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# Emissions Trading and International Trade*

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Abstract

We explore the effects of international trade in goods and emission permits on global warming and welfare in a two-country, two-good, general-equilibrium model with both Ricardian and Heckscher-Ohlin features. According to our findings, international commodity trading cannot successfully reduce greenhouse-gas (GHG) emissions if the comparative advantage stems from differences in per-capita emission allowances; however, it may reduce emissions if the comparative advantage is also based on differences in technologies. International emissions trading cannot mitigate global warming. Whether it improves welfare would depend on how it affects the terms of trade in goods and climate change. A country with high per-capita emission allowances may import permits and suffer from deterioration in the terms of trade in goods.

Keywords: global warming; trade in emission permits; comparative advantage; terms of trade
JEL classification: F11, F18, Q54, Q56



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# 1 Introduction

Global warming is one of the greatest concerns of the world. The global average temperature increased by 0.85°C between 1880 and 2012.[1] Rising global temperatures have been accompanied by climate changes, causing extensive damage. For example, in recent times, unusual weather conditions have been causing a high number of floods and droughts and severe heat waves across the world.

The whole world has united its efforts to tackle global warming. An international environmental treaty, the United Nations Framework Convention on Climate Change (UNFCCC), was adopted at the Earth Summit held in Rio de Janeiro in 1992. The first session of the Conference of Parties (COP) to the UNFCCC was held in Berlin in 1995.[2] Since then, the COP has been meeting every year. Of all the COP meetings, the 1997 COP3 Kyoto and 2015 COP21 Paris sessions are the most noteworthy.

The Kyoto Protocol, adopted in the COP3 session, resulted in two important agreements. First, the industrialized countries, called the Annex I Parties, committed to decrease their greenhouse-gas (GHG) emissions to 5.2% below their 1990 baseline levels over the 2008–2012 period. Second, three market-based mechanisms, so called the Kyoto mechanisms, were introduced. These are the emissions trading, the clean development mechanism (CDM) and the joint implementation (JI).[3] In particular, emissions trading has attracted considerable attention. For example, the European Commission has proposed market-based carbon trading as an instrument for countries to reach their targets at minimum cost. In 2005, the European Union (EU) launched a "cap & trade" emissions trading called the EU emissions trading system (ETS). Under the cap & trade system, a cap is set on the GHGs permissible for a country to emit.[4] Under this system, spare allowances can

[1] https://www.jccca.org/chart/chart02_01.html

[2] The UNFCCC came into effect in March 1994; it has been ratified by 197 countries. These countries constitute the "Parties" to the Convention.

[3] JI allows the Annex I Parties to purchase emission allowances from projects in other Annex I Parties that reduce or remove emissions, while CDM allows the Annex I Parties to purchase emission allowances from projects in non-Annex I Parties.

[4] Another system is the "baseline & credit" system.

be sold in the market.[5]

The Kyoto Protocol is a notable step toward the reduction in GHGs. However, developing countries have no obligation to reduce GHGs.[6] In the COP21 sessions, 197 Parties including both developed and developing countries submitted their specific GHG emission reduction targets, but these targets were heterogeneous because the Parties set their emission targets noncooperatively. For example, the EU's target is a 40% GHG reduction by 2030 from their 1990 level,[7] while China's target is a 60-65% reduction in $CO_2$ emissions per unit of GDP by 2030 from their 2005 level. Since China's reduction target is in terms of per unit of GDP, their emissions are expected to continue to increase and reach the maximum in 2030.[8]

Emissions trading would be inevitable for many countries to meet their targets. According to the World Bank, there are 28 implemented and three scheduled ETSs. However, the jurisdictions of these ETSs (except for the EU ETS) are either national or subnational.[9] Thus, international emissions trading is yet to fully develop. This study explores the effects of international emissions trading between a home (North) and foreign (South) country. To this end, we develop a simple two-country, two-good, general equilibrium international trading model for goods and emission permits. The primary factor used for producing the two goods is labor. However, following the idea of Meade (1952), we consider GHG emissions an environmental resource

[5] The Kyoto protocol provides the following emission allowances (i.e., carbon credits). Assigned Amount Unit (AAU): this is the level assigned to a Party initially under the protocol; Removal Unit (RMU): this is emissions level removed from land use, land-use change and forestry (LULUCF) activities; Certified Emission Reductions (CER): this is obtained from CDM projects; and Emission Reduction Units (ERU): this is obtained from JI projects.

[6] The United States (US) was a signatory to the protocol but has not ratified it. Thus, it was freed from its reduction commitment.

[7] The US, Japanese, and Russian targets are, respectively, a 26–28% reduction by 2025 from their 2005 level, a 26% reduction by 2030 from their 2013 level, and a 25–30% reduction by 2030 from their 1990 level.

[8] India's target is similar to China's. It is a 33–35% reduction in emissions per unit of GDP by 2030 from the 2005 level.

[9] On January 1, 2020, the Swiss and EU ETSs were linked. The United Kingdom is considering to construct its own ETS and link it to the EU ETS. https://www.gov.uk/government/publications/legislation-for-a-uk-emissions-trading-system/legislation-for-a-uk-emissions-trading-system.

input for production.[10] Moreover, we consider the technology gap between the two countries, assuming that the home country has superior technologies for both industries.

Specifically, we explore the following two questions: Would trade liberalization in goods lead to economic and environmental benefits? Would international emissions trading be beneficial under free trade in goods? In particular, we are interested in whether the difference in emission allowances between countries is an important matter in international emissions trading.

Helm (2003) uses a non-cooperative game to consider the endogenous determination of emission allowances. He shows that with international emissions trading, countries more concerned with the environment would choose fewer permits, whereas those less concerned with the environment would choose more permits. In view of this finding, we assume that per-capita emission allowance of countries is exogenously given, with the foreign country receiving greater allowance than the home country.

Our model is based on Ishikawa and Kiyono (2006), where both Ricardian and Heckscher-Ohlin features are used to compare the different emissions regulations in an open economy. However, they examine only the unilateral emissions regulations. In their analysis, therefore, emissions trading is introduced only in the North. We extend their analysis to the case in which both countries have an emission quota.

Ishikawa, Kiyono, and Yomogida (2012) (henceforth IKY) examine the welfare and environmental implications of emissions trading using a similar model. However, we examine issues not considered in IKY. They focus more on the welfare and environmental effects of domestic emissions trading, given that the countries are engaged in free international trade in goods. In contrast, our current work examines the welfare and environmental effects of trade liberalization in goods, given that each country has its own domestic emissions trading scheme. IKY also consider international emissions trading, but focus on a specific case. Our investigation is more general than theirs.

[10] For example, Copeland and Taylor (1994,1995,2005), Ishikawa and Kiyono (2006), Ishikawa, Kiyono and Yomogida (2012) follow this idea.

Simply put, IKY and our current study are complementary.[11]

We further show that trade liberalization in goods, coupled with domestic emissions trading, cannot successfully decrease GHG emissions if the comparative advantage stems from only the difference in per-capita emission allowances, but could decrease them if the comparative advantage is based also on technology differences. Furthermore, international emissions trading cannot successfully mitigate global warming. Whether international emissions trading improves welfare would depend on how it affects the terms of trade in goods and global warming. A country may suffer from both worsening terms of trade in goods and deterioration in global warming. If these double losses are large enough to overwhelm the direct gains from global emissions trading (that is, efficiency gains), the country would lose. Even if international emissions trading improves a country's terms of trade, the deterioration of global warming could reduce its welfare. Interestingly, the question whether international emissions trading could deteriorate a country's terms of trade in goods does not depend on the initially allocated per-capita emissions allowance.

Studies have analyzed emissions trading from different perspectives.[12] We specifically follow the literature employing trade theory to investigate emissions trading (Copeland and Taylor, 1995, 2005; Abe et al., 2012; Marschinski et al., 2012; Kiyono and Ishikawa, 2013; Konishi and Tarui, 2015). Our study is also related to the trade theory literature with capital mobility, such as Mundell (1957), Jones (1980, 2000), Brecher and Choudri (1982), Markusen (1983), Grossman (1983), and Yomogida (2006). Since we consider GHG emissions an input for production, we treat trade in emissions permits as a trade in capital. However, unlike capital, GHG emissions comprise a global public bad. Thus, we evaluate the emissions trading welfare effect in terms

[11] Our current work provides findings that are not shown in IKY. While IKY show that a country with technical advantage in the production of an emission-intensive good imports emission permits, we show that this is not necessarily true; that is, a country with technical disadvantage in the production of an emission-intensive good may also import emission permits. Furthermore, unlike IKY, we show the possibility of international emissions trading worsening global warming by increasing the global GHG emissions.

[12] The early studies include Montgomery (1972), Tietenberg and Tietenberg (1985), and Bohm (1992).

of global warming and the standard effects of factor mobility.

To examine the welfare effects of international emissions trading, Copeland and Taylor (1995, 2005) develop a general equilibrium international trade model based on the Heckscher-Ohlin model. Copeland and Taylor (1995) show that if factor prices are not equalized by the trade in goods, allowing international emissions trading decreases global emissions. Copeland and Taylor (2005) examine three countries, West, East, and South; they assume that the West and the East are constrained by an emissions treaty but the South is not. They find that international emissions trading between the West and East may lead to international carbon leakage, because the resulting adjustments in the goods market would induce the unconstrained South to expand production of the emission-intensive good, thus increasing its GHG emissions.[13]

Following Copeland and Taylor (1995, 2005), we assume that domestic emissions trading is implemented from the beginning. However, unlike Copeland and Taylor (1995, 2005), we use both the Heckscher-Ohlin and Ricardian features in our model, to show that international emissions trading can increase global emissions even when all countries are involved.

The rest of this paper is organized as follows. Section 2 develops the basic model and examines the autarky equilibrium. Section 3 extends the basic model to a two-country setting and explores the economic and environmental effects of commodity trading. Section 4 analyzes the welfare effect of international emissions trading under free trade in goods. Section 5 concludes the paper.

[13] Factor prices in the Heckscher-Ohlin model are equalized in the free trade equilibrium when the countries are incompletely specialized. Since this holds in Copeland and Taylor (1995, 2005), the prices of emissions permits (a production factor) are equalized in the free trade equilibrium with incomplete specialization. Clearly, no trade in emission permits would occur in this equilibrium. To generate the difference in permit prices between countries, Copeland and Taylor (2005) assume that the West specializes in the clean good and the East produces both goods. In our model, we do not assume a specific specialization pattern, because the asymmetric technology used leads to different permit prices between countries.

# 2 The Basic Model

Two goods ($X$ and $Y$) are initially produced with a single factor (labor) under a constant returns to scale technology and consumed by the household. Whereas production of good $Y$ leads to no GHG emissions, that of good $X$ does.[14] GHG emissions worsen global warming and harms the household. We describe the production technology of each good below.

## 2.1 Production Technology

Following the idea of Meade (1952), we treat GHG emissions as the input of an environmental resource for the production of good $X$. This environmental resource is an unpaid and unregulated socially overused production factor. Thus, the environmental regulation internalizes the social opportunity cost of such resources for the private evaluation of costs and benefits. Hereafter, we refer to this environmental resource input as emissions for simplicity of exposition. We further specifically assume that the government enforces a total emission quota in the form of tradeable emissions permit in the domestic market. Thus, the emission price given below is also the emission permit price.

The production of one unit of good $Y$ requires $a_Y$ units of labor, while that of one unit of good $X$ requires both labor and environmental resources; that is, the output of good $X$ is a function of labor input, $L_X$, and the amount of GHG emissions during production, $Z_X$:

$$X = F(L_X, Z_X),$$

where $F$ is concave, continuously differentiable, and linearly homogeneous. Here, labor includes the inputs for emission abatement. Thus, a firm can substitute GHG emissions (an environmental resource) for labor inputs, but this has a limit, given by $(a_{XR}, e_{XR})$, where $a_{XR}$ is the minimum labor input

[14] Even if we assume that the production of good $Y$ emits GHGs, the essence of our analysis and results would remain the same. See Ishikawa and Kiyono (2006) and Ishikawa, Kiyono and Yomogida (2012) for a case where both industries $X$ and $Y$ emit GHGs.

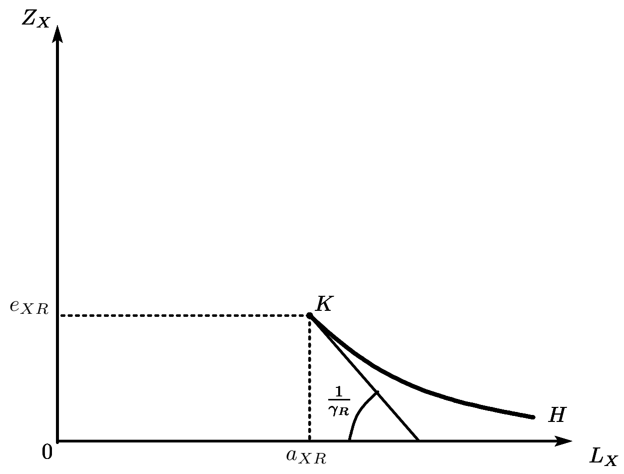

Figure 1: Technical substitution between labor inputs and emissions

and $e_{XR}$ is the maximum GHG emissions for the production of one unit of good $X$. A unit isoquant of good $X$ is illustrated in Figure 1. A substitution between labor inputs and GHG emissions is possible only in the region above $a_{XR}$. Obviously, without any environmental regulation, firms would choose $a_{XR}$ units of labor to produce one unit of good $X$.

We denote the wage rate by $w$ and the price of the environmental resource or GHG emissions by $r$. Then the unit cost function of good $X$ can be expressed by $c_X(r, w)$. From Shepherd's lemma, $\frac{\partial c_X(r,w)}{\partial r}$ is the *emission coefficient*, denoted by $e_X(r/w)$, and $\frac{\partial c_X(r,w)}{\partial w}$ is the labor coefficient, denoted by $a_X(r/w)$; therefore, the unit cost function of good $X$ is

$$c_X(r, w) = re_X(r/w) + wa_X(r/w).$$

Let $\gamma$ denote the relative emission price, $r/w$, and $\gamma_R$ denote the critical relative emission price above which the emission price regulation is effective and promotes abatement in the production of good $X$ (see Figure 1). We also define $z_X(\gamma) := e_X(\gamma)/a_X(\gamma)$ and call it the *emission intensity* for the production of good $X$. The critical emission intensity for $\gamma_R$ is denoted by $z_{XR}$ $(:= e_{XR}/a_{XR})$. The relation between $\gamma$ and $z$ can be visualized by the downward-sloping curve shown in Figure 2.

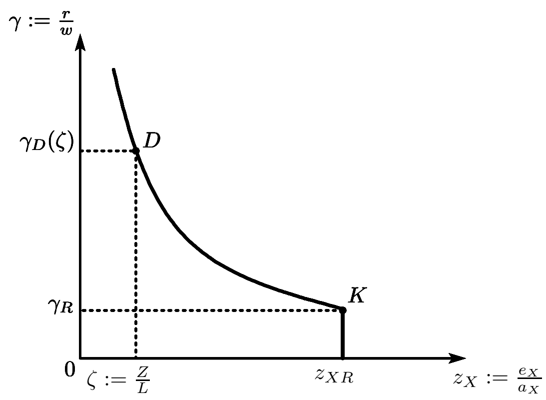


Figure 2: Substitution between labor inputs and emissions

In Figure 2, $\zeta := \frac{Z}{L}$ denotes the per-capita emission quota, where $L$ represents the labor endowment and $Z$ the total emission quota imposed by the government. The emission regulation will be effective when the following assumption is satisfied:

**Assumption 1** *The government imposes the per-capita emission quota* $\zeta < z_{XR}$.

When the emission intensity of good $X$ is equal to this per-capita emission quota, given the full employment of resources, no labor would be left for the production of good $Y$, and the country would completely specialize in good $X$. The associated relative emission price, represented by $\gamma_D$, depends on the per-capita emission quota. We express this relation by the function $\gamma_D(\zeta)$ as shown in Figure 2.

When the relative emission price is less than $\gamma_D(\zeta)$ but higher than $\gamma_R$, a substitution would occur between labor and emissions along segment $DK$. However, if the relative emission price is equal to or lower than $\gamma_R$, the substitution would cease and the emission intensity would become constant at the critical value $z_{XR}$.

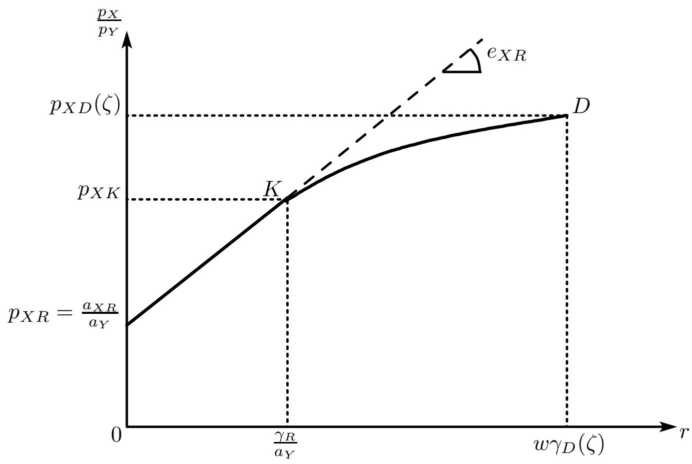


Figure 3: The relation between the relative price of good X and the emission price

## 2.2 Supply-side Equilibrium

### 2.2.1 Unit Cost Curve

Given the prices of goods $X$ and $Y$, $p_X$ and $p_Y$, respectively, the competitive conditions for the goods are represented by

$$c_X(w, r) \geq p_X,$$
$$wa_Y \geq p_Y = 1,$$

where the price of good $Y$ is normalized to 1 because we assume the good $Y$ is a numeraire.

The price of good $X$ relative to good $Y$ is illustrated as a curve $p_{XR}KD$ in Figure 3. As Figure 1 shows, no substitution occurs between labor and emissions for $r \leq \gamma_R/a_Y$, and the relative price of good $X$ is equal to $re_{XR} + a_{XR}/a_Y$. The resulting relation between the relative price and the emission price is shown by the line segment $p_{XR}K$, where $p_{XR} = a_{XR}/a_Y$.

As curve $DK$ shows, a substitution occurs between labor and GHG emissions for $r \in (\gamma_R/a_Y, w\gamma_D(\zeta))$; thus, as Shepherd's lemma shows the tangent slope to the relative price curve is equal to the emission coefficient $e_X(ra_Y)$.

A higher emission price promotes the substitution of GHG emissions with labor, and the tangent slope becomes flatter, as shown by the curve $DK$.

No substitution is possible between labor and GHG emissions for $r \geq w\gamma_D(\zeta)$, because the emission intensity of the economy cannot be less than the per-capita emission quota $\zeta$ (see Figure 2). We also find that the country completely specializes in the production of good $X$, implying that the wage rate exceeds $1/a_Y$ and $\gamma_D(\zeta) = r/w$. Since $\zeta = z_X(\gamma_D(\zeta))$ holds, the the unit cost is equal to

$$\begin{aligned} re_X(\gamma_D(\zeta)) + \frac{r}{\gamma_D(\zeta)}a_X(\gamma_D(\zeta)) &= r\left\{e_X(\gamma_D(\zeta)) + \frac{a_X(\gamma_D(\zeta))}{\gamma_D(\zeta)}\right\} \\ &= ra_X(\gamma_D(\zeta))\left\{\zeta + \frac{1}{\gamma_D(\zeta)}\right\}, \end{aligned} \tag{1}$$

where we use $\zeta = z_X(\gamma_D(\zeta))$.

### 2.2.2 Production Possibility Frontier

Factor constraints are represented by

$$\begin{aligned} a_X(r/w)X + a_YY &\leq L, \\ e_X(r/w)X &\leq Z. \end{aligned}$$

Prior to the introduction of emission quotas, producers of good $X$ did not incur GHG emitting costs, with the unit cost of producing good $X$ equaling the minimum labor cost $wa_{XR}$. Thus, the production possibility frontier is illustrated as a downward straight line as in the Ricardian model.

After the government imposed a total emission quota on production activities and created a market for trading emission permits, producers had to incur the GHG emission costs. Given the total emission quota $Z$, the production possibility frontier is illustrated in Figure 4. Under Assumption 1, the total emission quota constrains the capacity to produce good $X$.

Clearly, the production pattern depends on the relative price of good $X$. When the relative price of good $X$ is less than $p_{XK} := \gamma_R e_{XR}/a_Y + a_{XR}/a_Y$, the permit price will be less than $\gamma_R/a_Y$, making the emission intensity con-

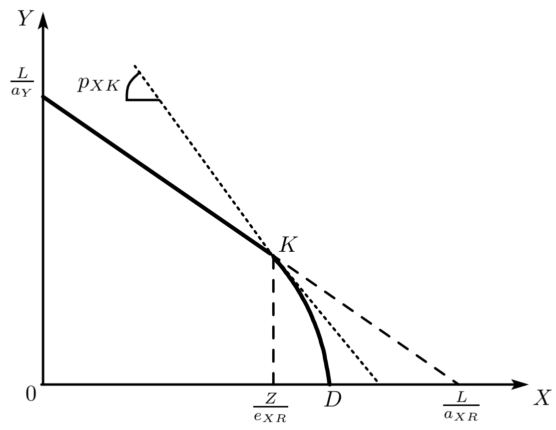


Figure 4: The production possibility frontier

stant at $z_{XR}$. Moreover, the outputs will remain constant until the permit price equals zero. This is because the economy is at the kinky point $K$ along the production possibility frontier. Once the permits become free, the economy will be only Ricardian, and the resulting relative price would remain at $p_{XR} := a_{XR}/a_Y$. When the price of good $X$ is less than $p_{XR}$, the economy will specialize in good $Y$ and stop emitting GHGs.

If the price of good $X$ is equal to or greater than $p_{XK}$, the emission regulation would be effective, and the emission as well as labor constraint would hold with equality. An increase in the price of good $X$ would raise the output of good $X$ relative to good $Y$ along the production possibility frontier, with the emission price rising because an increase in the production of good $X$ leads to greater demand for emission permits (see Figure 3). If the price of good $X$ reaches $p_{XD}(\zeta)$, the country would completely specialize in producing good $X$.

### 2.2.3 Relative Supply Curve

The relative supply curve is illustrated in the first quadrant of Figure 5. When the price of good $X$ is equal to or less than $p_{XR}$, the emission constraint will not bind, and the relative supply curve will be similar to that of the Ricardian case. For $p \in (p_{XR}, p_{XK})$, the supply of good $X$ relative to

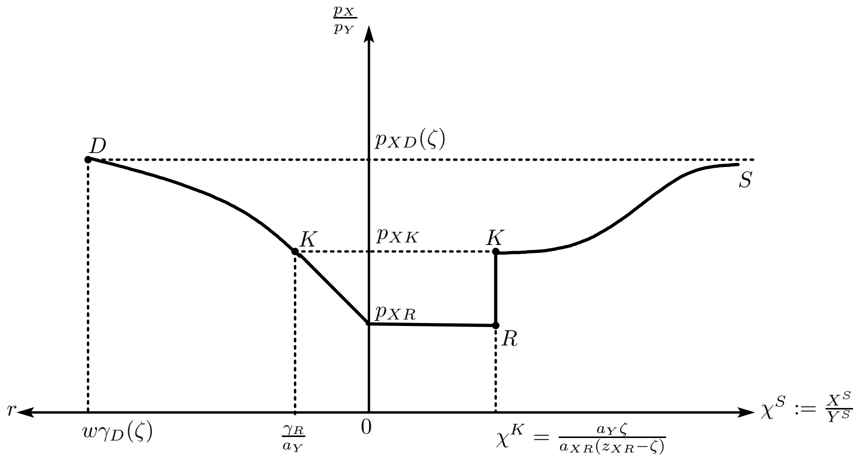


Figure 5: The relative supply curve

good $Y$ is fixed because production takes place at the kinky point $K$ on the production possibility frontier. With the factor constraints, we can derive the relative output of good $X$ to good $Y$ as

$$\chi^K = \frac{a_Y\zeta}{a_{XR}(z_{XR}-\zeta)}.$$

At this relative output level, the producers of good $X$ will use the most emission-intensive technology, $z_{XR}$, and the permit price would increase with the price of good $X$ and the fixed slope $e_{XR}$ (see the second quadrant).

If $p_X \in (p_{XK}, p_{XD})$, then the substitution between labor and emissions arises, and the competitive conditions, $p_X = c_X(w,r)$ and $1 = wa_Y$, would determine the ratio of the demand price of permits to the wage rate, $\gamma = r_D(p_X)a_Y$. Furthermore, the set of factor constraints would yield the equilibrium relative supply of good $X$ to good $Y$,

$$\chi^S(p_X,\zeta) = \frac{X^s}{Y^s} := \frac{a_Y\zeta}{a_X(r_D(p_X)a_Y)\left[z_X(r_D(p_X)a_Y)-\zeta\right]}. \tag{2}$$

For $p_X \in (p_{XK}, p_{XD})$, the relative supply of good $X$ is strictly increasing in the relative price $p_X$ because $r_D'(p_X) > 0$.[15]

[15] We can rewrite $\chi^S$ as $\chi^S = a_Y\zeta/(e_X(r_Da_Y) - a_X(r_Da_Y)\zeta)$. Since $e_X(r/w)' < 0$ and

## 2.3 National Welfare

The national welfare of the country is measured by the utility of the representative household with the following utility function:

$$U = U\left(u(X^c, Y^c), Z^W\right), \tag{3}$$

where $X^c$ is the consumption of good $X$, $Y^c$ is the consumption of good $Y$, $u(\cdot)$ is a sub-utility function, and $Z^W$ is the total GHG emissions in the world. We may impose the following assumption on the household's utility function.

**Assumption 2** *The household's utility function satisfies the following properties.*

*A 2-1:* $U(u, Z^W)$ *is (i) strictly increasing in the sub-utility* $u$ *(ii) strictly decreasing in* $Z^W$*, and (iii) twice continuously differentiable.*

*A 2-2:* $u(X^c, Y^c)$ *is (i) strictly increasing in the consumption of each good, (ii) twice-continuously differentiable, (iii) strictly concave, and (iv) homothetic. It also satisfies (v)* $\lim_{\chi^C \to +0} \frac{\partial u(\chi^C,1)/\partial X^c}{\partial u(\chi^C,1)/\partial Y^c} = +\infty$ *and* $\lim_{\chi^C \to +\infty} \frac{\partial u(\chi^C,1)/\partial X^c}{\partial u(\chi^C,1)/\partial Y^c} = 0$ *where* $\chi^C := X^c/Y^c$.

Given Assumption 2, the relative demand for good $X$, $\chi^D(p_X)$, depends on only its relative price $p_X$, and is decreasing in the relative price $p_X$.

## 2.4 Autarky Equilibrium

We first explore the autarky equilibrium, which is governed by

$$\chi^S(p_X, \zeta) = \chi^D(p_X).$$

Assumption 2 implies that the demand for good $X$ relative to good $Y$, that is, the relative demand for good $X$, depends only on the relative price $p_X$.

$a_X(r/w)' > 0$, an increase in $p_X$ leads to a rise in $\chi^S$.

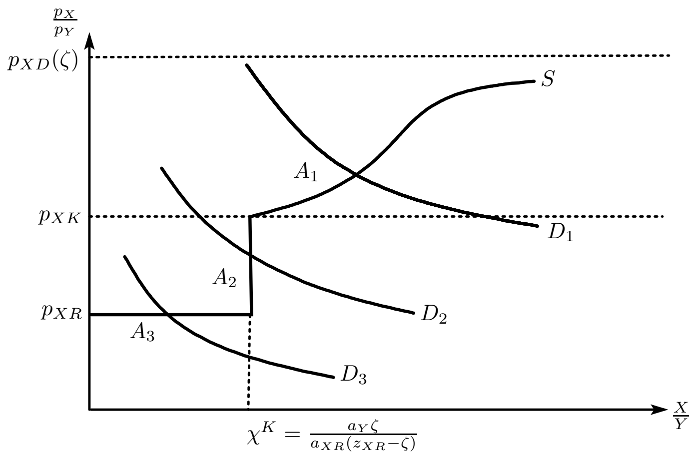


Figure 6: Autarky equilibrium

This relative demand is described by the downward sloping curve $D$ in Figure 6.

There are possible equilibria, that is, $A_i(i = 1, 2, 3)$ for each relative demand curve $D_i$. The emission quota is strictly binding at $A_1$, and is strictly unbinding at $A_3$. It is just binding at $A_2$.

# 3 Free Trade in Goods

In this section, we examine the international trade in goods between two countries that have already implemented domestic emission quotas. We examine the impact of trade liberalization on total emissions under two potential causes for international trade, emission quotas and production technology. First, we consider the case in which a difference in per-capita emission quotas leads to the trade in commodities. In this setting, we show that trade liberalization does not curb global warming. Second, we extend the model to the case in which a technology gap also leads to trade. In this extended setting, trade liberalization could result in double gains from trade, global warming mitigation and the standard gains from trade.

## 3.1 Comparative Advantage Based on Emission Quotas

We consider the case in which the two countries differ on the evaluation of external damage from global warming. This difference in perception of environmental damage leads to different emission quotas for the two countries. We assume that the per-capita emission quota of the home country is less than that of the foreign country,

$$\frac{Z}{L} < \frac{Z^*}{L^*}.$$

Furthermore, we assume that the production technology for good $X$ in the foreign country is given by the function

$$X^* = \frac{1}{\lambda_X} F(L_X^*, Z_X^*), \ \lambda_X > 1.$$

The home country has a Hicks-neutral technical advantage for the production of good $X$ over the foreign country. As in the home country, producers of good $X$ in the foreign country have an abatement limit up to which they can reduce their emissions with the use of labor. For a unit output of good $X$, the abetment constraint is given by $(\lambda_X a_{XR}, \lambda_X e_{XR})$, where the minimum emission intensity for the production of good $X$ is $z_{XR}$, the same as that for the home country. The production technology for good $Y$ in the foreign country is given by

$$Y^* = \frac{L_Y^*}{\lambda_Y a_Y}, \ \lambda_Y > 1.$$

Note that the parameter for measuring the technology gap between countries is $\lambda_i$ ($i = X,Y$). When $\lambda_X = \lambda_Y$ holds, the technology gap is the same as that between the sectors, and technological differences do not lead to a comparative advantage. Thus, under the assumption that $\lambda_X = \lambda_Y$, trade could arise from the comparative advantage based on difference in per-capita emission quotas between the countries. In this section, we consider the case in which $\lambda_X = \lambda_Y$ holds.

Figure 7 shows the world trading equilibrium when the two countries

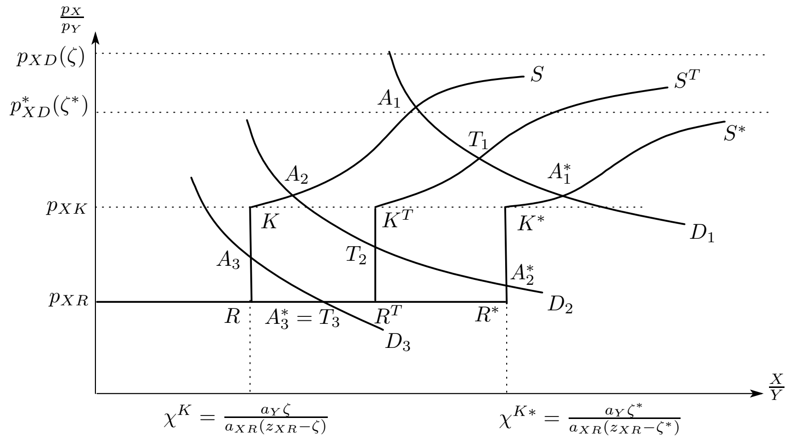


Figure 7: Free commodity-trade equilibrium under $\lambda_X = \lambda_Y$

liberalize their trade in commodities, given the emission quota in autarky.[16] Figure 7 gives the home country's relative supply curve by $p_{XR}RKS$, the foreign country's by $p_{XR}R^*K^*S^*$, and the world relative supply curve by $p_{XR}R^TK^TS^T$, while the three downward sloping curves $D_i(i = 1, 2, 3)$ are the possible relative demand curves showing the relative demand for each country as well as the world.[17] Point $A_i(i = 1, 2, 3)$ shows the associated autarky equilibrium for the home country, while $A_i^*$ is the foreign counterpart. The world trading equilibrium is then shown by point $T_i$. Note that for each possible case, the foreign country has a comparative advantage in the production of good $X$.

We next examine each equilibrium in more detail. When the relative demand curve is given by $D_1$, each country faces the binding emission quota at both the autarky and commodity-trading equilibria, because the two countries incompletely specialize in both goods. The global GHG emissions remain the same before and after commodity trade liberalization.[18]

[16]We can show hat $p_{XR} = p^*_{XR}$ and $p_{XK} = p^*_{XK}$ (see Appendix A for details).

[17]Needless to say, each relative supply curve coincides with the vertical axis for $p_X < p_{XR}$. In addition, the world relative supply of good $X$ is the weighted average of each country's relative supply of good $X$ with the weight of each country's production share of good $Y$.

[18]This result may not hold when either country regulates the environment through emission taxes rather than quotas. See Ishikawa and Kiyono (2006).

When the relative demand curve is given by $D_2$, the emission quota would be strictly binding for the home country and just binding for the foreign country. After commodity trade liberalization, the two countries incompletely specialize in both goods and produce at the kinky point on the production possibility frontier. Thus, the emission quotas are just binding for both countries. Again, we find no change in the global GHG emissions.

Finally, with the relative demand curve $D_3$, the situation is a little different. Following the free trade in commodities, the home country would produce both goods or specialize in good $Y$, while the foreign country would produce both goods. Only the home country gains from commodity trade because the world relative price at the free trade equilibrium would be the same as the autarky price in the foreign country. Free trade in commodities would expand the production of good $X$ and increase GHG emissions globally. This is because the foreign producers that use less efficient technology would expand their production of good $X$.[19] Interestingly, free trade in goods would increase GHG emissions globally even if the home emission quota becomes unbinding and the foreign emission quota remains unbinding. If we consider the effects of increased emissions, commodity trade would be detrimental to the foreign country, and may or may not benefit the home country.

In sum, we can present the results in the following proposition.[20]

**Proposition 1** *If the technology gap is the same between industries (that is, $\lambda_X = \lambda_Y$), commodity trade would arise from comparative advantage based on the difference in per-capita emission quota between countries. That is, the home country would export good $Y$ and the foreign country would export good $X$. Trade liberalization in goods cannot successfully mitigate global warming.*

[19] The home country that uses a more efficient technology may reduce its output of good $X$, negatively affecting global emissions. However, even in this case, free trade in commodities would necessarily increase global emissions because an expansion in output of good $X$ in the foreign country would outweigh the reduction in output of good $X$ in the home country.

[20] The proposition holds without any technology gap (that is, with $\lambda_X = \lambda_Y = 1$).

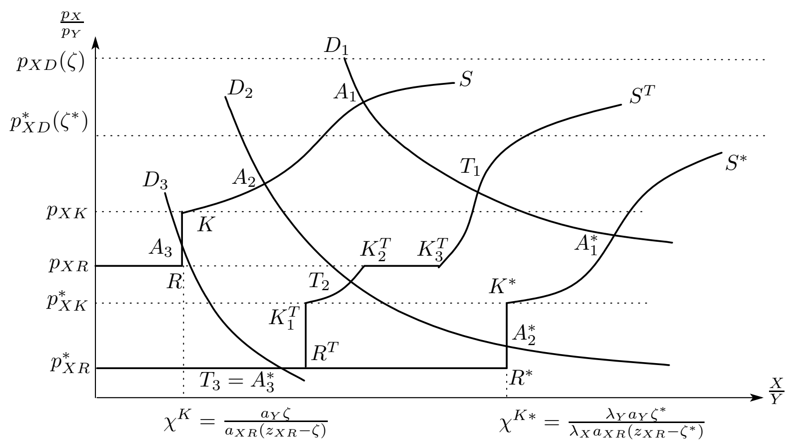


Figure 8: Free commodity-trade equilibrium under $\lambda_X < \lambda_Y$

## 3.2 Comparative Advantage Based on Production Technology and Emission Quotas

Next, we consider the case in which production technology as well as per-capita emission quotas affect the comparative advantage of each country. As in the previous case, we have a situation in which the per-capita emission quota of the foreign country is larger than that of the home country. However, rather than assume that $1 < \lambda_X = \lambda_Y$, we consider two different situations. First, we assume that $1 < \lambda_X < \lambda_Y$; this implies a smaller technology gap for good $X$ than for good $Y$ between the countries. Under this assumption, the gap in production technology would reinforce both the countries' comparative advantage based on per-capita emission quota. Next, we assume that $1 < \lambda_Y < \lambda_X$; this implies a technology gap for good $X$ is larger than for good $Y$ between the countries, and the gap in production technology would weaken both the countries' comparative advantage based on per-capita emission quota. Under these situations, we obtain a novel finding that could not be obtained in the previous subsection. Before discussing further details, let us present our finding: *commodity trading may generate double gains, the standard gains from trade and the additional benefits from the mitigation of global warming.*

In the first case, where $1 < \lambda_X < \lambda_Y$, the relative supply curves of good $X$ can be illustrated as in Figure 8. When the emission quota is not binding for both countries, the foreign country's relative labor cost of good $X$, $p^*_{XR} = \lambda_X a_{XR}/\lambda_Y a_Y$, would be lower than that of the home country, $p_{XR} = a_{XR}/a_Y$.[21] Since a technology gap would reinforce the comparative advantage based on emission quotas, the foreign country's relative supply curve $p^*_{XR}R^*K^*S^*$ is located to the right of that of the home country, $p_{XR}RKS$, for the given relative price of good $X$. From the pattern of relative demand, three different equilibria $T_i$ $(i = 1, 2, 3)$ would arise, with the foreign country having a comparative advantage in good $X$ at any trade equilibrium, as illustrated in Figure 8. If the relative demand curve is $D_1$, the emission quotas would be binding for both countries before and after trade liberalization. In this case, trade liberalization will not affect global GHG emissions, and both countries would enjoy the standard gains from commodity trade.

If the relative demand curve is $D_3$, trade liberalization would expand the global GHG emissions. The logic behind this result is similar to that adopted in the previous section: trade liberalization would enlarge the foreign but reduce the home production of good $X$. Thus, the global GHG emissions would expand from the increase in the production of good $X$ using less efficient technology in terms of emissions.[22] These results suggest that commodity trade can worsen global warming, as found in the previous setting.

However, when the demand curve is $D_2$, trade liberalization would reduce the global GHG emissions. In this case, the emission quota binds both countries before, and only the foreign country after, trade liberalization. In fact, the home country does not emit GHGs in free trade equilibrium because it specializes in good $Y$. Thus, the global GHG emissions decline, implying that the countries benefit from global warming mitigation in addition to the standard gains from commodity trade.

Next, we examine the case of $1 < \lambda_Y < \lambda_X$, where the technology gap for good $Y$ is smaller than that for good $X$. This implies that the technology gap

[21] We can show that $p^*_{XK} < p_{XK}$ (see Appendix A for details).

[22] This result holds because the emission quota binds only the home country before, and neither country after, trade liberalization.

weakens the comparative advantage based on per-capita emission quotas. In this setting, the relative supply curve of the home country, $p_{XR}RKS$, can intersect with that of the foreign country, $p^*_{XR}R^*K^*S^*$, and the world relative supply curve will be $p_{XR}R^TK_1^TK_2^TK_3^TS^T$ as illustrated in Figure 9.[23] Again, we have three different equilibria $T_i$ $(i = 1, 2, 3)$ based on the pattern of relative demand. If the relative demand is $D_1$, the foreign country would have a comparative advantage in good $X$ because its larger per-capita emission quota would allow it to have a lower relative cost for good $X$ than the home country. Under this situation, free trade in goods would not affect global warming because the emission quota is binding for both countries before and after trade liberalization.

If the relative demand is $D_2$ or $D_3$, then the home country would have a comparative advantage in good $X$ because technology gap plays a more important role in determining the comparative advantage than the difference in per-capita emission quotas. Free trade in goods can curbs global warming under both relative demand curves. The reason for this is the same as in the previous case. The foreign country specializes in good $Y$ and its emissions decrease, while the home country incompletely specializes, and so its emission quota is binding before and after trade liberalization.

In sum, we can present the results in the following proposition.

**Proposition 2** *Suppose that the technology gap for good $Y$ is smaller than that for good $X$ (i.e., $1 < \lambda_Y < \lambda_X$). Then, the foreign country can have a comparative advantage in good $Y$. If it does, trade liberalization in goods will reduce the global GHG emissions. Thus, both countries benefit from improvement in global warming besides the conventional gains from commodity trade.*

Note that the foreign country will have a comparative advantage in good $Y$ only if $1 < \lambda_Y < \lambda_X$ holds. Moreover, the above proposition has a

[23] See Appendix A for the proof that $p_{XR} < p^*_{XR}$ and $p_{XK} < p^*_{XK}$. Figure 9 shows the case where $\chi^K < \chi^{K*}$; this occurs because of the difference in per-capita emission quotas is sufficiently large. Otherwise, we would have $\chi^K > \chi^{K*}$. Then, the home country would have a comparative advantage in producing good $X$. The following results would continue to hold even in a different situation.

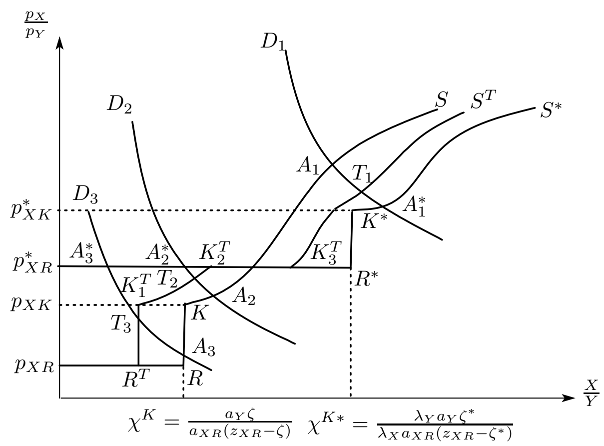


Figure 9: Free commodity-trade equilibrium under $\lambda_Y < \lambda_X$

sufficient condition for emission reductions; that is, even if the foreign country has a comparative advantage in good $X$, free trade in goods may reduce the global emissions. This is the case when the foreign emission quota is binding before and after trade liberalization (recall the case where the relative demand is given by $D_2$ in Figure 8). Form Propositions 1 and 2, global emissions increase only if trade liberalization increases foreign emissions.

# 4 International Emissions Trading with Free Trade in Goods

We next consider the effect of emissions permit trading after the liberalization of commodity trade. As already shown, commodity trading may result in the double gains globally, that is, the standard gains from commodity trade and the gains from improvement in global warming. In this section, we examine how emissions permit trading affects global warming and discuss its implications for the welfare of countries.

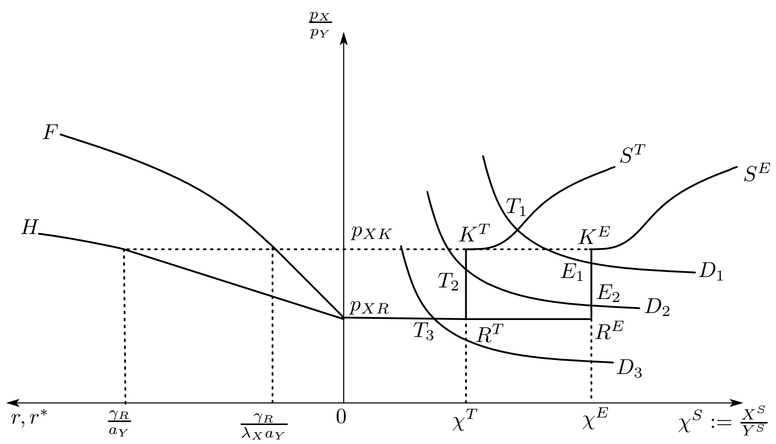


Figure 10: The effects of emissions trading under $\lambda_X = \lambda_Y$

## 4.1 International Emissions Trading and GHG Emissions

First, we consider the case in which technology gaps do not affect trade patterns; that is, the comparative advantage arises from only the international difference in per-capita emission quota. In this situation, international emissions trading will not affect the global GHG emissions. Figure 10 shows how the prices of emissions permit differ between countries under incomplete product specialization. The first quadrant in Figure 10 replicates the free trade equilibria in Figure 7 with the relative demand curve, $D_i$, and the world relative supply curve, $S^T$. The second quadrant in Figure 10 shows the relation between the relative price of good $X$ and the emissions permit price in the home country, $p_{XR}H$, as well as for the foreign country, $p_{XR}F$. Given the relative price of good $X$, which is greater than $p_{XR}$, the emissions permit price in the home country, $r$, is necessarily higher than that in the foreign country, $r^*$, because the home producers have technical advantage in the production of good $X$. This suggests that the home country would buy emission permits from the foreign country under free trade in both permits and commodities.

When international emissions trading is liberalized, the world relative supply curve is illustrated as $p_{XR}R^EK^ES^E$ in the first quadrant of Figure

10.[24] This situation arises under the assumption that the labor endowment of both countries is large enough to absorb the total world GHG emission permits,

$$Z^W < \min\{z_{XR}L, z^*_{XR}L^*\}, \tag{4}$$

where $Z^W = Z + Z^*$. This condition implies that the emission quota can bind even if all the permits are allocated to either country.[25]

From Figure 10, when the relative demand is $D_1$, the trade in emission permits would shift the equilibrium from $T_1$ to $E_1$. As the home country imports all permits from the foreign country, the production of good $X$ in the foreign country would completely relocate to the home country, reversing the trade pattern; that is, international emissions trading would induce the home country to export rather than import good $X$. The movement of emission permits does not affect global GHG emissions because emission quotas necessarily bind the countries. Similarly, when the relative demand is $D_2$, international emissions trading would reverse the trade pattern and not affect total emissions. When the relative demand is $D_3$, the price of emission permits would collapse to zero because emission quotas do not bind either country, and no emissions trading would occur between the countries. In sum, trade in emission permits does not affect the global GHG emissions.

The above mentioned finding on the neutrality of international emissions trading for global warming does not necessarily hold when the trade in commodities is driven by two sources of comparative advantage, production technology and emission quota. First, consider the case where $\lambda_X < \lambda_Y$ holds and the technology gap reinforces both countries' comparative advantage in production. Figure 11 illustrates how permit prices differ between the countries under this situation. Unlike in the previous case, foreign producers of good $X$ can offer a higher permit price than the home producers for a given relative price of good $X$ that is greater than $p^*_{XR}$.[26] In this case, the gap

[24] See Appendix B for the proof of this result.

[25] This assumption guarantees that the emissions permit prices are positive even when all permits are absorbed by either country under international emissions trading.

[26] Obviously, the home country's permit price could be higher than that of the foreign country if the gap in relative labor costs between $p_{XR}$ and $p^*_{XR}$ is significantly small. The second quadrant of Figure 11 shows that $p^*_{XR}F$ would intersect with $p_{XR}H$, and that

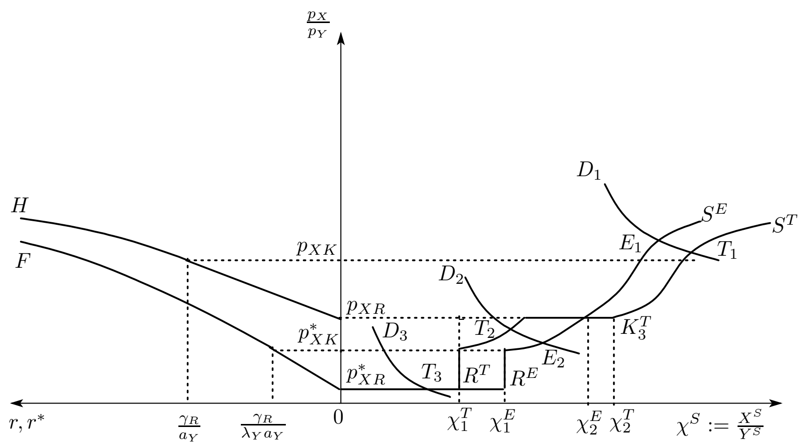


Figure 11: The effects of emissions trading under $\lambda_X < \lambda_Y$

in labor productivity between the countries is smaller for good $X$ than good $Y$, implying that the foreign wage rate is lower than the home rate under incomplete specialization in production.[27] The lower wage rate could allow the foreign producers of good $X$ to offer a higher reward for emission permits than the home producers even when the foreign country has a lower productivity in emission permits use as compared to the home country.

The first quadrant of Figure 11 replicates the world commodity market equilibria with the relative demand curve, $D_i$, and the world relative supply curve, $p^*_{XR}R^T K_1^T K_2^T K_3^T S^T$, as illustrated in Figure 8.[28] When the trade in emission permits is liberalized between the countries, the foreign country would expand its production of good $X$ by importing permits from the home country. Thus, the home country would specialize in good $Y$, while the foreign country would produce both goods under the emission quota condition (4), and the world relative supply curve would shift to $p^*_{XR}R^E S^E$ from $p^*_{XR}R^T K_3^T S^T$. The effect of international emissions trading on the world relative supply would depend on the initial production pattern of both countries.

above the intersection, the home permit price would be higher than the foreign price. This possibility affects the pattern of emissions trading, but does not affect the following main results on the emissions trading implications for the global environment.

[27] The foreign producers of good $Y$ can be competitive compared with the home counterparts because its lower wage rate offsets the disadvantage in labor productivity.

[28] In Figure 11, we abbreviate $K_1^T$ and $K_2^T$ for better clarity.

Suppose that $p_X \in [p^*_{XR}, p_{XR})$ before allowing for international emissions trading. Then, the home country would specialize in the production of good $Y$, and its emission quota would not bind. Meanwhile, the foreign country would specializes incompletely in the production and fully utilize its emission quota. Under this situation, emission trading would necessarily expand the world relative supply of good $X$, and increase the global GHG emissions, because the unused emission permits owned by the home country would be sold to the foreign country. This outcome is illustrated as a shift in equilibrium from $T_2$ to $E_2$ when the relative demand curve is $D_2$.

If $p_X \geq p_{XR}$, then international emissions trading could reduce the world relative supply of good $X$.[29] This is because the production of good $X$ relocates to the technologically less efficient foreign country but the production of good $Y$ moves to the technologically advanced home country. In this situation, international emissions trading would not affect the global GHG emissions because the emission quota is binding for both countries before and after the liberalization of international emissions trading.[30] This outcome is illustrated as a shift in equilibrium from $T_1$ to $E_1$ under the relative demand curve $D_1$. Finally, when the relative demand is $D_3$, no international emissions trading would occur because the emission quota would not binding and the permit prices would be zero in both countries.

Next, we consider the case where $\lambda_Y < \lambda_X$ and the technology gap would weaken the comparative advantage based on international difference in per-capita emission quota. From Figure 12, unlike in the previous case, the home country always offers a higher emissions price than the foreign country, given the relative price of good $X$ which is greater than $p_{XR}$. This is because the home country has a comparative labor cost advantage in producing good $X$ (a lower relative labor cost of good $X$) as well as an absolute advantage (higher productivity) in emission permits use. When the trade in permits and commodities is liberalized, the home country would import permits from the foreign country. The first quadrant in Figure 12 replicates the free commodity

[29] We provide the proof of this claim in Appendix B.

[30] If the relative price of good $X$ equals $p_{XR}$, then the home country may incompletely specialize in production and its quota may not be binding before allowing for emissions trading. In this case, emissions trading would expand the global GHG emissions.

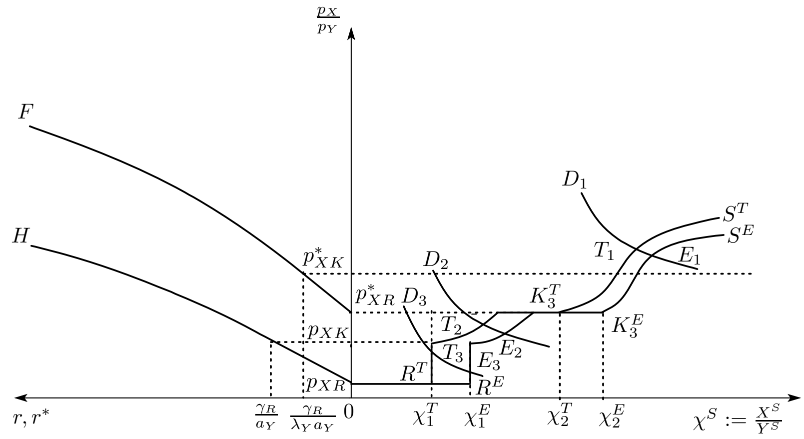


Figure 12: The effects of emissions trading under $\lambda_Y < \lambda_X$.

trade equilibria $T_i$ with the relative demand curve $D_i$ and the world relative supply curve $p_{XR}R^T K_1^T K_2^T K_3^T S^T$, as illustrated in Figure 9.[31] Given the relative price of good $X$, international emissions trading expands the world relative supply of good $X$ because the home country with technical advantage produces more of good $X$ relative to good $Y$, with the opposite occurring for the foreign country with technical disadvantage. This implies that the world relative supply curve under international emissions trading $p_{XR}R^E K_3^E S^E$ is located to the right of $p_{XR}R^T K_3^T S^T$ for the given relative price of good $X$ in Figure 12.[32]

The effect of international emissions trading on global warming depends on the pattern of the relative demand. If the relative demand curve is $D_1$, then international emissions trading would not affect the global emissions because the emission quota continues to bind. However, when the relative demand is $D_2$ or $D_3$, the global emissions increase because of international emissions trading. The reason for this result is the same in the previous case. International emissions trading allows the foreign country specializing in good $Y$ to sell unused emission permits to the home country. Thus, the home country emits more GHGs using imported permits and expands its

[31] In Figure 12, we abbreviate $K_1^T$and $K_2^T$ for better clarity.

[32] We assume that the emissions quota condition, (4), holds. See Appendix B for the proof.

production of good $X$. Again, this suggests that international emissions trading worsens global warming.

Note that the two technology gap cases have common properties in the effects of international emissions trading on global warming. First, if international emissions trading increases the global emissions, it would completely offset the reduction in the emissions because of trade liberalization in goods. Second, international emissions trading expands the global GHG emissions because it allows for the country specializing in good $Y$ to export unused permits to the other country, which can use them to increase its production of good $X$.

We summarize the above results as the following proposition.

**Proposition 3** *If a comparative advantage is based only on the international difference in per-capita emission quota, then the international trade in emission permits under free trade in goods would not affect the global GHG emissions. On the other hand, if a comparative advantage is based on the technology gap as well as difference in per-capita emission quota, with one country completely specializing in good $Y$, then the global GHG emissions would increase from international trade in emission permits.*

## 4.2 Welfare Implications of International Emissions Trading

We now discuss the welfare implications of international emissions trading. Since we treat emission permits as an environmental resource input, we can use the literature on international factor movements for our purpose. Grossman (1984) showed that a country engaging in free trade in goods can gain from international factor movements if its terms of trade in goods improve. Since Grossman (1984) does not consider the external effect of GHG emissions, we need to take into account the effect of international emissions trading on global warming as well as the conventional terms of trade effect. When the comparative advantage is based on the difference in per-capita emission quota between the countries, international emissions trading would not affect the global GHG emissions. Thus, the welfare effects of international emissions trading depends only on the terms of trade effect. Since international emissions trading would expand the relative supply of good $X$, the country importing good $X$ would benefit from the improvement in the terms of trade. Nonetheless, as shown in Figure 10, international emissions trading reverses the pattern of trade and thus makes it ambiguous as to which country would gain from the trade in emission permits.

When the comparative advantage is affected by the technology gap as well as the difference in per-capita emission quotas, the welfare effect of international emissions trading may also depend on its impact on global warming. When the relative demand curve is given by $D_1$ in Figures 11 or 12, international emissions trading would not affect the global GHG emissions. Thus, in both cases, the welfare effect of international emissions trading is determined by the terms of trade effect alone. As regards Figure 11 (with the relative demand curve $D_1$), where the technology gap reinforces the comparative advantage based on the difference in per-capita emission quota, international emissions trading would reduce the relative supply of good $X$ because the foreign technologies are less efficient than the home technologies. Thus, the foreign country exporting good $X$ benefits from improvement in its terms of trade. As regards Figure 12 (with the relative demand curve $D_1$), where the technology gap weakens the comparative advantage based on the difference in per-capita emission quota, the welfare effect of international emissions trading is ambiguous because the trade pattern is reversed.

If the relative demand curve is given by $D_2$ in Figure 11 or by $D_2$ or $D_3$ in Figure 12, then international emissions trading would expand the global GHG emissions, implying a negative external effect on both countries. Concurrently, the world relative supply of good $X$ would increase, benefiting the country importing good $X$ because of improvement of its terms of trade. As regards Figure 11, the terms of trade effect would benefit the home country, and as regards Figure 12, it would benefit the foreign country. In both cases of the technology gap, the country having positive terms of trade effect exports emission permits. Moreover, if the negative effect on global warming offsets the positive effect on the terms of trade, international emissions trading would hurt the country.

**Proposition 4** *i) Suppose that the comparative advantage is based only on the international difference in per-capita emission quota. Then, international emissions trading under free trade in goods would reverse the trade pattern, and the effect of international emissions trading on the terms of trade in goods would become ambiguous. ii) Suppose that the comparative advantage arises from the technology gap in addition to international difference in per-capita emission quota. Unless the trade pattern is reversed, international emissions trading would improve the terms of trade in goods for the country importing good $X$ and exporting emission permits. Nonetheless, the country's welfare would worsen if the deterioration in global warming because of international emissions trading outweighs the gains from international emissions trading.*

Note that the results of the above proposition are derived assuming that the foreign country with technological disadvantage has a greater per-capita emission quota than the home country with more advanced technology. Under the alternative assumption that the home country has a greater per-capita emission quota than the foreign country, most of the results would hold except when the comparative advantage is based on the international difference in per-capita emission quotas alone. In this case, the trade pattern would not reverse, and the result would be modified as follows: international emissions trading would benefit the foreign country importing good $X$ and exporting emission permits because of improvement in its terms of trade. When the technology gap is an additional factor of comparative advantage, we can confirm that the results derived in the above proposition would hold.[33]

[33] In this alternative case, with the technology gap reinforcing the comparative advantage based on per capita emissions quota, the negative effect of deterioration in global warming could outweigh the positive effect of improvement in the terms of trade for the foreign country importing the emission-intensive good and exporting emission permits. Similar consequences occur for the home country when the technology gap weakens the comparative advantage based on per capita emissions quota.

## 5 Conclusion

In this study, we have examined the welfare effects of international commodity and emissions trading. The total welfare effect of international commodity trading involves two effects: efficiency gains from trade in goods, and gains or losses from the change in global warming. When a comparative advantage stems from only the difference in per-capita emission allowances, commodity trading cannot successfully reduce global warming. However, in case of technology differences between countries, commodity trading may generate an extra benefit from improvement in global warming.

Global trade in emission permits does not guarantee further gains for the countries. International emissions trading never mitigates global warming, because the unused permits could be traded for use in production of the emission-intensive good. This would occur regardless of which country is given a more generous emission quota. The total welfare effect of international emissions trading can be decomposed into three effects: efficiency gains from trade in emission permits, gains or losses from a change in the terms of trade in goods, and losses from aggravated global warming.

International emissions trading can also worsen the welfare of the countries as compared to autarky. If the emission quota does not bind under autarky, emissions as well as commodity trading would induce specialization in the emission-intensive good, and its world production could expand. This would worsen global warming as compared to autarky. If the negative impact of increase in emissions is large enough to nullify the positive benefit due to an increase in production efficiency, the welfare level would fall below the autarky level.

Of course, given the binding emission quotas under autarky, the simultaneous liberalization of the international commodity and emissions trading would make neither country worse off, but improve the welfare of both countries in general. In this sense, our propositions on the potential welfare losses from international emissions trading does not necessarily imply that the countries are worse off, compared with autarky. The problem arises when countries do not liberalize their trade in commodities and permits simultaneously. A serious conflict can arise in the interests of countries that have already liberalized their commodity trading when they get an opportunity to cooperate in the control of global warming through permits trade. This reminds us of the importance of the order of trade liberalization in goods and factors of production, as discussed in Bhagwati and Brecher (1980).

# Appendix A: The Relation between Technology Gaps and Relative Unit Costs

We examine the relation between technology gaps and relative unit costs. For the home country, the competitive conditions for production under incomplete specialization and an unbound emission quota are given by

$$p_{XR} = wa_{XR},$$
$$1 = wa_Y.$$

Taking the ratio of these conditions, we have $p_{XR} = a_{XR}/a_Y$. Similarly, for the foreign country, we have

$$p^*_{XR} = w^*\lambda_X a_{XR},$$
$$1 = w^*\lambda_Y a_Y.$$

The ratio of these conditions is $p^*_{XR} = \lambda_X a_{XR}/\lambda_Y a_Y$. We can show that $p_{XR} = p^*_{XR}$ when $\lambda_X = \lambda_Y$ and $p_{XR} \lesseqgtr p^*_{XR}$ if $\lambda_X \gtreqless \lambda_Y$. Under incomplete specialization and an emission quota that is just binding, the competitive conditions for good $X$ production in the home and foreign countries are, respectively,

$$p_{XK} = wa_{XR} + re_{XR},$$
$$p^*_{XK} = w^*\lambda_X a_{XR} + r^*\lambda_X e_{XR}.$$

The unit costs of good $X$ in terms of good $Y$ can be derived as

$$p_{XK} = p_{XR} + \frac{e_{XR}}{a_Y}\gamma_R,$$
$$p^*_{XK} = p^*_{XR} + \frac{\lambda_X e_{XR}}{\lambda_Y a_Y}\gamma^*_R.$$

Recall that $\gamma_R$ denotes the critical ratio of emission price to wage rate above which the emission regulation induces producers to abate their emissions through the use of labor. Under the Hicks-neutral technology gap, both countries have the same critical emission intensities, that is, $z_{XR} = e_{XR}/a_{XR} = \lambda_X e_{XR}/\lambda_X a_{XR} = z^*_{XR}$, and the same critical ratios of the emission price to the wage rate, $\gamma_R = \gamma^*_R$. Thus, we can show that $p_{XK} = p^*_{XK}$ for $\lambda_X = \lambda_Y$ and $p_{XK} \lesseqgtr p^*_{XK}$ for $\lambda_X \gtreqless \lambda_Y$.

# Appendix B: The Effect of Emissions Trading on the World Relative Supply of Good $X$

We show how international emissions trading would affect the world relative supply of good $X$. Before the international emissions trading is allowed, the world relative supply of good $X$ can be derived as

$$\chi^S = \frac{X + X^*}{Y + Y^*}, \tag{5}$$

where $X = (Z^W - Z^*)/e_X(\gamma)$, $X^* = Z^*/\lambda_X e_X(\gamma^*)$, $Y = (L - a_X(\gamma)X)/a_Y$, and $Y^* = (L^* - \lambda_X a_X(\gamma^*)X^*)/\lambda_Y a_Y$. We can derive $X + X^*$ and $Y + Y^*$ as

$$X + X^* = Z^W - [1/e_X(\gamma) - 1/\lambda_X e_X(\gamma^*)]Z^*,$$
$$Y + Y^* = L/a_Y + L^*/\lambda_Y a_Y - a_X(\gamma)Z^W/a_Y e_X(\gamma)$$
$$+ [a_X(\gamma)/a_Y e_X(\gamma) - a_X(\gamma^*)/\lambda_Y a_Y e_X(\gamma^*)]Z^*.$$

First, consider the case in which the comparative advantage is based on the difference in per-capita emission quota only. Then, we have $a_X(\gamma) = a_X(\gamma^*) = a_{XR}$ and $e_X(\gamma) = e_X(\gamma^*) = e_{XR}$ for $p_X \in [p_{XR}, p_{XK}]$. Under these conditions and $\lambda_X = \lambda_Y > 1$, $\chi^S$ decreases with $Z^*$. Thus, the movement of emission permits from the foreign to home country would raise the world relative supply of good $X$, $\chi^E > \chi^T$ in Figure 10. For $p_X > p_{XK}$, $a_X(\gamma) > a_X(\gamma^*)$ and $e_X(\gamma) < e_X(\gamma^*)$, because $\gamma > \gamma^*$. Thus, $K^E S^E$ is located to the right of $K^T S^T$ in Figure 10.

Next, we turn to the case in which the technology gaps affect the comparative advantage in production. First, consider the case with $1 < \lambda_X < \lambda_Y$. Before international emissions trading is allowed, the home country specializes in good $Y$, and $X = 0$ for $p_X \in [p^*_{XR}, p^*_{XK})$. The world relative supply of good $X$ is derived as

$$\chi^S = \frac{Z^*/\lambda_X e_X(\gamma^*)}{L/a_Y + L^*/\lambda_Y a_Y - \lambda_X a_X(\gamma^*) Z^*/\lambda_Y a_Y e_X(\gamma^*)},$$

where $a_X(\gamma^*) = a_{XR}$ and $e_X(\gamma^*) = e_{XR}$. This equation implies that the foreign country's emission permit imports from the home country would move the world relative supply curve of good $X$ to the right and $\chi_1^T < \chi_1^E$ in Figure 11. For $p_X \geq p_{XR}$, the home country can incompletely specialize in production. Then, the world relative supply of good $X$ is derived as (5). Since $\gamma < \gamma^*$ for $p_X \geq p_{XR}$, we have $a_X(\gamma) < a_X(\gamma^*)$ and $e_X(\gamma) > e_X(\gamma^*)$. Under these conditions of factor inputs, the movements of emission permits from the home to foreign country would reduce the world relative supply of good $X$ if the technical advantage of the home country is sufficiently large,

$$\lambda_X > \frac{e_X(\gamma)}{e_X(\gamma^*)}, \ \lambda_Y > \frac{e_X(\gamma)/a_X(\gamma)}{e_X(\gamma^*)/a_X(\gamma^*)}. \tag{6}$$

This result suggests that the movements of emission permits from the home to foreign country would shift the world relative supply curve of good $X$ to the left for $p_X \geq p_{XR}$ and $\chi_2^E < \chi_2^T$ in Figure 11.

We next turn to the case where $1 < \lambda_Y < \lambda_X$. Before international emissions trading is liberalized, the foreign country specializes in good $Y$, and $X^* = 0$ for $p_X \in [p_{XR}, p^*_{XR})$. The world relative supply of good $X$ is

$$\chi^S = \frac{(Z^W - Z^*)/e_X(\gamma)}{L/a_Y + L^*/\lambda_Y a_Y - a_X(\gamma)(Z^W - Z^*)/a_Y e_X(\gamma)},$$

where $e_X(\gamma) = e_{XR}$ and $a_X(\gamma) = a_{XR}$ for $p_X \in [p_{XR}, p_{XK})$. Under international emissions trading, the home country buys permits from the foreign country, and thus a reduction in $Z^*$ would raise $\chi^S$, to result in $\chi_1^T < \chi_1^E$ in Figure 12. For $p_X \geq p^*_{XR}$, the foreign country incompletely specializes in production and the world relative supply is derived as (5). Because $\gamma > \gamma^*$ for $p_X \geq p^*_{XR}$, we have $a_X(\gamma) > a_X(\gamma^*)$ and $e_X(\gamma) < e_X(\gamma^*)$, and (6) is necessarily holds. Thus, the movement of emission permits from the foreign to home country would shift the word relative supply curve to the right for a given relative price of good $X$, and $\chi_2^T < \chi_2^E$ in Figure 12.

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