e_1/e_2 > \zeta_2/(1-\zeta_1)$ *but could increase if* $e_1/e_2 < \zeta_2/(1-\zeta_1)$.

6 Strategic Interdependence and Subgame Nash Equilibria

In this section, we find subgame perfect Nash equilibria in the following two-stage policy game. In the first stage, both fuel-consuming countries independently choose their emission regulation instrument, either emission taxes or emission quotas, and then, in the second stage, after observing which emission regulation instrument the other country has chosen, determine the specific level of the policy instrument chosen in the first stage.

6.1 Specific Level of Policy Instruments in the Different Policy Games

The result of the strategic non-equivalence of emission taxes and quotas implies that the quality of the global environment will differ depending on each country's choice of policy instrument. These differences are shown in Figure 3. Figure 3 (a) shows the case in which the reaction curves of both fuel-consuming countries are downward-sloping, while Figure 3 (b) shows the case in which they are upward-sloping.

In the figures, each intersection of the reaction curves of the two countries represent a non-cooperative environmental policy equilibrium for each possible combination of instrument choices. Thus, for example, point E_{TQ} shows the equilibrium when country 1 chooses emission taxes and country 2 emission quotas.

6.2 Welfare Comparison

As already discussed in Section 4.1, in the quota-quota policy game, both countries tend to strengthen their environmental regulation compared with

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[20] In Case A, the iso-GHG-emissions curve has a slope of less than unity by virtue of Lemma 2.

the tax-tax policy game. Moreover, in view of Proposition 4, one may be tempted to conclude that both countries would be better off at the quota-quota policy game equilibrium E_{QQ} than at the tax-tax policy game equilibrium E_{TT}.

In general, however, this is not correct. The reason is that E_{QQ} does not always lie within the set of the tax profiles dominating E_{TT} for both countries. A possible case is depicted in Figure 3 (b). If the welfare contours going through point E_{TT} are given by w_1^T and w_2^T, then both countries would be better off at E_{TT} than at E_{QQ}. Note that from Proposition 9, although both t_1 and t_2 are higher at E_{QQ} than at E_{TT}, total world GHG emissions could be larger at E_{QQ} than at E_{TT}. If $e_1/e_2 < \zeta_2/(1-\zeta_1)$ holds and E_{QQ} is located below $T_1 z_W^T$ in Figure 2 (where E_{QQ} is not indicated), then world total GHG emissions are greater at E_{QQ} than at T_1 (i.e., E_{TT}).

Therefore, one may think it difficult to compare two equilibria, one or both of which are off the reaction curve, $R^{iT}(t_j)$, on the t_1-t_2 space. However, we can derive conditions that help us to make a welfare comparison among the possible equilibria. To derive the conditions, let us compare E_{QQ} with the equilibrium in which country i chooses emission taxes but country j chooses emission quotas. Movement from the latter to the former requires changes in the tax profile along country i's transformed reaction curve $R^{iQ}(t_j)$ (see Figures 3 (a) and (b)), because country j employs emission quotas and does not switch its policy. When country i switches to emission quotas, country j has an incentive to alter its emission quota so as to raise the price of domestic emission permits, or, effectively, the emission tax rate.

The associated effect on country i's welfare is given by:

$$
\begin{aligned}
&\frac{d\widehat{w}^{iQ}\left(\hat{z}^i\left(R^{iQ}(t_j),t_j\right),\hat{z}^j\left(R^{iQ}(t_j),t_j\right)\right)}{dt_j}\\
&= \frac{\partial\widehat{w}^{iQ}\left(\Gamma^i\left(\hat{z}^j\left(R^{iQ}(t_j),t_j\right)\right),\hat{z}^j\left(R^{iQ}(t_j),t_j\right)\right)}{\partial q_i}\frac{d\hat{z}^i\left(R^{iQ}(t_j),t_j\right)}{dt_j}\\
&+ \frac{\partial\widehat{w}^{iQ}\left(\Gamma^i\left(\hat{z}^j\left(R^{iQ}(t_j),t_j\right)\right),\hat{z}^j\left(R^{iQ}(t_j),t_j\right)\right)}{\partial q_j}\frac{d\hat{z}^j\left(R^{iQ}(t_j),t_j\right)}{dt_j}\\
&= -\left(f_i\widehat{r}_j^Q+\theta_i D'\right)\frac{d\hat{z}^j\left(R^{iQ}(t_j),t_j\right)}{dt_j} && (32)\\
&= -\left(f_i\widehat{r}_j^Q+\theta_i D'\right)\hat{z}_i^j\left\{\frac{dR^{iQ}(t_j)}{dt_j}-\frac{e_j(1-\zeta_j)}{e_i\zeta_i}\right\}, && (33)
\end{aligned}
$$

where use was made of the envelope theorem, (15), (29) and (30). Thus, country i is better off by switching to emission quotas given country j's choice of emission quotas if and only if country j's GHG emissions decrease with an increase in its emission tax rate along country i's transformed reaction curve (see (32)), or alternatively if and only if $dR^{iQ}(t_j)/dt_j < e_j(1-$

$\zeta_j)/e_i\zeta_i$ (see (33)). Ceteris pairibus, a country gains from a reduction of the other country's GHG emissions. (32) tells us that as long as country i optimally responds to country j's reaction to country i's switch, country j's GHG emissions decrease makes country i better off. If country i's transformed reaction curve, $R^{iQ}(t_j)$, is downward-sloping (i.e., $dR^{iQ}(t_j)/dt_j < 0$),[21] then country i's switch decreases t_i and increases t_j and hence country j's GHG emissions decrease. Thus, country i's welfare improves. If $R^{iQ}(t_j)$ is upward-sloping, on the other hand, both t_i and t_j increase. If t_i rises a lot relative to t_j (which arises when $dR^{iQ}(t_j)/dt_j$ is large), however, country i's switch could actually increase country j's GHG emissions,[22] which worsens country i's welfare.

Similarly, we obtain

$$\begin{aligned}
&\frac{d\widehat{w}^{jQ}\left(\hat{z}^i\left(R^{iQ}(t_j),t_j\right),\hat{z}^j\left(R^{iQ}(t_j),t_j\right)\right)}{dt_j}\\
=&\ -\left(f_j\widehat{r}_i^Q+\theta_j D'\right)\frac{d\hat{z}^i\left(R^{iQ}(t_j),t_j\right)}{dt_j}\\
=&\ -\left(f_j\widehat{r}_i^Q+\theta_j D'\right)\hat{z}_i^i\left\{\frac{dR^{iQ}(t_j)}{dt_j}-\frac{e_j\zeta_j}{e_i(1-\zeta_i)}\right\}.
\end{aligned}$$

Thus, country j is better off by country i's switch from emission taxes to emission quotas given country j's choice of emission quotas if and only if country i's GHG emissions decrease with an increase in country j's emission tax rate along country i's transformed reaction curve, or alternatively if and only if $dR^{iQ}(t_j)/dt_j > e_j\zeta_j/e_i(1-\zeta_i)$. If $R^{iQ}(t_j)$ is downward-sloping, then country i's switch makes country j worse off because t_i falls and t_j rises and hence country i's GHG emissions increase. If $R^{iQ}(t_j)$ is upward-sloping, on the other hand, both t_i and t_j increase. If t_i increases a lot relative to t_j, however, country i's switch could decrease country i's GHG emissions, which improves country j's welfare.

Let $E_{T_iQ_j}$ denote the equilibrium in which country i chooses emission taxes and country j emission quotas, and $E_{QQ} \succ_i E_{T_iQ_j}$ mean that country i's welfare is strictly higher at E_{QQ} than at $E_{T_iQ_j}$. Then the above discussion can be summed up in the following proposition.

Proposition 10 *1. $E_{QQ} \succ_i E_{T_iQ_j}$ if and only if country j's GHG emissions decrease with an increase in its emission tax rate along country i's transformed reaction curve (i.e., $dR^{iQ}(t_j)/dt_j < e_j(1-\zeta_j)/e_i\zeta_i$).*

2. $E_{QQ} \succ_j E_{T_iQ_j}$ if and only if country i's GHG emissions decrease with

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[21] Note that $dR^{iQ}(t_j)/dt_j < 0$ implies $dR^{iQ}(t_j)/dt_j < e_j(1-\zeta_j)/e_i\zeta_i$, because $e_j(1-\zeta_j)/e_i\zeta_i > 0$.

[22] Recall that the iso-GHG-emissions curve for each country is upward-sloping as in Figure 2.

an increase in country j's emission tax rate along country i's transformed reaction curve (i.e., $dR^{iQ}(t_j)/dt_j > e_j\zeta_j/e_i(1-\zeta_i)$*).*

The following two things should be noted. First, in Figure 3 (a), $dR^{iQ}(t_j)/dt_j < 0 < e_j(1-\zeta_j)/e_i\zeta_i$ holds. Thus, we obtain $E_{QQ} \succ_i E_{T_iQ_j}$ and $E_{T_iQ_j} \succ_j E_{QQ}$. In Figure 3 (b), however, what we can tell with respect to the slope of reaction curve, R^{iQ}, is just $dR^{iQ}(t_j)/dt_j > 0$. Thus, $E_{QQ} \succ_i E_{T_iQ_j}$ may not hold. $E_{T_iQ_j} \succ_j E_{QQ}$ may not hold, either. Second, in view of Proposition 4, we can claim that on $R^{iQ}(t_j)$, a higher t_j leads to the higher welfare of country i. Thus, $E_{Q_iT_j} \succ_i E_{TT}$ holds.

The above results are summarized in Figure 4. Noting $e_i(1-\zeta_i)/e_j\zeta_j > e_i\zeta_i/e_j(1-\zeta_j)$, we have four regions in the figure. We can easily confirm in the figure that the quota-quota policy game equilibrium E_{QQ} may not be the best for both countries.

6.3 Policy Instrument Choices

We are now ready to determine which combination of the environment regulation instruments emerges as a subgame perfect Nash equilibrium for our full game. Noting Figure 4, we can draw Figure 5 that illustrates nine regions to be examined. Appendix D shows that when both countries simultaneously choose a policy instrument, E_{QQ} arises in *Regions I, II, IV* and *V*; E_{QT} arises in *Regions VII* and *VIII*; E_{TQ} arises in *Regions III* and *VI*; and E_{TQ} and E_{QT} could arise in *Region IX*.

The above result is summarized in Figure 6. In *Region QQ*, a quota policy is the dominant strategy for both countries, so that E_{QQ} arises. In *Region QT (TQ)*, the choice of a quota policy dominates that of a tax policy for country 1 (country 2) but country 2 (country 1) prefers emission taxes when country 1 (country 2) chooses quotas, so that E_{QT} (E_{TQ}) arises. *Region U*, each country is better off by choosing a policy instrument different from the other's choice, so that there are at least three equilibria; two are pure-strategy equilibria, E_{TQ} and E_{QT}, and the last is a mixed-strategy equilibrium.[23]

The above result is summarized in the following proposition.

Proposition 11 *Both countries choose emission quotas if both* $dR^{1Q}(t_2)/dt_2 < e_2(1-\zeta_2)/e_1\zeta_1$ *and* $dR^{2Q}(t_1)/dt_1 < e_1(1-\zeta_1)/e_2\zeta_2$ *hold (i.e., in Region QQ in Figure 6). Countries 1 and 2, respectively, choose an emission tax and an emission quota if both* $dR^{1Q}(t_2)/dt_2 > e_2(1-\zeta_2)/e_1\zeta_1$ *and* $dR^{2Q}(t_1)/dt_1 < e_1(1-\zeta_1)/e_2\zeta_2$ *hold (i.e., in Region TQ), and vice versa if both* $dR^{1Q}(t_2)/dt_2 < e_2(1-\zeta_2)/e_1\zeta_1$ *and* $dR^{2Q}(t_1)/dt_1 > e_1(1-\zeta_1)/e_2\zeta_2$ *hold (i.e., in Region QT).*

---

[23] A mixed-strategy equilibrium is easily obtained. See Appendix D.

This proposition suggests a reason why employed policy instruments are different across countries. If both (transformed) reaction curves are downward-sloping, then both countries necessarily choose an emission quota. If both (transformed) reaction curves are upward-sloping, on the other hand, other combinations are also possible.

A decrease in e_1/e_2 expands *Region QT* and shrinks *Region TQ*. Moreover, given ζ_s, a decrease in ζ_1, or, an increase in ζ_2 also expands *Region QT* and shrinks *Region TQ*. Whereas a shrinkage in *Region TQ* implies that country 1 is more likely to choose emission quotas, an expansion of *Region QT* implies that country 2 is more likely to choose emission taxes.

Therefore, as the countries become more asymmetric, they are more likely to employ different environmental policies. In particular, a small e_1, or, a large e_2 implies that country 1 has better environmental technologies. Also, a small ζ_1 or, a large ζ_2 is likely to be the case when country 1 is relatively small and/or has a relatively small price elasticity of demand. Thus, a country with better environmental technologies, a smaller size, and a smaller price elasticity of demand is more likely to employ emission quotas, while a country with worse environmental technologies, a larger size, and a larger price elasticity of demand is more likely to employ emission taxes. The intuition behind this is as follows. When e_2 and/or ζ_2 are large, country 2's GHG emissions are large. Also carbon leakage caused by country 1's environmental regulation is large. By adopting emission quotas, country 1 can induce country 2 to strengthen the environmental regulation (recall Proposition 8) and mitigate GHG emissions and carbon leakage. Analogously, when e_1 and/or ζ_1 are small, country 1's GHG emissions and carbon leakage caused by country 2's environmental regulation are small. This implies that even if country 2 can induce country 1 to strengthen the environmental regulation by employing emission quotas, a decrease in the country 1's emission is relatively small. Thus, country 2 has less incentive to employ emission quotas, or, tougher environmental regulations.

We should also mention that since all equilibria are non-corporative, they may not achieve the first-best outcome from the welfare viewpoint. For example, suppose that both $dR^{1Q}(t_2)/dt_2 < e_2\zeta_2/e_1(1-\zeta_1)$ and $dR^{2Q}(t_1)/dt_1 < e_1\zeta_1/e_2(1-\zeta_2)$ hold. Then, E_{QQ} is realized as a subgame perfect Nash equilibrium. However, the best equilibrium among four equilibria is E_{QT} for country 1 and is E_{TQ} for country 2. Furthermore, even if both countries employ emission quotas, they can improve welfare by simultaneously lowering their quota levels from those at E_{QQ} (recall Proposition 6).

7 Conclusion

In this paper, we explored environmental policy choices in the presence of international carbon leakage caused by fuel price changes, explicitly taking into account international trade in fossil fuel. We considered a world consisting of two fuel-consuming countries emitting GHG and a fuel-producing country. The fuel-consuming countries non-cooperatively regulate GHG emissions through emission taxes or quotas. The two policy instruments are equivalent for each country if the other country's choice of policy instrument is given. However, the presence of the carbon-leakage effect affects each country's policy stance on global warming once the other country switches its policy instrument. That is, non-equivalence between emission taxes and quotas could arise. In particular, we pointed out that in the presence of carbon leakage, environmental quotas are a more stringent policy instrument than environmental taxes in the sense that environmental quotas strengthen environmental regulations in the other country.

Such strategic non-equivalence affects the subgame perfect equilibrium when the countries commit to either emission taxes or quotas before determining their specific level. We examine which combination of instruments emerges as a subgame perfect Nash equilibrium for our full game and obtain three pure-strategy equilibria: (i) both countries always choose emission quotas; (ii) one country always chooses emission quotas and, given this, the other chooses emission taxes; (iii) neither country has fixed preferences for policy instruments, but both want to choose the different instruments from the other's choice. This result sheds new light on the question of why adopted policy instruments could be different among countries.

As an illustration of the implications of the results obtained here, we may regard country 1 as North (developed countries with better environmental technologies) and country 2 as South, because developed countries such as Japan and Germany have been leading the R&D of carbon capture and storage (CCS) technologies. When only North introduces or tightens environmental regulations, there is a danger that world total GHG emissions increase, rather than decrease, thus aggravating global warming. This corresponds to the situation with the Kyoto Protocol, in which only Annex I Parties are legally obligated to decrease GHG emissions. What would be required is to call on South to cooperate with North in dealing with global warming. Thus, the Durban Platform, in which all major emitters are required to prepare some measures to control GHG emissions, is a step in the right direction. However, this step is not sufficient, because countries have non-corporatively chosen an emission regulation and its specific level. Our policy choice game captures this aspect. In particular, our result suggests a reason why South (particularly, large emitters with worse environmental technologies) tends to employ emission taxes, while North tends to adopt emission quotas. Adopting an emission quota in the presence of carbon leakage, North can induce South to strengthen the level of South's environmental regulation. On the other hand, since carbon leakage caused by South's environmental regulation is relatively small, South has less incentive to adopt a tough regulation, i.e., emission quotas. This may explain why

EU employs an emission quota, while India and China employ an emission tax.

We should mention that even if both countries take environmental regulations, a realized equilibrium under non-corporative choices does not lead to Pareto optimum. Thus, policy coordination should be secured. Moreover, in our analysis, North's environmental regulations worsen global warming only if environmental technologies are different between North and South. The technology gap can be reduced by technology transfer from North to South. Thus, technology transfer plays an important role in dealing with global warming.

The purpose of this paper was to present a simple, stylized model in order to focus on the international carbon leakage caused by changes in the fuel price. To do so, we assumed that the production of the non-tradable good alone is responsible for GHG emissions and that the fuel-producing country does not emit GHG. Although we conjecture that our insights are still valid in more generalized models, it would be worthwhile to examine the implications of our approach in those models. Another restrictive assumption is that emission coefficients are exogenous and country-specific parameters. Since the investment in CCS takes time and has been led by developed countries, this assumption may be justified to some extent. However, the choice of emission regulations could affect the investment behavior, and vice versa. The relationship between emission regulations and technological decisions is an interesting research topic to pursue, but it is beyond the scope of our analysis and is left for a future investigation.

Appendix

A. Proof of $\hat{z}_1^W + \hat{z}_2^W < 0$

This appendix proves Lemma 2. Equation (15) shows

$$\hat{z}_i^W = \Delta_r e_i \zeta_i \left\{ e_j \zeta_j - e_i (1 - \zeta_i) \right\},$$

which yields

$$\frac{1}{\Delta_r} \left(\hat{z}_1^W + \hat{z}_2^W \right) = 2 e_1 e_2 \zeta_1 \zeta_2 - e_1^2 \zeta_1 (1 - \zeta_1) - e_2^2 \zeta_2 (1 - \zeta_2).$$

Consider the right-hand side as a quadratic equation in e_1. Then, the associated determinant is equal to

$$\zeta_1^2 \zeta_2^2 e_2^2 - \zeta_1 \zeta_2 (1 - \zeta_1)(1 - \zeta_2) e_2^2 = e_2^2 \zeta_1 \zeta_2 (\zeta_1 + \zeta_2 - 1) < 0,$$

which implies that the given equation never becomes non-negative given $e_1 e_2 \neq 0$. This establishes

$$\hat{z}_1^W + \hat{z}_2^W < 0.$$

B. Proof of $\partial \hat{w}^{iT} / \partial t_j > 0$

In this appendix, we prove Proposition 4. By construction of the welfare function, one can derive

$$\begin{aligned} \frac{\partial \hat{w}^{iT}}{\partial t_j} &= \frac{\partial \tilde{w}^i}{\partial t_j} + \frac{\partial \tilde{w}^i}{\partial r} \hat{r}_j = \frac{\partial \tilde{w}^i}{\partial t_j} - \frac{\hat{r}_j}{\hat{r}_i} \frac{\partial \tilde{w}^i}{\partial t_i} \\ &= -\theta_i D' z_t^j - \frac{f_t^j}{f_t^i} (t_i - \theta_i D') z_t^i = -f_t^j \left\{ \theta_i D' e_j + (t_i - \theta_i D') e_i \right\} \\ &= -f_t^j \left\{ \theta_i D' e_j + e_i \left\{ f_i \left(\frac{\hat{r}_i}{\hat{z}_i^i} \right) + \theta_i D' \left(\frac{\hat{z}_i^j}{\hat{z}_i^i} \right) \right\} \right\}, \end{aligned}$$

or alternatively,

$$\begin{aligned} -\frac{\hat{z}_i^i}{f_t^j} \frac{\partial \hat{w}^{iT}}{\partial t_j} &= e_i f_i \hat{r}_i + e_j \theta_i D' \hat{z}_i^i + e_i \theta_i D' \hat{z}_i^j \\ &= e_i f_i (-e_i \zeta_i) + e_j \theta_i D' \times e_i^2 (1 - \zeta_i) f_r^i + e_i \theta_i D' \left(-e_i e_j \zeta_i f_r^j \right) \\ &= -e_i^2 f_i \zeta_i + e_i^2 e_j \theta_i D' (1 - \zeta_i) f_r^i - e_i^2 e_j \theta_j D' \zeta_i f_r^j. \end{aligned}$$

Thus,

$$\begin{aligned} -\frac{1}{e_i^2} \frac{\hat{z}_i^i}{f_t^j} \frac{\partial \hat{w}^{iT}}{\partial t_j} &= -f_i \zeta_i + \Delta_r e_j \theta_i D' (\zeta_i \zeta_j - \zeta_i (1 - \zeta_i)) \\ &= -f_i \zeta_i - \Delta_r e_j \theta_i D' \zeta_i \zeta_s < 0, \end{aligned}$$

which establishes

$$\frac{\partial \hat{w}^{iT}}{\partial t_j} > 0.$$

C. Proof of Unilateral Equivalence

To prove the unilateral equivalence between emission taxes and quotas, we must show that there is a one-to-one relationship for each fuel-consuming country between the emission tax rate and the emission quota given the other. Let us prove this first for the case in which the other country chooses emission taxes.

Given country j's emission tax rate t_j, let q_i denote the emission quota or GHG emissions by country i. The equilibrium condition requires:

$$q_i = e_i f^i(r, t_i), s(r) = \frac{q_i}{e_i} + z^j(r, t_i).$$

Solving the second equation for the fuel price and denoting the solution by $r^T(q_i, t_j)$, the latter satisfies:

$$\frac{\partial r^T(q_i, t_j)}{\partial q_i} = \frac{1}{e_i(s'(r) - e_j f_r^j)} > 0.$$

Insert this relation into the first equation and solve the latter for the equilibrium emission tax rate or emission permit price t_i. Let $t^{iT}(q_i, t_j)$ express the solution. It satisfies:

$$\frac{\partial t^{iT}(q_i, t_j)}{\partial q_i} = \frac{e_i f_t^i}{1 - e_i f_r^i r_q^T} < 0,$$

by virtue of (8). This establishes the result.

Next, consider the case in which the other country chooses emission quotas. Let q_j denote country j's emission quota. Then again the equilibrium requires:

$$q_k = e_k f^k(r, t_k), s(r) = \sum_k \frac{q_k}{e_k}$$

The equilibrium fuel price depends on the quota profile $\boldsymbol{q}$. We express this relation by $r^Q(\boldsymbol{q})$. It satisfies:

$$\frac{\partial \widehat{r}^Q(\boldsymbol{q})}{\partial q_i} = \frac{1}{e_i s'(r)} > 0.$$

Insert this into the first equation. Then the emission tax rate is determined by the quota profile, the relation of which we express by $\widehat{t}^i(\boldsymbol{q})$. It satisfies

$$\frac{\partial \widehat{t}^i(\boldsymbol{q})}{\partial q_i} = \frac{1 - e_i f_r^i \frac{\partial \widehat{r}^Q(\boldsymbol{q})}{\partial q_i}}{e_i f_t^i} < 0,$$

which establishes the result.

D. Subgame Perfect Nash Equilibrium

We first obtain Figure 6 by examining each region in Figure 5. In *Regions I, II, V* and *IV*, we have

$$E_{QQ} \succ_1 E_{TQ}, E_{QT} \succ_1 E_{TT}, \tag{D-1}$$

$$E_{QQ} \succ_2 E_{QT}, E_{TQ} \succ_2 E_{TT}. \tag{D-2}$$

(D-1) ((D-2)) means a quota policy is the dominant strategy for country 1 (2). Thus, a quota policy is the dominant strategy for both countries, so that E_{QQ} arises.

In *Regions III* and *VI*, since (D-2) holds, a quota policy is the dominant strategy for country 2. Thus, we only need to check which policy country 1 prefers when country 2 chooses quotas. Since $E_{TQ} \succ_1 E_{QQ}$, E_{TQ} arises. The choice of a quota policy dominates that of a tax policy for country 2 but country 1 prefers emission taxes when country 2 chooses quotas, so that E_{TQ} arises.

Similarly, in *Regions VII* and *VIII*, since (D-1) holds, a quota policy is the dominant strategy for country 1. Thus, we only need to check which policy country 2 prefers when country 1 chooses quotas. Since $E_{QT} \succ_2 E_{QQ}$, E_{QT} arises. The choice of a quota policy dominates that of a tax policy for country 1 but country 2 prefers emission taxes when country 1 chooses quotas, so that E_{QT} arises.

In *Region IX*, we have $E_{TQ} \succ_1 E_{QQ} \succ_1 E_{QT} \succ_1 E_{TT}$ and $E_{QT} \succ_2 E_{QQ} \succ_2 E_{TQ} \succ_2 E_{TT}$, which implies that each country is better off by choosing a policy instrument different from the other's choice. Thus, there are at least three equilibria; two are pure-strategy equilibria, E_{TQ} and E_{QT}, and the last is a mixed-strategy equilibrium.

Next we obtain a mixed-strategy equilibrium in *Region U* in Figure 6. Let ρ_j^T denote the probability that country j chooses emission taxes. Then country i is indifferent between taxes and quotas if and only if

$$\rho_j^T w^i_{Q_iT_j} + (1-\rho_j^T) w^i_{QQ} = \rho_j^T w^i_{TT} + (1-\rho_j^T) w^i_{T_iQ_j},$$

where $w^i_{T_iQ_j}$ for example represents country i's equilibrium welfare when country i chooses emission taxes and country j emission quotas. The above equation shows that the equilibrium probability ρ_j^T satisfies

$$\rho_j^T = \frac{w^i_{T_iQ_j} - w^i_{QQ}}{(w^i_{Q_iT_j} - w^i_{TT}) + (w^i_{T_iQ_j} - w^i_{QQ})}.$$

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Figure 1: Changes in emission taxes and world total GHG emissions

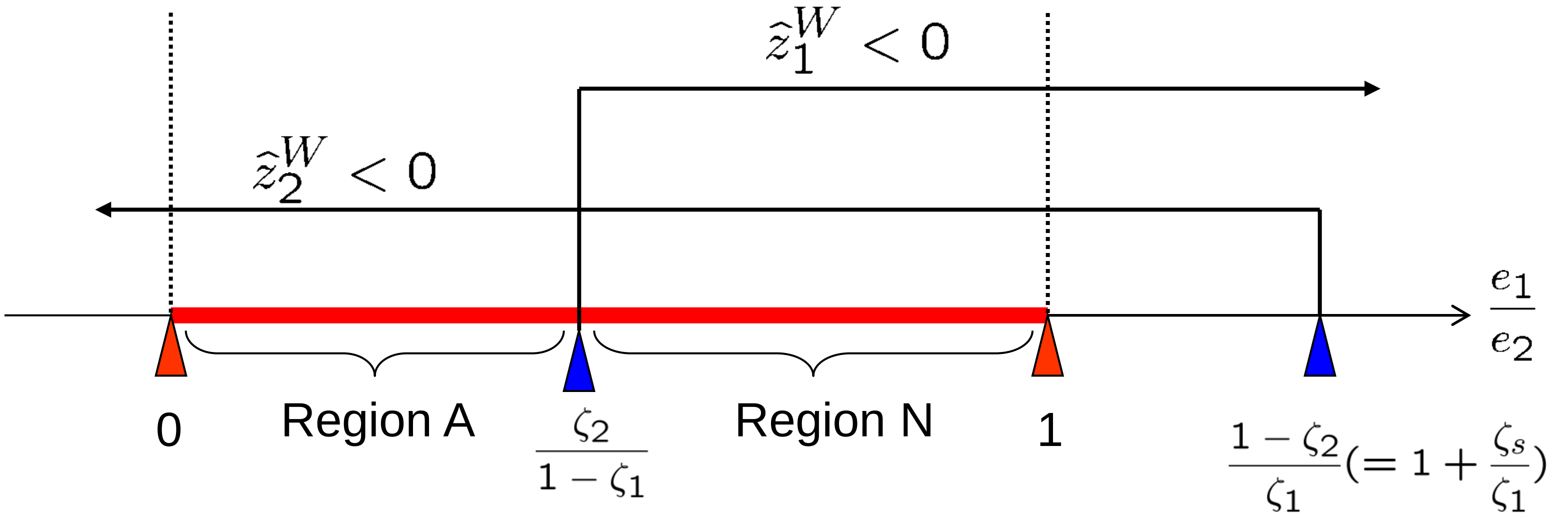

Figure 2: Jointly better tax profiles for the fuel-consuming countries

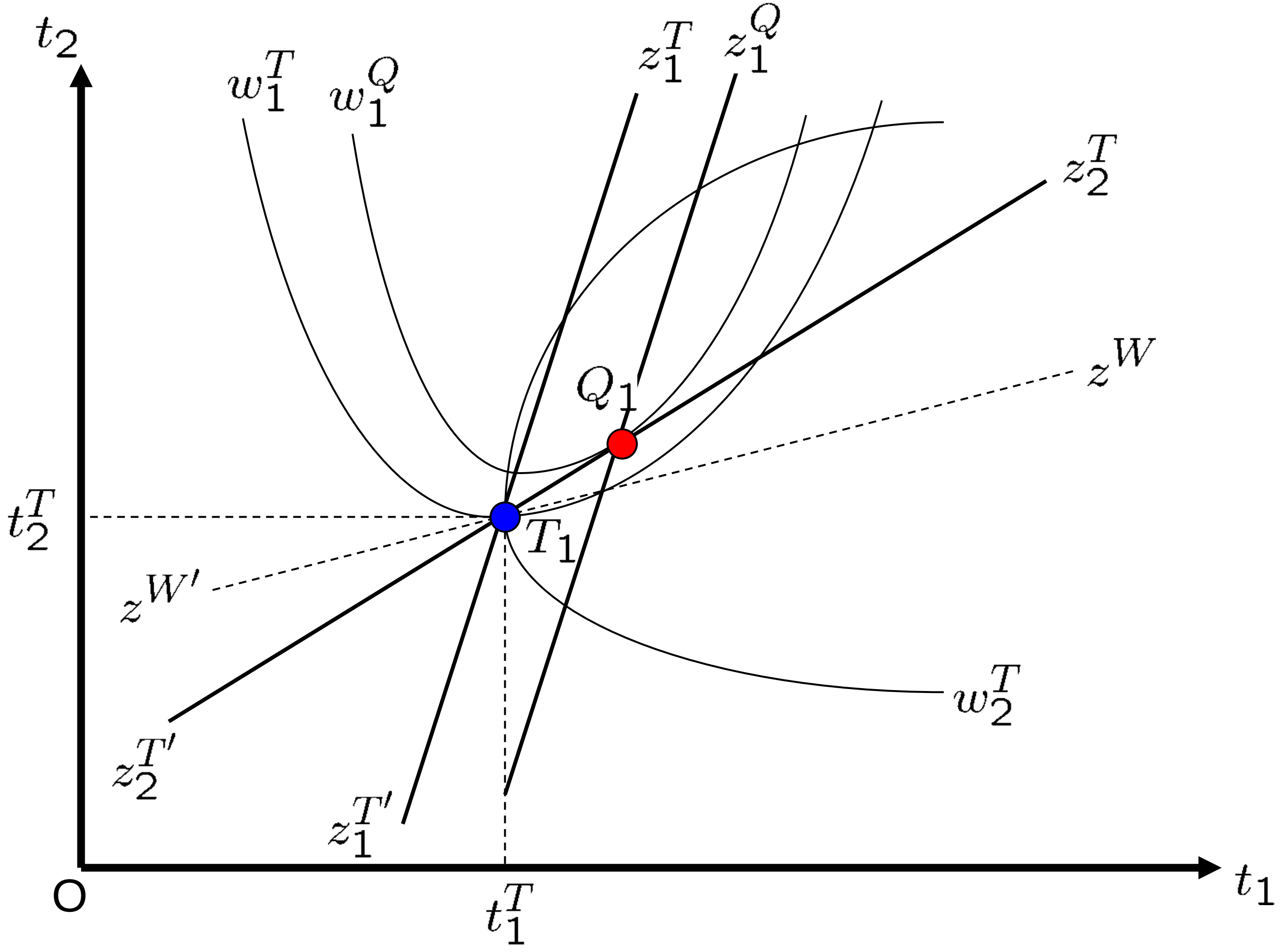

Figure 3 (a): Reaction curves: The case of strategic substitutes

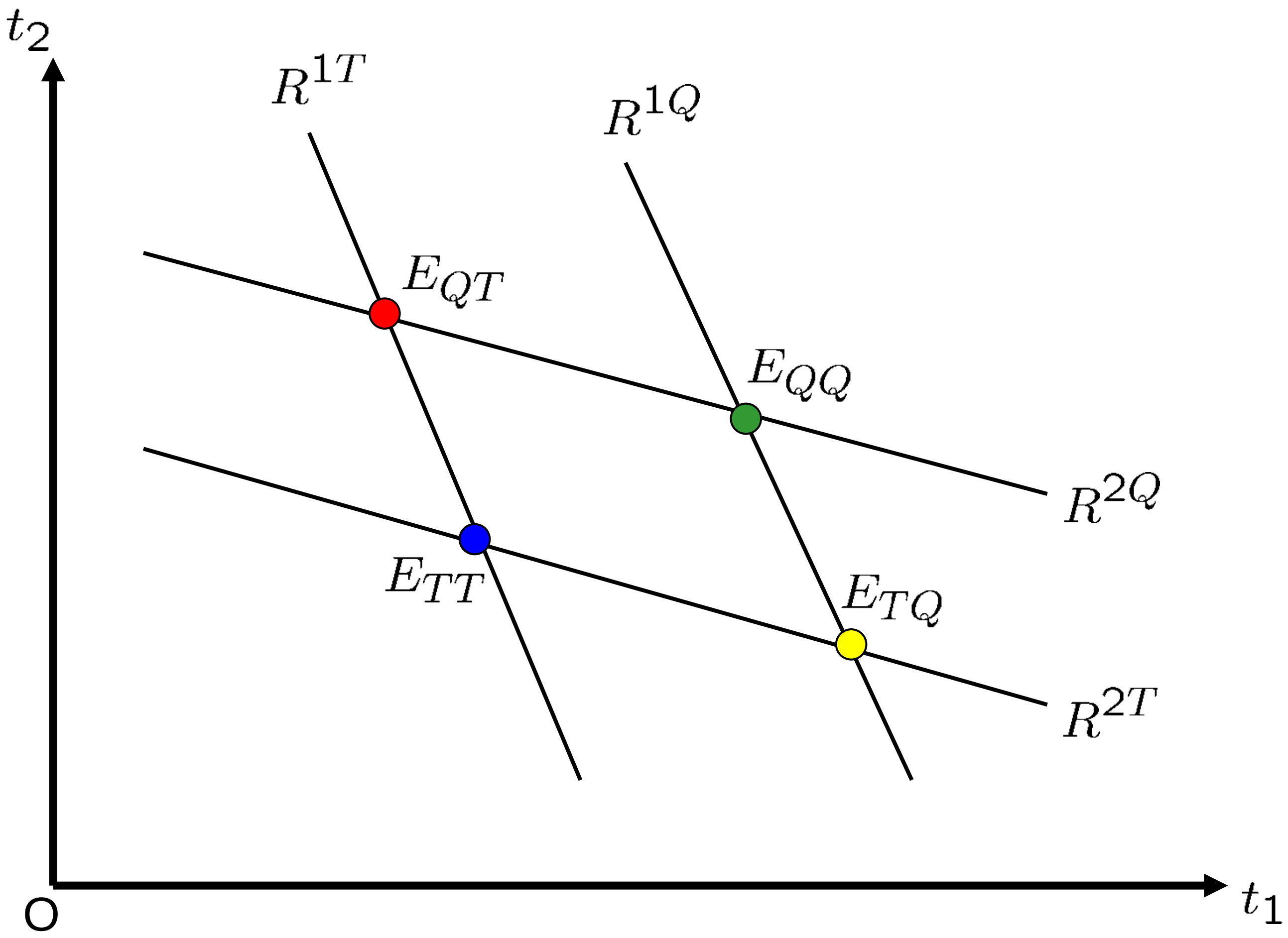

Figure 3 (b): Reaction curves: The case of strategic complements

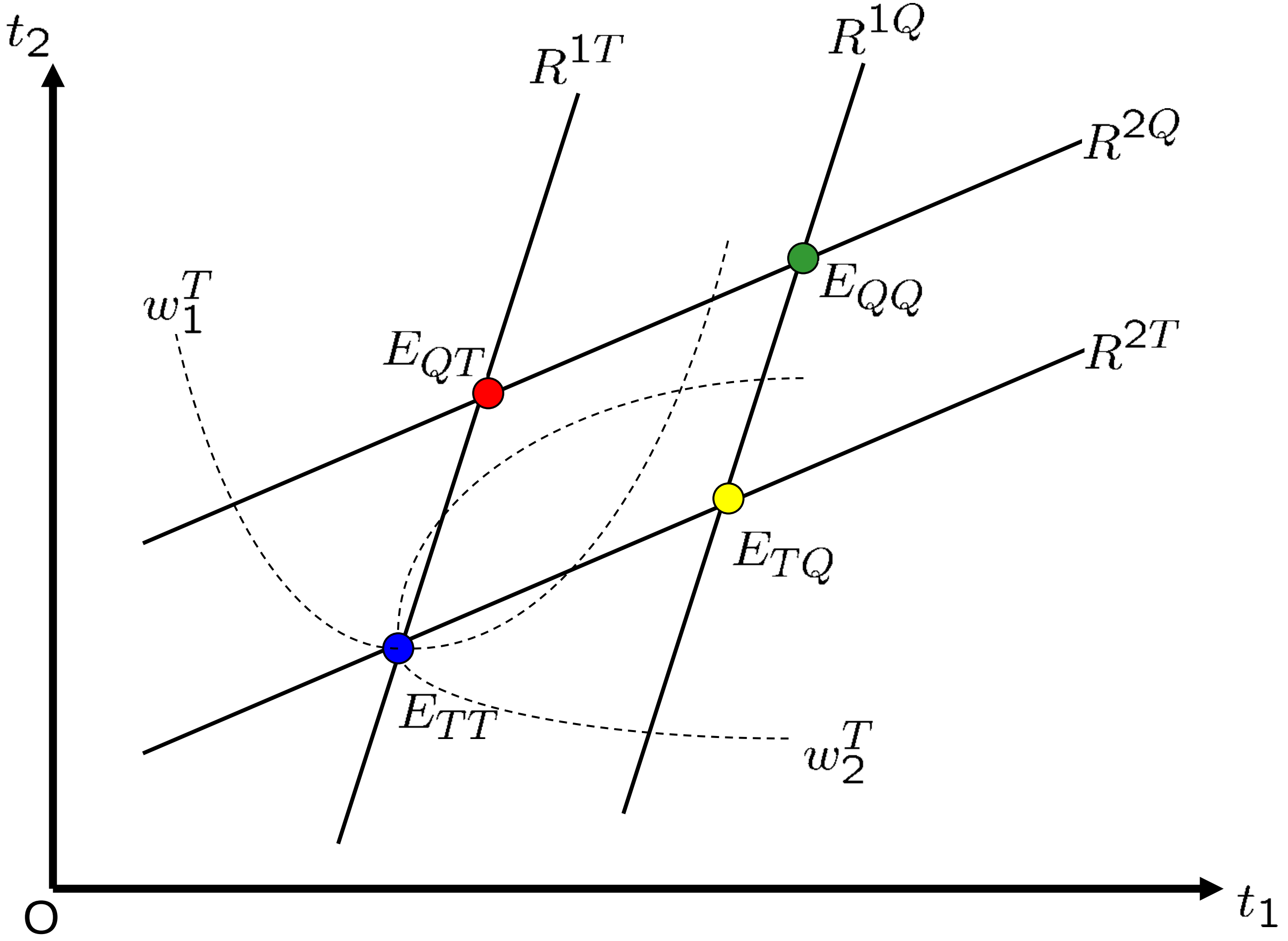

Figure 4: Welfare ranking of possible equilibria for country *i*

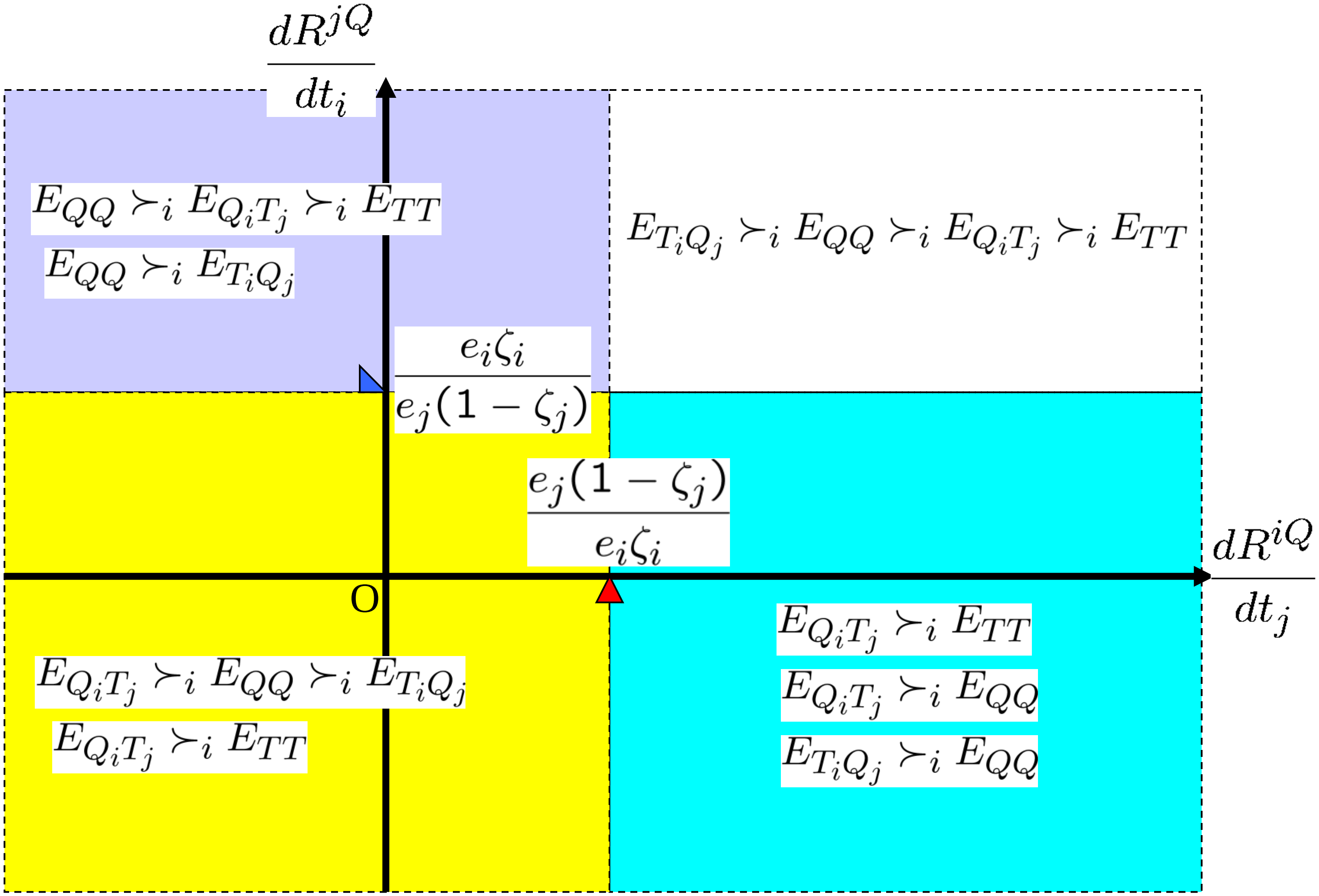

Figure 5: Nash equilibria

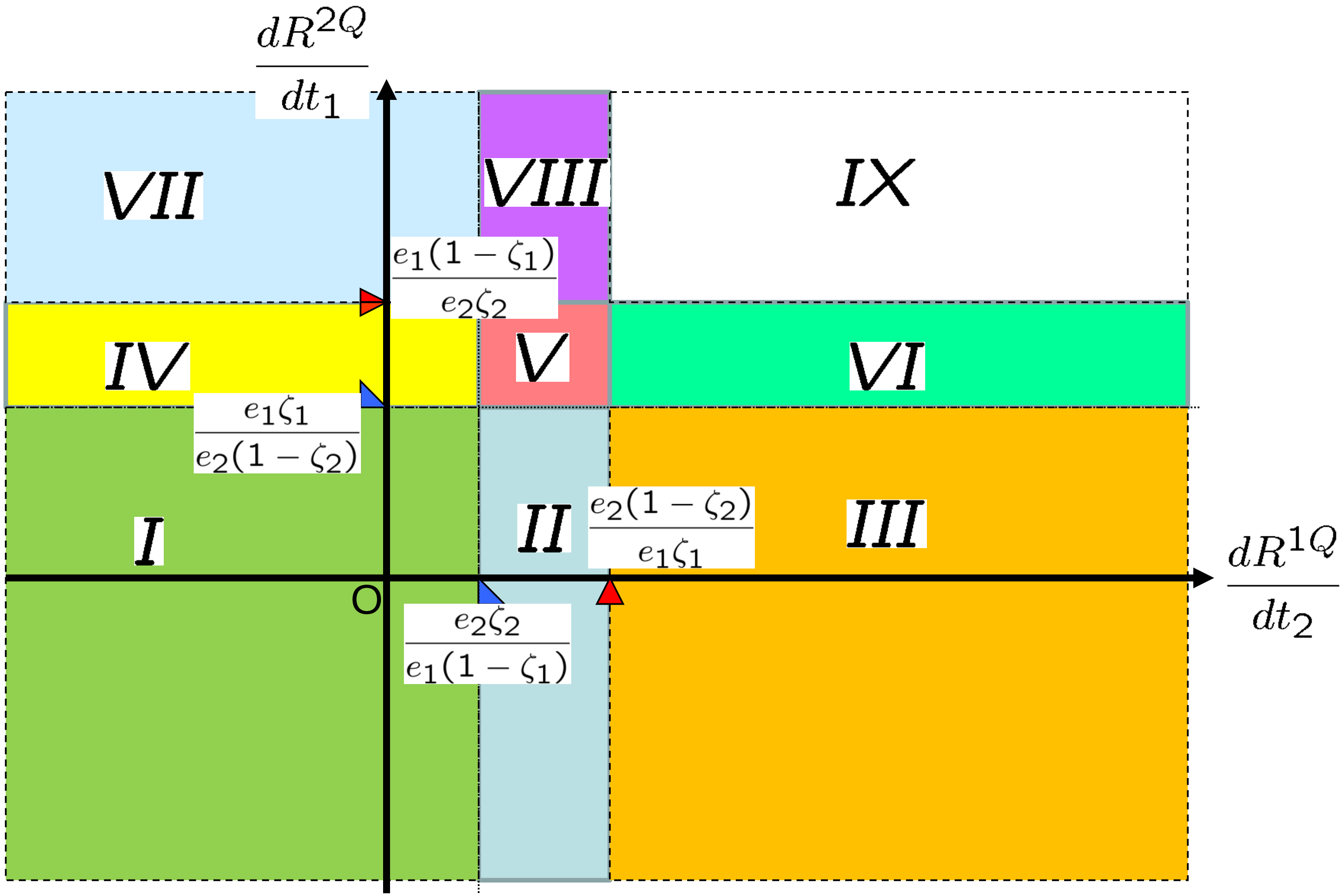

Figure 6: Possible equilibria