Greenhouse-Gas Emission Controls in an Open Economy*

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Abstract

To examine how greenhouse-gas emission controls affect country's industrial and trade structures, this paper presents an open economy model that has both Ricardian and Heckscher-Ohlin features. We specifically compare emission quotas, emission taxes and emission standards. The patterns of production and trade critically hinge on those policy tools. It is shown that a domestic emission control may lead to carbon leakage and may not reduce the world emission and that emission standards may work as a "hidden" production subsidy towards an emission-intensive industry.

Keywords: global warming, open economy, emission quota, emission tax, emission standard, carbon leakage

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1 Introduction

Global warming, which is caused by an increase in the level of greenhouse gases (GHGs) such as carbon dioxide, is expected to seriously affect economic activities through climate changes. The reduction of GHGs has been discussed in a number of international conventions. In particular, the third Conference of Parties to the United Nations Framework Convention on Climate Change (COP3) held in Kyoto at the end of 1997 was notable in the sense that a legally binding protocol, so-called Kyoto Protocol, was adopted.

In the protocol, the targets of reduction in GHGs in 38 developed countries were explicitly set. Annex I countries (which consist of the OECD members and the countries in the former USSR and eastern Europe) as a whole reduce emission 5.2 percent below 1990 levels between 2008 and 2012. For this, each country was required to commit to a specific target level.[1] An important question faced by these countries is, however, how these targets should be implemented.

The purpose of this paper is to theoretically examine GHG emission regulations in the framework of an open economy. We specifically investigate and compare emission quotas, emission taxes, and emission standards. There are some studies extensively discussing the issue such as Chichilnisky and Heal (2000b) and Xepapadeas (1997). However, to our knowledge, there exist no theoretical models rigorously dealing with the problem and elucidating the conditions for equivalence and non-equivalence among the alternative environmental policies in an open economy. We also explicitly consider the effects of those regulations on an open economy under free trade, which has not been analyzed in the previous literature.

In our model, two goods are produced using a primary factor, which is referred to as labor. GHGs are emitted during production. However, there exists a technology to abate GHG emissions. This technology requires labor as an input. Thus, our model has a Ricardian feature without any GHG emission regulations. The introduction of the GHG emission regulations, however, results in a two-factor Heckscher-Ohlin (HO) type model where the output of each good can be written as a function of labor input and the amount of GHG emissions.[2] Specifically, we consider a situation where only domestic country introduces emission regulations in the two-country model.

The HO type of model structure where one of the factors is environmental resources has been adopted in a series of studies of trade and environment by Chichilnisky, Copeland and Taylor. However, our focus is different from theirs. For example, Chichilnisky (1994) discusses how the system of property rights over environmental resources affects their overuse. In her model, the North-South trade and the overuse of environmental resources arise because of the

[1] For example, the targets of EU, US, Japan, Russia and Australia are, respectively, -8%, -7%, -6%, 0% and +8%. However, the US has withdrawn from the protocol.

[2] Introducing emission taxes into a standard HO framework, Takeda (2001) extends our model to a 2-good, 3-factor model. His focus is, however, on carbon leakages across industries, which is not examined in the present paper.

difference in property rights between the North and the South. Copeland and Taylor (1994, 1995) analyze linkages among national income, pollution, and international trade between North and South. Copeland and Taylor (2000) explicitly focuses on the relationship between global warming and international trade. Copeland and Taylor (1994) and Copeland and Taylor (1995, 2000), respectively, deal with emission taxes and emission quotas (or emission permits). In their studies, those policies are already imposed in autarky, which is in contrast with the present study. Moreover, factor price equalization and/or income effects play crucial roles to derive their main conclusions.

Three important results are as follows. First, the government may not be able to replicate the free-trade equilibrium under an emission quota with the equivalent emission tax.[3] The equivalence between emission quota and emission tax could break down, because the emission level is endogenously determined under emission taxes.

Second, when an emission quota is replaced by the equivalent emission standards, only complete specialization in the emission-intensive industry is possible at the resulting equilibrium. In the case of emission standards, once firms adopt technologies meeting the standard, they do not have to incur any additional costs. Therefore, the replacement basically changes the model structure from a HO type to a Ricardian one and hence the economy is led to complete specialization.

Third, a domestic emission control lowers the domestic emission but may raise the world emission. The domestic control could affect the foreign production pattern as well as the domestic one. As a result, the increase in the foreign emission may be greater than the decrease in the domestic emission. That is, the carbon leakage could occur.[4]

The rest of the paper is organized as follows. In section 2, we first show that when the abatement activity is formulated as further inputs of labor, the economy can be modeled as a standard two-good, two-factor HO model where the two factors are labor and environmental resources. The economic effects of emission controls in the form of emission quotas are clarified when the economy is a small open economy (SOE). Section 3 explores the effects of policy switches from emission quota to other equivalent policies such as emission taxes and emission standards in a SOE. Section 4 extends the analysis to a two-country model where only domestic country adopts emission regulations. Section 5 concludes the paper.

[3] This possibility is also pointed out in Chichilnisky and Heal (2000b).

[4] In general, carbon leakage arises through several routes. The first one is through the change in a country's industrial structure as in Copeland and Taylor (2000) as well as the present study. That is, when a country imposes environmental protection, the comparative advantage of the pollution-intensive industry shifts towards abroad. The second is through the relocation of plants, particularly those in the pollution-intensive industries, as discussed in Markusen et al. (1993, 1995) and Ulph and Valentini (2001). And the last is through a change in the fuel price as in Ishikawa and Kiyono (2000). However, the studies listed here assume imperfect competition among firms. See also Hoel (2000).

2 Production and Trade Structures with Emission Quotas

2.1 The Basic Model: A Small-Open-Economy Model

We consider a SOE facing free trade in goods. There are two goods (goods 1 and 2) which are produced using a single factor (labor) with a constant-returns-to-scale technology in competitive markets. The labor coefficient of good i ($i = 1, 2$) is given by a_i. The endowment of labor is given by L. Full employment is assumed.

Production of one unit of good i ($i = 1, 2$) emits e_i units of GHG. GHG reduces economic welfare, but does not generate production externalities.[5] While GHG is often discussed as a joint output in the previous literature,[6] it is convenient to describe the output of good i ($i = 1, 2$) as a function of labor input, L_i, and the amount of GHG emitted during production, Z_i:[7]

$$X_i = F^i(L_i, Z_i), \quad i = 1, 2, \tag{1}$$

where F^i is concave, continuously differentiable, and linearly homogeneous. One should note that here labor includes inputs for emission abatement behind technical substitution between labor and emission expressed by (1). Thus although a firm can reduce labor input by increasing GHG emission, this substitution has the limit which is given by $(\bar{a}_i, \bar{e}_i)$. That is, $\bar{a}_i$ is the minimum amount of labor input while $\bar{e}_i$ is the maximum amount of GHG emission for one unit of good i production.

This can be illustrated using a unit isoquant (see Figure 1). The smooth substitution between labor input and GHG emission is possible only in the region above $\bar{a}_i$. It is obvious that firms will use $\bar{a}_i$ units of labor to produce one unit of good i without any emission regulation.

We let good 2 be the numeraire and assume that the world relative price of good 1, $p^W (\equiv p_1^W / p_2^W)$, is exogenously given. Without any emission regulation, the production structure is that of the Ricardian model. Thus, the economy specializes in good 1 under free trade if

$$\frac{\bar{a}_1}{\bar{a}_2} < p^W. \tag{2}$$

In the following, we assume (2) and examine various kinds of emission regulations.

The social utility function is assumed to be separable between the commodity consumption and the damages from GHG emissions, i.e.,

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[5] The previous literature such as Copeland (1996) and Copeland and Taylor (1994, 1995, 2000) also assumes that emissions harm consumers, but do not generate production externalities.

[6] See Xepapadeas (1997) for example.

[7] The formulation here follows the idea proposed by Meade (1952) that the emission permits are treated as "unpaid" factors.

$$U = U(u(X_1, X_2), \Omega),$$

where $u(\cdot)$ is the subutility of commodity consumption and Ω is the world emission level. $u(\cdot)$ is homothetic and satisfies the standard conditions for well-behaved utility functions. $U(\cdot)$ is strictly increasing in u but strictly decreasing in Ω, continuously differentiable and strictly concave. Under these assumptions, the changes in GHG emissions do not affect the relative commodity demand as far as the relative commodity price is fixed. That is, the effects of all environmental damages are captured as the change in the real income. We should note that a SOE can affect neither the world prices nor the global environmental quality.[8]

2.2 Emission Quotas

As a benchmark of emission regulation, we first consider emission quotas.[9] The government sets an aggregate level of domestic GHG emissions which is denoted by Z. To implement the emission level, the government issues Z units of the tradeable emission permit. The permit can be traded freely within the economy and the price of the permit is denoted by r.

Once the permits have been issued, the economy behaves like a two-good, two-factor HO model which is described for the incomplete specialization case by the following:

$$c_1(r, w) = p^W, \tag{3}$$

$$c_2(r, w) = 1, \tag{4}$$

$$\sum_i a_i(r, w) X_i = L, \tag{5}$$

$$\sum_i e_i(r, w) X_i = Z, \tag{6}$$

where w is the wage rate and $c_i(r, w)$ $(i = 1, 2)$ is the unit cost function of good i. If $c_1(r, w) > p^W$ (resp. $c_2(r, w) > 1$), then the economy completely specializes in good 2 (resp. good 1). (5) shows the full employment of labor. In the HO model, both factors are assumed to be fully employed, but inequality could hold in (6). If this is the case, the permit price becomes zero.

The unit cost curve of good i is illustrated in Figure 2. Since the substitution between labor input and GHG emission is not always possible as is shown in Figure 1, the unit cost

[8] However, as part of the global agreements to lower emissions that were mentioned in the introduction, a SOE may still take measures to reduce emission.

[9] For various issues related to tradable emission markets, see the papers in Chichilnisky and Heal (2000a).

curve has a segment portion, $L_i L_i'$. The slope of $L_i L_i'$ is equal to $\bar{e}_i/\bar{a}_i(\equiv \bar{z}_i)$. For the following analysis, we define emission intensity:

$$z_i(r,w) \equiv \frac{e_i(r,w)}{a_i(r,w)} = \frac{Z_i(r,w)}{L_i(r,w)} \tag{7}$$

and assume that good 1 is always more emission-intensive relative to good 2.[10] That is, $z_1(r,w) > z_2(r,w)$ holds for any (r,w). Using Shepherd's lemma, the slope of the unit cost curve of good i equals $z_i(r,w)$.

We now examine free trade equilibria both with and without emission quota with the aid of Figure 3. Without any emission regulation, the production possibility frontier (PPF) is given by $L_1^0 L_2^0$, the slope of which is $\bar{a}_1/\bar{a}_2$. With (2), the economy completely specializes in good 1 and its output is $L/\bar{a}_1$. The production and consumption points are, respectively, given by L_1^0 and C which is located on the world-relative-price line, $p'p'$, going through L_1^0. We can easily verify that when $\bar{z}_1 > \bar{z}_2$, the following lemma, which is useful for the rest of the analysis, holds.[11]

Lemma 1. *The emission increases as the production of good 1 (the more emission-intensive good) rises and that of good 2 (the less emission-intensive one) falls.*

We should note that this lemma holds even in the presence of substitution between labor and GHG emissions as long as the factor intensity reversals are absent. Moreover, this lemma implies that the emission in this economy increases by shifting from autarky to free trade.

When a certain level of emission quota is introduced, the production structure becomes just like a HO model and hence a part of the PPF becomes strictly concave to the origin. In Figure 3, the PPF is given by $FQQ'L_2^0$. The PPF has a segment part $Q'L_2^0$, because the substitution between labor and emission is not possible when a_i is below $\bar{a}_i$.[12] The production point shifts from L_1^0 to Q where the world-relative-price line, pp, is tangent to the PPF. This shift can be decomposed into the following two effects.

The first is the introduction of an emission quota without substitution between labor input and GHG emission. We call this effect the impact effect. Without the substitution, the PPF is $Z_1^0 Q' L_2^0$ which is defined by (5) with $a_i = \bar{a}_i$ (i.e., $L_1^0 L_2^0$) and (6) with $e_i = \bar{e}_i$ (i.e., $Z_1^0 Z_2^0$). Because $z_1(r,w) > z_2(r,w)$, $Z_1^0 Z_2^0$ cuts $L_1^0 L_2^0$ from above. The impact effect corresponds to the shift from L_1^0 to Q' where the world-relative price line is tangent to $Z_1^0 Q' L_2^0$.

The second is the substitution effect. The emission quota affects both permit price and wage and hence the substitution between labor input and emission arises. With the sub-

[10] The case in which good 2 is more emission-intensive is not very interesting to analyze, because emission controls do not affect the production and trade patterns. That is, the economy remains to completely specialize in good 1.

[11] When the output of good 2 falls by one unit, that of good 1 rises by $\bar{a}_2/\bar{a}_1$. Thus, the emission from the good-2 sector decreases by $\bar{e}_2$ unit, whereas that from the good-1 sector increases by $(\bar{a}_2/\bar{a}_1)\bar{e}_1$.

[12] Here we assume that the emission intensity of good i is less than $\bar{e}_i/\bar{a}_i$ with emission quotas. For simplicity, we impose this assumption in the rest of our analysis.

stitution, even when the emission quota is the same at the initial level, the emission quota constraint becomes less binding. That is, the decreases in the emission coefficients in both sectors shift the emission quota constraint from the initial curve, $Z_1^0 Z_2^0$, outward to the new one, $Z_1 Z_2$. On the other hand, the substitution between labor and emission through abatement activities increases the labor coefficients, which leads to the inward shift of the labor endowment constraint from $L_1^0 L_2^0$ to $L_1 L_2$.[13] The new equilibrium under the emission quota is represented by point Q along the new PPF. The substitution effect corresponds to the shift from Q' to Q.[14]

The following should be remarked. In our model, the Rybczynski line associated with changes in the number of emission permit is given by $L_1^0 L_1 Q L_2 O$.[15] Thus, when the level of emission quota is high, the economy remains completely specialized in good 1, that is, the economy is between $L_1^0 L_1$. As the quota becomes tighter, the economy becomes diversified. In this case, $Z_1 Z_2$ shifts in parallel from L_1 to L_2 and the production is determined at the intersection between $Z_1 Z_2$ (which is shifting) and $L_1 L_2$ (which is fixed). When the quota level becomes low enough, the economy completely specializes in good 2.

With the aid of Figure 4, we examine the effects of emission quota on the permit price, wage rate, GDP, and specialization patterns. In the figure, $L_i C_i$ $(i = 1, 2)$ is the unit cost curve of good i (i.e., (3) and (4)). Since $z_1(r, w) > z_2(r, w)$ for any (r, w), the unit cost curve of good 1 cuts that of good 2 from above. The factor price frontier (FPF) is given by $L_1 Q C_2$.

Without any emission regulation, $r = 0$. Thus, the equilibrium is given by L_1. The wage rate of industry 1 which is indicated by L_1 is higher than that of industry 2 indicated by L_2 and hence the economy completely specializes in good 1. An emission quota shifts the production point from L_1 to Q if the economy is diversified and to the point on the FPF (i.e., $L_1 Q C_2$) where its slope is equal to Z/L if the economy completely specializes. The economy is diversified with $z_2(r_Q, w_Q) < Z/L < z_1(r_Q, w_Q)$. The economy completely specializes in good 1 if $Z/L \geq z_1(r_Q, w_Q)$ and good 2 if $Z/L \leq z_2(r_Q, w_Q)$.[16]

The per capita GDP, which is given by $y = w + (Z/L)r$, can be measured by the intercept of the line that has the slope Z/L and goes through the equilibrium point. It can easily be verified that as the level of emission quota lowers, the equilibrium point shifts down along the FPF, $L_1 Q C_2$, which corresponds to a shift of the production point on the Rybczynski line, $L_1^0 L_1 Q L_2 O$, in Figure 3. We should note that a lower GDP level generated by a lower quota level does not necessarily imply lower economic welfare, because the emission level is also lower.

In Figure 3, point Q happens to be located on OC which is a ray from the origin. Since

[13] $Z_1^0 Z_2^0$ and $Z_1 Z_2$ are usually not parallel. $L_1^0 L_2^0$ and $L_1 L_2$ are usually not parallel, either.

[14] If the substitution between labor and emission is not restricted at all as in the standard HO model, Q' is located inside the PPF.

[15] If the substitution between labor input and GHG emission is not allowed at all, the Rybczynski line is given by $L_1^0 Q' L_2^0 O$.

[16] Q' in Figure 3 corresponds to Q' in Figure 4.

the social utility function is homothetic with respect to the commodity consumption, Q is also the consumption point. If the level of emission quota becomes tighter, therefore, the trade pattern is reversed.

The above analysis is summarized in the following proposition.

Proposition 1. *Suppose that a SOE specializing in the more emission-intensive good 1 introduces an emission quota under free trade. The SOE remains completely specialized in good 1 if the quota level is high. If the level is low, however, the SOE is diversified or completely specializes in good 2. With the homothetic social utility function, as the quota level falls, the exports of good 1 decrease and the trade pattern is eventually reversed. The lower the quota level is, the lower the GDP level.*

We assume that the emission permit is freely traded only within the domestic economy. However, it is not difficult to incorporate international trade in the emission permit into our SOE model. Suppose that Z units of the emission permit are given to the SOE. We let r^D denote the permit price when the permit is traded within the economy alone and r^W denote the world price of the permit. Obviously, the economy exports the permit if $r^D < r^W$ and imports it if $r^D > r^W$. Moreover, the economy completely specializes in good 1 with $r^W < r_Q$ and in good 2 with $r^W > r_Q$ (see Figure 4). If $r^W = r_Q$, the production and trade pattern cannot uniquely be determined. As long as $r^W \neq r_Q$, the opening of international trade in the emission permit raises GDP.

3 Switch from Emission Quota to Other Policies

3.1 Quota-Equivalent Emission Taxes

We next examine a specific emission tax (i.e., a tax per unit of GHG emission). The government sets the emission tax rate, r, to reduce GHG emission. That is, in equations (3) - (6), Z is now endogenously determined and r is exogenously given. The effect of a specific emission tax can be seen with the aid of Figure 4. Once the tax rate is determined, the wage rate is also determined by the FPF, L_1QC_2. If $r = r_T$, for example, then the wage rate is determined at T (i.e., $w = w_T$) and specializes in good 1. The per capita GHG emission is given by the slope of the FPF at T. The economy completely specializes in good 1 if $0 < r < r_Q$ and good 2 if $r > r_Q$.

It is obvious that the complete specialization equilibrium under emission quota can be attained by setting the permit price equal to the emission tax. We call this emission tax rate the quota-equivalent emission tax. However, the quota-equivalent emission tax alone cannot lead to the incomplete specialization equilibrium under an emission quota, which is shown by Q in Figure 4. When the government sets $r = r_Q$, the wage rate becomes identical. However, GHG emission may be different between the emission tax and quota. This is because the emission tax alone cannot uniquely determine the outputs of goods 1 and 2 under free trade and hence the amount of GHG emissions. In terms of equations, there are three endogenous variables (i.e., X_1, X_2, and Z) and two equations, (5) and (6).[17] Therefore, these three endogenous variables are indeterminate.

We thus obtain the following proposition.

Proposition 2. *If a SOE completely specializes in the presence of a domestic emission quota, the equilibrium can be attained with the emission tax by setting the permit price equal to the emission tax rate, i.e., the quota-equivalent emission tax. If the SOE is diversified under an emission quota, however, the equilibrium may not be attained by the quota-equivalent emission tax alone.*

The result of this inequivalence hinges on the initial condition that the economy is initially diversified given the total volume of the emission permits. As in a diversified SOE subject to the standard HO model, the factor prices are then independent of the resource endowments including the emission permits, which govern the output configurations. Thus, there could exist various supply-side equilibria including diversification and complete specialization. The inequivalence is still valid in the higher-dimensional model insofar as the emission quota is binding and the equilibrium factor prices are (locally) insensitive to the resource endowments. However, when there are some factors being specific to some industries as in the short run analysis like Neary (1978), our result may not hold.

We next establish the following proposition:

Proposition 3. *A diversified equilibrium under the quota-equivalent emission tax is unstable for a SOE, and the economy may specialize in either good.*

Using Figure 4, we can confirm this result. Suppose that the economy is initially diversified at Q and then the world relative price of good 1 rises. The unit cost curve of good 1 shifts outward (from L_1C_1 to $L_1'C_1'$). Given $r = r_Q$, the good-1 sector is now willing to pay a higher wage than the good-2 sector. This leads the economy to completely specialize in good 1 with a rise in the per-capita GHG emission. Once the economy specializes in good 1, however, the production equilibrium is now locally stable against small changes in the world prices. If the world relative price of good 1 falls, on the other hand, the economy completely specializes in good 2 and the per capita GHG emission falls.

Thus, even if the quota-equivalent emission tax can support the incomplete specialization equilibrium with an emission quota, a small change in the world price may lead to drastic changes in GHG emission as well as the production and trade structures when emission taxes are used.[18] This is again due to the feature that the level of GHG emissions are endogenously

[17] When the SOE is diversified with an emission tax, w is determined by (3) or (4). Thus, either (3) or (4) is redundant.

[18] This could also arise when the economy introduces some trade taxes/subsidies. For example, when good 1 is exported, an export subsidy shifts the unit cost curve of good 1 outward.

determined in the case of emission taxes in contrast to the case of emission quotas.

We should note that as long as the economy is a SOE, the results obtained in the case of emission taxes directly apply to the case with *international* trade in the emission permit. This implies that creation of international emissions trading market may make the trade and industrial structure of a SOE very volatile against change in the world economic environment.

3.2 Quota-Equivalent Emission Standards

We investigate emission standard under which the government sets the level of e_i $(i = 1, 2)$. This is actually equivalent to set the level of z_i (i.e., the emission intensity), or, to choose a specific technology. Once z_i is determined, the substitution between labor input and GHG emission becomes essentially impossible. This is because once the government replaces emission quotas with the quota-equivalent emission standards, the industries do not have to pay emission permit prices, i.e., the costs for GHG emission, and thus they try to minimize the abatement activities as much as possible. The result is that each industry just meets the government emission standard requirement.

We first consider the case where the economy is diversified with emission quota. Although there are many possible emission standard levels to choose, we focus our attention on the emission standard which can replicate the emission-quota equilibrium in the sense of achieving the same volume of GHG per output in each sector. We call such an emission standard the quota-equivalent emission standard.[19]

Now we consider the effects of replacing the emission quota with the quota-equivalent emission standard by using Figure 4. Noting that z_i is equal to the slope of the unit cost curve of good i, the FPF with the quota-equivalent emission standard is formed by the tangent lines to the unit cost curves. As a result, the unit cost curve with the emission standard is given by E_iQE_i' for the good-i industry.

Since the emission permit is useless with the quota-equivalent emission standards, the permit price becomes zero. Thus, the equilibrium is located on the vertical axis. Since the good-1 sector with the higher emission intensity can save the expenses for the emission permit more, it is willing to pay the higher wage OE_1 than the maximum wage OE_2 that the good-2 sector is willing to pay. That is, the quota-equivalent emission standards work as hidden production subsidies to the emission-intensive industry.[20] Thus, the economy is driven to complete specialization in the emission-intensive good-1 sector. In Figure 3, the production equilibrium is now given by point L_1 with the larger GHG emission than at the emission quota equilibrium.

[19] The quota-equivalent emission standard requires different rates of allowable emission rates per unit of output between the sectors. In this sense, this standard must be distinguished in general from the simple uniform emission standard which requires each and every industry to emit the same volume of GHG emission per unit of, say, fossil fuel input.

[20] See also Kiyono and Okuno-Fujiwara (2003).

This result basically stems from the difference in how firms incur the costs of emission controls. In the case of emission standards, once firms adopt technologies meeting the standard, they do not have to incur any additional costs. In the case of emission quotas (resp. taxes), however, not only do firms adjust their technologies but they purchase the emission permit (resp. pay tax).

Although the incomplete specialization equilibrium with emission quota cannot be attained by the emission standard, any complete specialization equilibrium can be attained. If the equilibrium is at T under an emission quota in Figure 4, for instance, it can be attained by setting $z_1 = z_1(r_T, w_T)$ and $z_2 \leq z_1(r_T, w_T)$. It should be noted, however, that the wage rate is different between two policy measures, because firms do not have to pay emission permit price with emission standard.

To summarize the result,

Proposition 4. *If a SOE completely specializes under a domestic emission quota, the equilibrium can be attained by the quota-equivalent emission standard. If the SOE is diversified under an emission quota, however, the quota-equivalent emission standard leads the economy to completely specialize in the emission-intensive industry and increases the GHG emission level.*

4 A Two-country Model

4.1 Emission Quotas

In the previous sections, the relative price is assumed to be constant. In this section, we consider a two-country (domestic and foreign countries) model where only domestic country introduces GHG emission regulations. In the following, the foreign valuables and parameters are distinguished by asterisk.

We assume

$$A \equiv \frac{\bar{a}_1}{\bar{a}_2} < \frac{\bar{a}_1^*}{\bar{a}_2^*} \equiv A^*, \tag{8}$$

that is, the domestic country has the comparative advantage in good 1 without any emission regulation; and $\bar{e}_1^*/\bar{a}_1^* > \bar{e}_2^*/\bar{a}_2^*$, that is, good 1 is relatively more emission-intensive than good 2. We should note that $\bar{e}_i = \bar{e}_i^*$ $(i = 1, 2)$ does not usually hold. We also assume identical and homothetic tastes in commodity consumption in both countries. Therefore, the world relative demand function is given by

$$\frac{D_1^W}{D_2^W} \left(\equiv \frac{D_1 + D_1^*}{D_2 + D_2^*}\right) = D(p);\ D' < 0, \tag{9}$$

where D_i is the demand for good i. The world equilibrium is obtained by

$$D(p) = \frac{X_1^W}{X_2^W} (\equiv \frac{X_1 + X_1^*}{X_2 + X_2^*}). \tag{10}$$

The equilibrium without any emission regulation can be obtained by using the world relative supply and demand curves in Figure 5. In the figure, the RS curve (i.e., $AGHI$) shows the world supply of good 1 relative to good 2, while the RD curve shows the world demand of good 1 relative to good 2. The world equilibrium is given by the intersection of RS and RD. The domestic country completely specializes in good 1 if $p < A$ and in good 2 if $p > A$. Similarly, the foreign country completely specializes in good 1 if $p < A^*$ and in good 2 if $p > A^*$.

We specifically focus on the case where the domestic country completely specializes in good 1 in the absence of any emission regulation. There are two cases when the domestic country completely specializes in good 1. The foreign country completely specializes in good 2 in one case, while it is diversified in the other. Suppose that the RD curve is given by RD_1. Then the equilibrium is given by E and both countries completely specialize.

We first examine the effect of domestic emission quotas in this case. The introduction of an emission quota shifts the RS curve to the left, because the domestic PPF shrinks. Moreover, since the domestic PPF is no longer given by a straight line, a part of RS curve is now upward-sloping. This part corresponds to FQ' in Figure 3. As long as the relative price is between A and B in Figure 5, the domestic country is diversified.

Suppose that the RS curve with a domestic emission quota is given by $AQ'FF'I$. The new relative price is determined by the intersection between RD_1 and the new RS curve (i.e., Q). It is obvious that the emission quota makes the relative price of good 1 higher. When the equilibrium shifts from E to Q, the domestic production of good 1 falls and that of good 2 becomes positive,[21] whereas the foreign production is not affected at all (i.e., the foreign country remains completely specialized in good 2). Thus, the world level of GHG emission necessarily falls.

We should note that if the RD curve is given by RD_2, the new relative price is equal to $A^*(\equiv \bar{a}_1^*/\bar{a}_2^*)$. This is the case when RD intersects the new RS curve on $F'H$. In this case, the foreign country becomes diversified and the world relative supply falls. The emission quota decreases the domestic emission but increases the foreign emission (recall Lemma 1). This is the so-called carbon leakage.[22] Therefore, the world emission may not lower. If $\bar{e}_1^*$ is high enough relative to $\bar{e}_1$, the increase in the foreign emission could be greater than the decrease

[21]The domestic production of good 2 remains zero if the new equilibrium is on the vertical segment of the new RS curve. However, it is possible that the new RS curve does not have a vertical segment. For example, this is the case if the slope of the PPF approaches infinite as the output of good 2 approaches zero. This is shown in Figure 6 where the RS curve with a domestic emission quota is given by $AQ'JMN$.

[22]See Kiyono and Ishikawa (2002) for the international interdependence of environmental management policies in the presence of carbon leakages.

in the domestic emission.

If the RD curve is given by RD_3, the domestic country completely specializes in good 1 and the foreign country is diversified without a domestic emission quota. In this case, the domestic emission quota does not affect the equilibrium relative price, because the shift of the RS curve does not affect the intersection of RD and RS. Since the world relative supply remains constant and the domestic PPF shrinks, the world outputs of both goods fall in the same proportion. In this case, the carbon leakage could occur, too. However, it occurs only if the foreign production of good 1 rises.

We thus obtain the following proposition.

Proposition 5. *A domestic emission quota reduces the domestic GHG emission. The quota causes carbon leakage if and only if the foreign country is diversified in the presence of the quota. When the carbon leakage occurs, the world GHG emission may rise if $\bar{e}_1^*$ is high enough relative to $\bar{e}_1$.*

4.2 Quota-Equivalent Emission Taxes

In this subsection, we examine quota-equivalent emission taxes. First, we consider the case where the foreign county remains completely specialized in good 2. If the domestic country is diversified, the world equilibrium is given by five equations: (3), (4), (5), (6) and (10). Noting that X_1^* and X_2^* are constant as long as the foreign country completely specializes in good 2, we have five unknowns (i.e., p, X_1, X_2, w, and r) when a domestic emission quota is introduced. When the quota is replaced by an emission tax, unknowns are p, X_1, X_2, w, and Z. However, as far as the tax rate is set equal to r under the emission-quota equilibrium (i.e., the quota-equivalent emission tax), it is obvious that the amount of emission Z under the emission tax is equal to the level of the emission quota. That is, the equilibrium under the domestic emission quota is identical to that under the quota-equivalent emission tax.

We should note that the above result contrasts with the SOE case where the quota-equivalent emission tax alone cannot lead to the equilibrium under an emission quota. The difference stems from (10). In the SOE case, the relative price p is exogenously given, while in the two-country model, it is endogenously determined by (10). Since the relative price changes, the equivalence between emission quotas and emission taxes is restored.

If the domestic country remains completely specialized in good 1, there are four equations (i.e., (3), (5), (6) and (10)) and four unknowns (i.e., p, X_1, w, and r) with a domestic emission quota; and there four equations and four unknowns (i.e., p, X_1, w, and Z) with a domestic emission tax. Thus, the equilibrium under the domestic emission quota and that under the quota-equivalent emission tax are the same.

Thus, we obtain the following proposition.

Proposition 6. *As long as the foreign country remains completely specialized in the presence of a domestic emission quota, the equilibrium under the domestic emission quota can be* *attained by the quota-equivalent emission tax.*

Next we consider the case where the foreign country is diversified. If the domestic country is also diversified under a domestic emission quota, the world equilibrium is now given by seven equations: (3), (4), (5), (6), (10),

$$p = \frac{\bar{a}_1^*}{\bar{a}_2^*}, \tag{11}$$

$$\bar{a}_1^* X_1^* + \bar{a}_2^* X_2^* = L^*. \tag{12}$$

With a domestic emission quota, there are seven unknowns: p, X_1, X_2, X_1^*, X_2^*, w, and r. Thus, the equilibrium is determined uniquely. With the emission-equivalent tax, however, either (3) or (4) becomes redundant. Therefore, there are seven unknowns (i.e., p_1, X_i, X_i^*, w, and Z) and six equations. This implies that the equilibrium is not unique. It should be noted that the case where the foreign country is diversified is similar to the case of a SOE. This is because the world relative price given by (11) is constant.

If the domestic country remains completely specialized in good 1, there are six equations (i.e., (3), (5), (6), (10), (11) and (12)) and six unknowns (i.e., p, X_1, X_1^*, X_2^*, w, and r) with a domestic emission quota; and there are six equations and six unknowns (i.e., p, X_1, X_1^*, X_2^*, w, and Z) with a domestic emission tax. Thus, the quota-equivalent emission tax reproduces the same equilibrium with a domestic emission quota.

Therefore, the following proposition is established.

Proposition 7. *Suppose that the foreign country is diversified in the presence of a domestic emission quota. The equilibrium under the domestic emission quota can be attained by the quota-equivalent emission tax if the domestic country completely specializes in good 1, but cannot be attained by the quota-equivalent emission tax alone if the domestic country is also diversified.*

4.3 Quota-Equivalent Emission Standards

As was examined in the last section, once the quota-equivalent emission standard is introduced, a_i $(i = 1, 2)$ is fixed and the PPF becomes a straight segment. Thus, the relative supply curve is like that of the standard Ricardian model (say, $A'G'F'I$ in Figure 5). Since $a_1^S/a_2^S (\equiv A')$ (where the superscript S stands for the quota-equivalent emission standard) is not usually equal to $\bar{a}_1/\bar{a}_2 (\equiv A)$, A' could be located below or above A in Figure 5. Since the domestic country completely specializes in good 1 as long as $p > a_1^S/a_2^S$, the vertical section is located to the right of the upward-sloping part of RS with a domestic emission quota. Therefore, the domestic economy completely specializes in good 1 in the presence of the quota-equivalent emission standard. In Figure 5, the equilibrium shifts from Q to F''.

It is obvious that the quota-equivalent emission standard can reproduce the production equilibrium with a domestic emission quota if the domestic economy remains completely specialized in good 1 with a domestic emission quota, but cannot if the domestic economy is diversified with a domestic emission quota.

When the equivalence does not hold, the switch from a domestic emission quota to the quota-equivalent emission standard increases the domestic emission, but may not increase the world emission level. This can be seen with the aid of Figure 6. The figure shows a case where the domestic country completely specializes in good 1 if $p < A$ but is diversified if $p > A$. In the figure, the RS curve is $AQ'JMN$ in the presence of a domestic emission quota and hence the equilibrium is given by L where the both countries are diversified. When the quota is replaced by the quota-equivalent standard, the RS curve becomes $A'G'KI$ and hence the equilibrium becomes L' where the both countries completely specialize. The switch reduces the output of good 1 and raises that of good 2 in the foreign country, which lowers the foreign emission. If this reduction is large enough, the world emission could fall as a result. It should be noted that this does not occur if the foreign country remains completely specialized in good 2.

We thus obtain the following proposition.

Proposition 8. *If the domestic country completely specializes in good 1 under an emission quota, the same production equilibrium can be attained by the quota-equivalent emission standard. If it is diversified under an emission quota, however, the quota-equivalent emission standard results in complete specialization in good 1. The switch raises the world emission as well as the domestic emission if the foreign country remains completely specialized in good 2, but may reduce the world emission if the foreign country is diversified under the quota.*

5 Concluding Remarks

We have constructed a simple open economy model, which has both Ricardian and HO features, to clarify the potential effects of choices over the domestic GHG emission controls. Specifically, we have compared three major tools: emission quotas, emission taxes and emission standards. It has been shown that the patterns of production and trade crucially depend on how GHG emissions are controlled and whether the economy is small or large. In particular, emission standards work as a "hidden" production subsidy towards the emission-intensive sector. The key factors to derive our results are both how the total emission level is determined and how the costs of emission reduction are incurred by firms.

A domestic emission control reduces the domestic emission. However, it may increase the foreign emission and hence the world emission as a whole in the absence of foreign emission controls. This carbon leakage stems from the difference in production technologies between the two countries.

We have built the simplest general equilibrium model to shed some light on the issue of GHG emission controls in an open economy. Since our model is based on the standard trade models, it seems like the natural starting point to examine the issue and leads to several clear-cut results. However, it is certainly worthwhile to build alternative models to understand the issue of GHG emission controls more deeply. The following are in particular worth mentioning and left for the future research.

First, our analysis is static. A reason why we have constructed a static model is that the targets of GHG emissions set in the Kyoto Protocol are not on the stock base but on the flow base and the time left to the target year is relatively short (i.e., only several years). However, it is interesting to investigate the issue of GHG emission controls in a dynamic framework.

Second, we have assumed that emissions harm consumers but do not generate any production externalities. If there exist any production externalities in the static framework, the social production possibility set may become non-convex, as discussed by Wong (1995, Chapter 5). However, such non-convexity causes multiple equilibria, which makes it hard in general to analyze the effects of policies.

Third, we have examined unilateral emission regulations in our analysis, which makes the carbon leakage clearer. In the presence of domestic emission regulations, the domestic country is subject to the HO structure while the foreign country is still subject to the Ricardian structure. A natural extension is to examine bilateral emission regulations. In this case, the model becomes a $2 \times 2 \times 2$ HO type model in which, however, production technologies are not necessarily identical between countries.

Last, we have referred to international trade in the emission permit in a SOE, but have not examined it in the two-country model.[23] International emissions trading allows the assigned units of emissions to move around the world and affects the production and trade structures of each country. For further inquiry into this problem, therefore, one may have to resort to possible implications from trade theories with free factor mobility.

[23]Elsewhere we discuss the welfare effects of creating a world emission-permit market (Kiyono and Ishikawa (2002)).

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Figure 1: Technical substitution between emission and labor

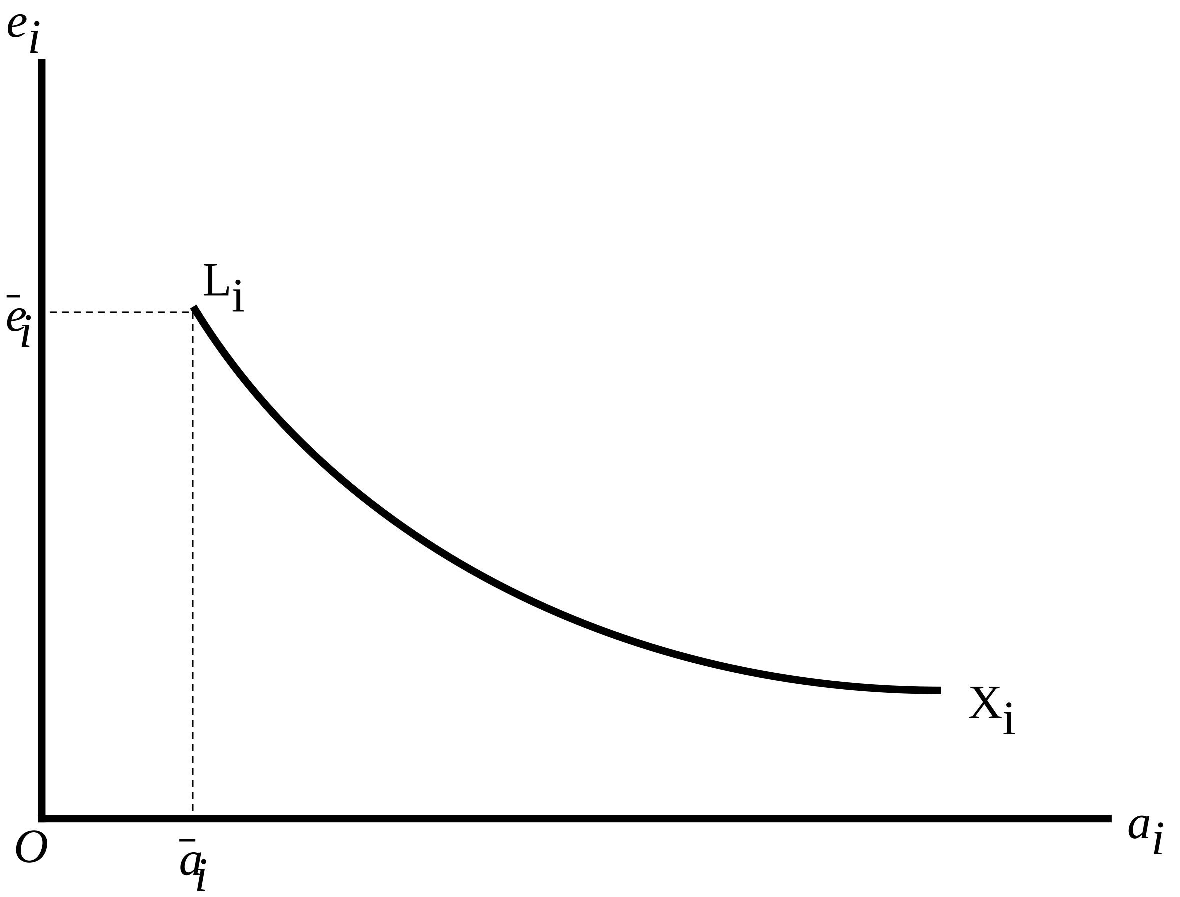

Figure 2: The unit cost cruve

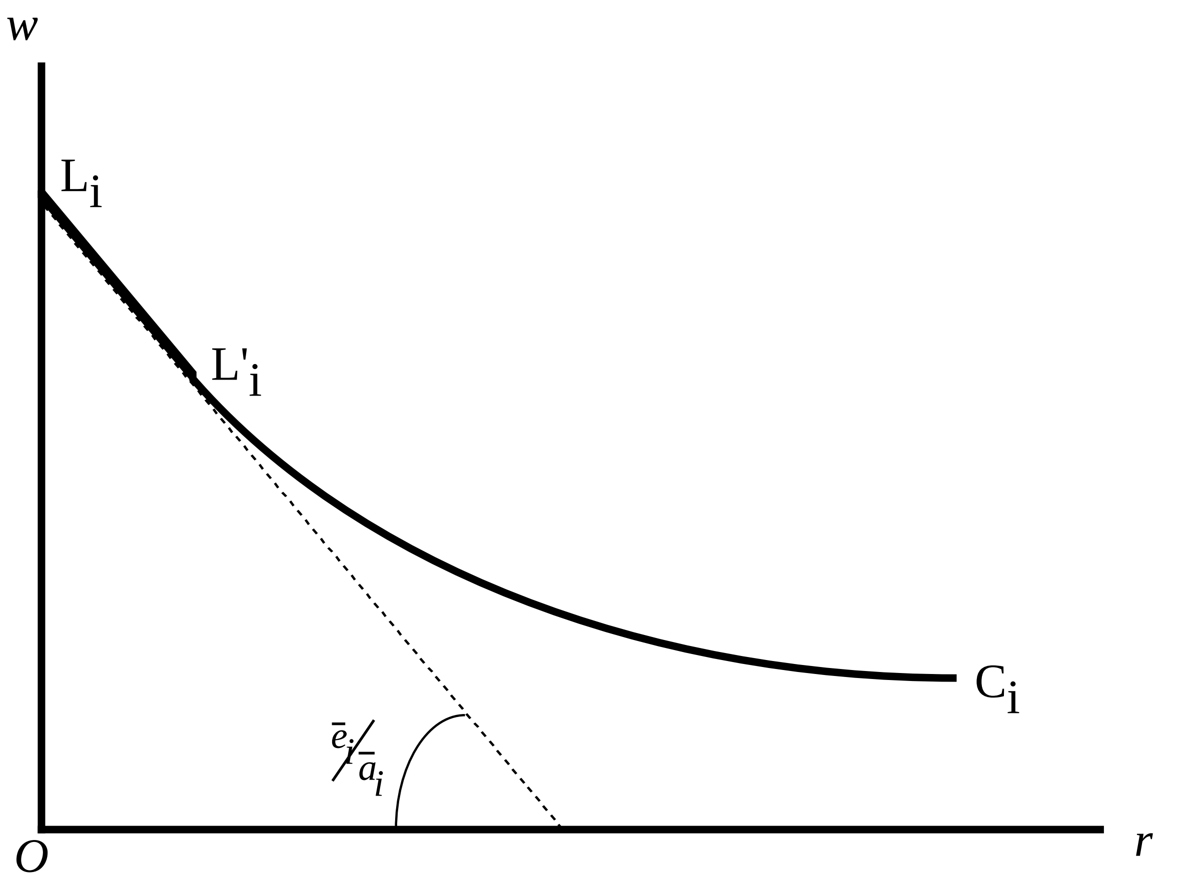

Figure 3: Trade and production patterns under emission controls

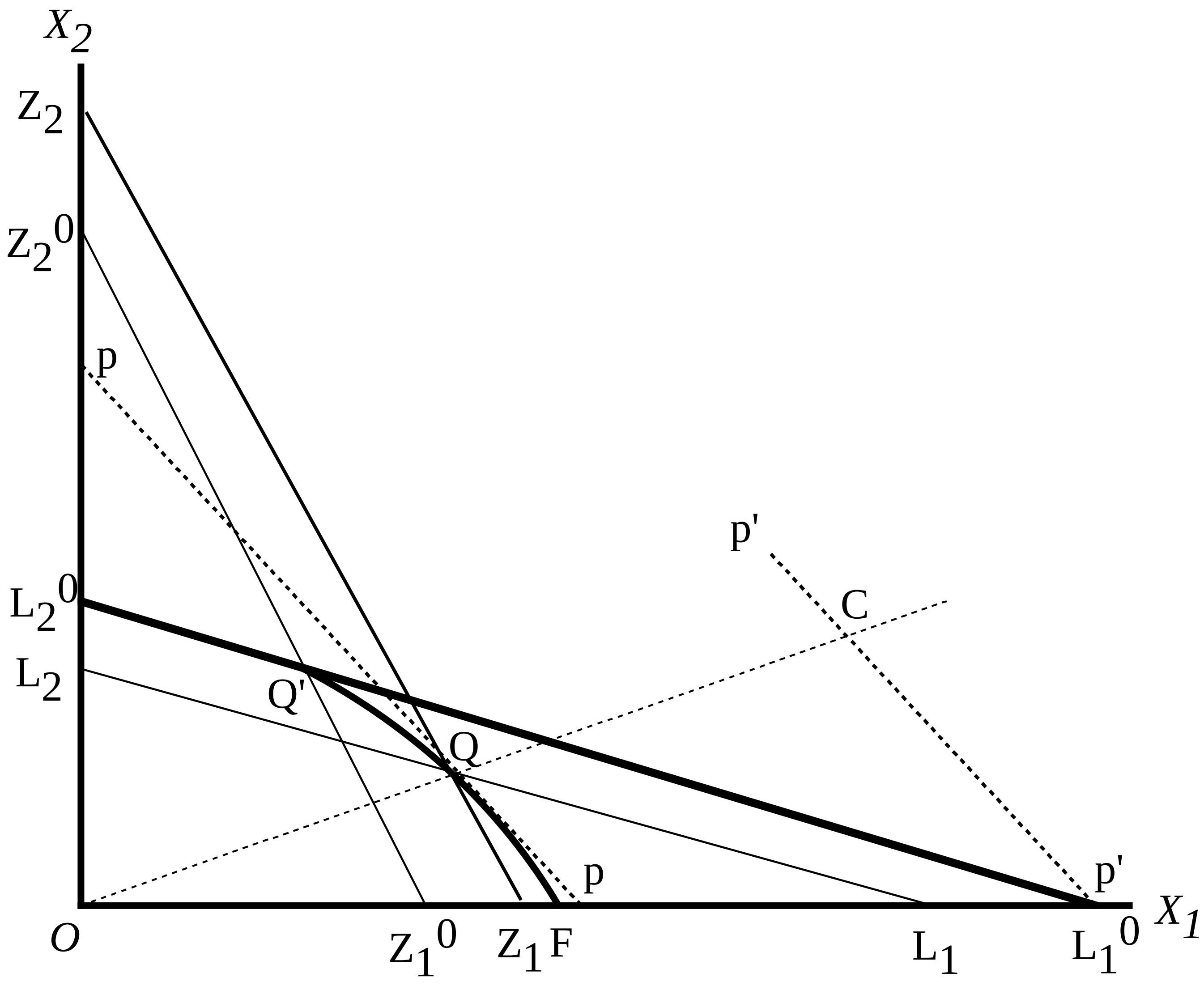

Figure 4: Input prices and emssion controls

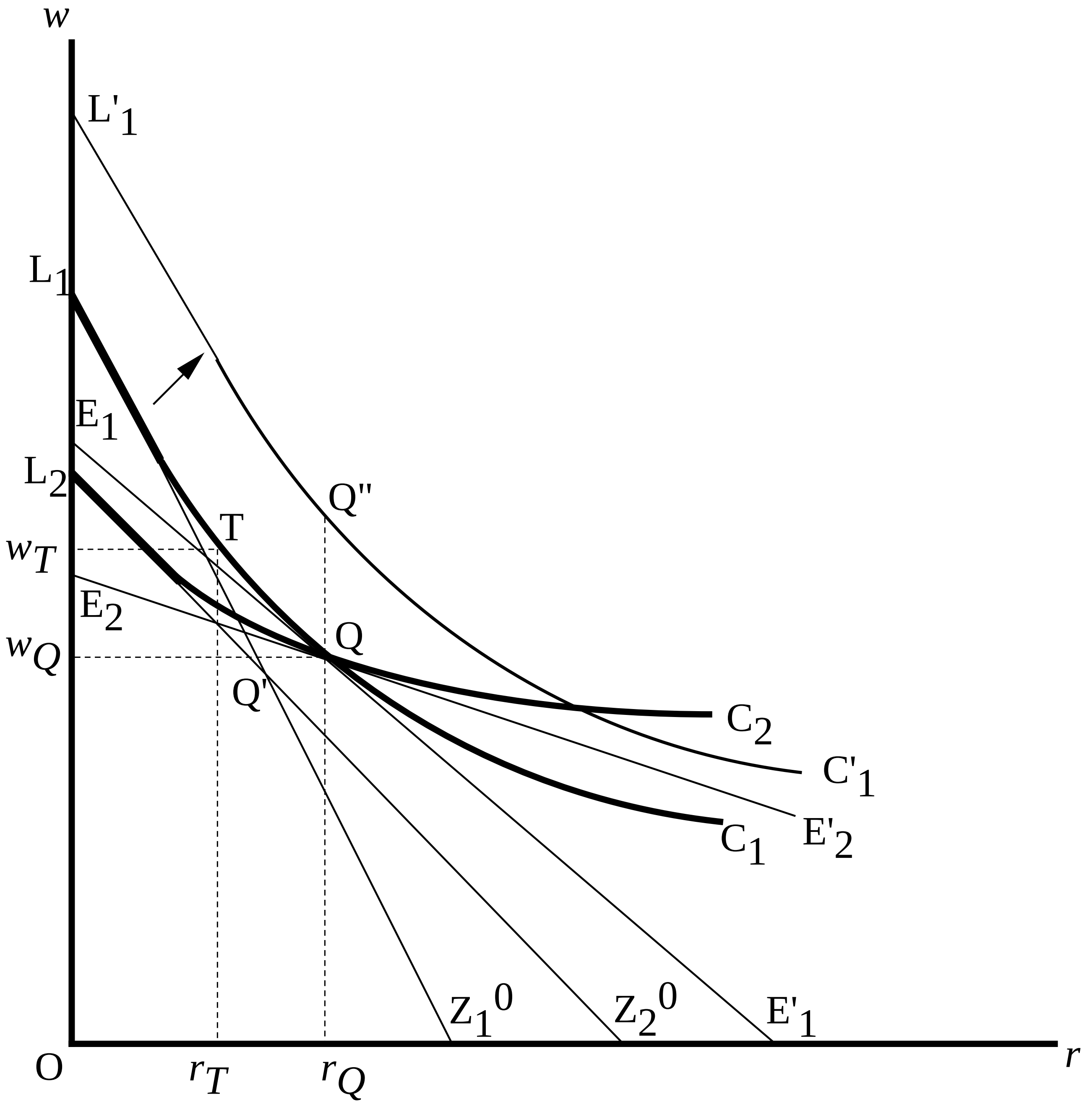

Figure 5: Emission controls in a two-country model

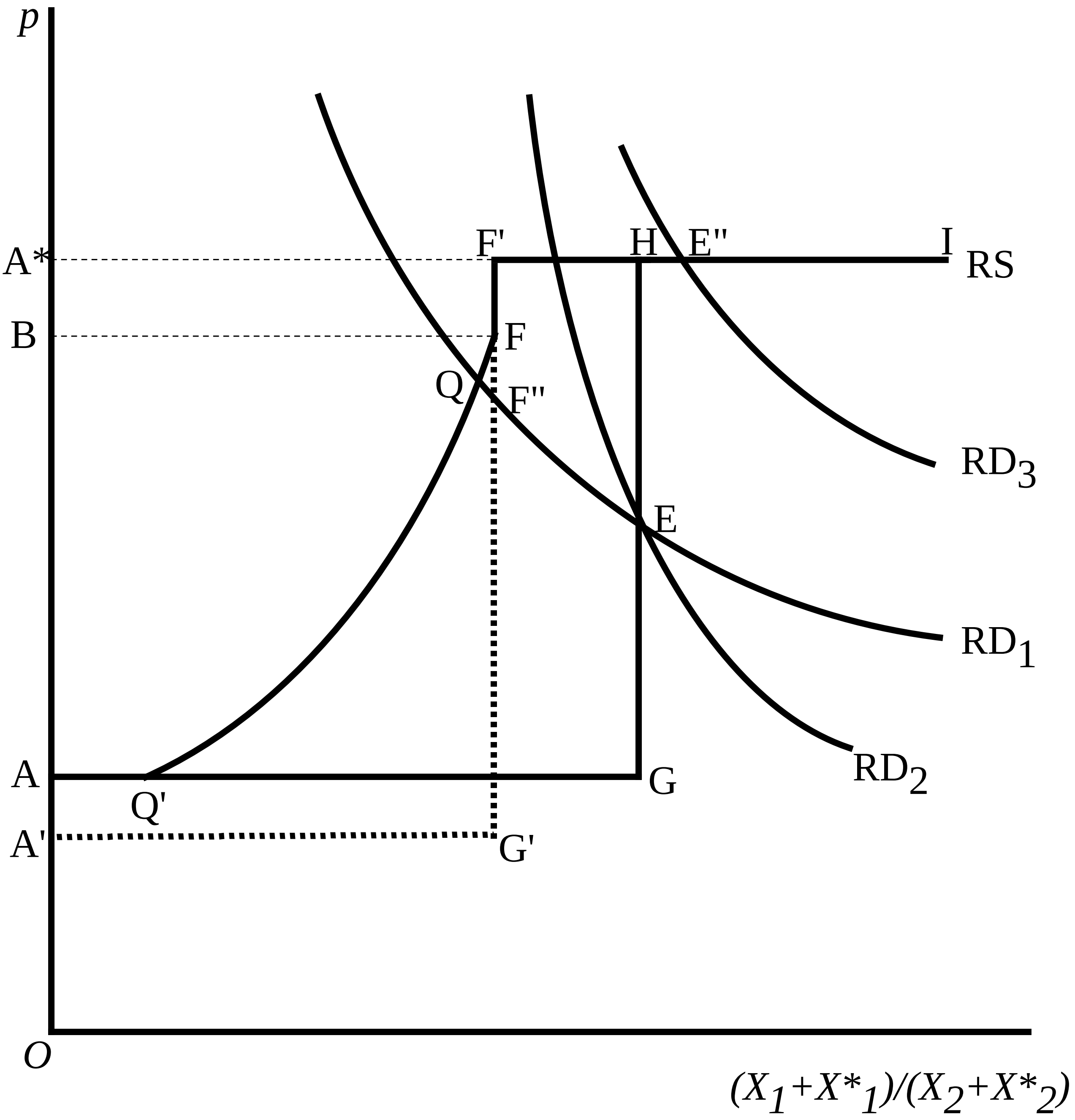

Figure 6: Emission quota and the emission equivalent emission standard