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Technology Transfer, Emissions Trading, and International Trade*

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Abstract

We explore the effects of international technology transfers on global warming and welfare in a two-country (home and foreign), two-good, general equilibrium model with Ricardian and Heckscher–Ohlin features. We consider a situation in which both countries enforce emissions trading, and the home country, which has superior technologies in both sectors, has a comparative advantage in less emissions-intensive goods under free trade. The home country benefits from technology transfers in the more emissions-intensive industry due to an improvement in its terms of trade. The foreign country can also gain because global greenhouse gas emissions (GHGs) decrease. Technology transfer in the less emissions-intensive sector can lead to a more significant reduction in GHG emissions but may harm the home country. When free trade in emission permits and goods is allowed between countries, technology transfers in either sector will likely increase the emissions permit price without affecting global GHG emissions. An increase in the permit price negatively affects the welfare of the home country that imports permits from the foreign country. International emissions trading may reduce the incentive for technology transfers because there is no environmental benefit, and the permit price is higher.

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

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1 Introduction

Global warming is one of the greatest global concerns. The global average temperature increased by 1.09 °C between 1850 and 2020.[1] Rising global temperatures have been accompanied by climate change, causing extensive damage. Recently, unusual weather conditions have caused floods, droughts, and severe heat waves worldwide.

The world has joined efforts to tackle global warming. The United Nations Framework Convention on Climate Change (UNFCCC), an international treaty, 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 met annually (except 2020). Of the COP meetings, the 1997 COP3 Kyoto and 2015 COP21 Paris sessions are the most noteworthy.

The Kyoto Protocol, adopted in the COP3 session, introduced three market-based mechanisms, the so called the Kyoto mechanisms. These are emissions trading, clean development mechanisms (CDMs) and joint implementation (JI).[3] In particular, emissions trading has attracted considerable attention. For example, the European Commission states that market-based carbon trading is an instrument for countries to reach their targets at least 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, the cap is set on the GHGs permissible for a country to emit.[4] Under this system, spare allowances can be sold in the market.[5]

The Kyoto Protocol is a notable step toward reducing GHGs. However, developing countries have no obligation to reduce GHGs.[6] In the COP21 sessions, the Paris Agreement was reached, which is a legally binding international climate change treaty. Following the agreement, 197 Parties, including developed and developing countries, submitted their specific GHG emission reduction targets. However, these targets were heterogeneous because the Parties set their emission targets noncooperatively. For example, the EU's current target is a 62% GHG reduction by 2030 from their 1990 level and zero net emissions by 2050.[7] China's target is more than 65% reduction in CO2 emissions per unit of GDP by 2030 from the 2005 level and zero net emissions by 2060. Since China's reduction target is in terms of per unit of GDP, their

[1] https://www.ipcc.ch/report/ar6/wg1/

[2] The UNFCCC came into effect in March 1994; it has been ratified by 198 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. CDM allows Annex I Parties to purchase emission allowances from projects in non-Annex I Parties.

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

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

[6] The United States (US) was a signatory to the protocol but has not ratified it.

[7] The US, Japanese, and Russian targets (as of August 2022) are, respectively, a 50–52% reduction by 2030 from their 2005 level and zero net emissions by 2050, a 46% reduction by 2030 from their 2013 level and zero net emissions by 2050, and a 30% reduction by 2030 from their 1990 level and zero net emissions by 2060, respectively.

emissions are expected to continue increasing, reaching the maximum in 2030.[8]

Many countries would meet their targets using carbon pricing, such as emission taxes and emissions trading. According to the World Bank, coverage shares of global GHG emissions of emission taxes and emission trading have been increasing. Their current shares are, respectively, 5.62% and 17.64%.[9] Thus, emissions trading as a countermeasure against global warming surpasses emission taxes.

Furthermore, the Paris Agreement emphasizes the importance of technology transfer for reducing GHG emissions. Article 10, paragraph 5, of the agreement states:

> Support, including financial support, shall be provided to developing country Parties for the implementation of this Article, including for strengthening cooperative action on technology development and transfer at different stages of the technology cycle, with a view to achieving a balance between support for mitigation and adaptation.

With respect to technology differences, it has been reported that emissions intensities significantly differ between developed and developing countries. In 2019, China had 0.45 in its CO2 emission intensity (kg of CO2 per PPP USD of GDP), while those of the EU, Japan, and the US are 0.13, 0.20, and 0.22, respectively (World Development Indicators). Douglas and Nishioka (2012) found a negative relationship between emission intensity and TFP, concluding that technology differences play an important role in explaining disparities in emission intensities across countries. They also pointed out that the current implicit emission prices differ due to international differences in production techniques and technology transfers could reduce global emissions.

Climate Technology Centre & Network (CTCN) has undertaken various technology transfers, which started operation in 2013 based on the Cancun Agreements in COP16. In response to requests submitted by developing countries, the CTCN provides technical assistance by experts on specific climate technology sectors. Examples include a substantial reduction in GHG emissions in the cement industry in South Africa and the development of sectoral Technological Action Plans for implementing Morocco's long-term strategy for low GHG emissions. Furthermore, countries like Japan have been promoting international technology transfer with high environmental and energy performance through Official Development Assistance.

Thus, emissions trading and technology transfers are core measures for decarbonization. Since we explored emissions trading elsewhere (Ishikawa and Kiyono, 2006; Ishikawa et al., 2012, 2020), this study tackles the following research question: What are the effects of international technology transfer on GHG emissions and welfare within the framework of an open economy? In particular, considering the importance of emissions trading, we address this question in the presence of domestic or international emissions trading.

[8] India's target, similar to China's, is a 45% reduction in emissions per unit of GDP by 2030 from the 2005 level.

[9] https://carbonpricingdashboard.worldbank.org/map_data

Our model is based on Ishikawa and Kiyono (2006), which compare different emissions regulations in an open economy, using both Ricardian and Heckscher-Ohlin features. Specifically, we developed a simple two-country, two-good, general equilibrium international trading model for goods and emission permits. Labor is the primary factor used to produce the two goods. However, following Meade (1952), we consider the GHG emissions as an environmental resource input for production.[10] Moreover, we consider a technology gap between the two countries, assuming that the home country (the North) has superior technologies for both industries compared to a foreign country (the South).

Helm (2003) used a noncooperative game to consider the endogenous determination of emission allowances. He showed that countries more concerned with the environment would choose fewer permits, with international emissions trading, whereas those with fewer environmental concerns would choose more permits. Based on this finding, we assume that per capita emission allowances of countries are exogenously given, by the foreign country (the South) receiving a greater allowance than the home country (the North).

Ishikawa and Kiyono (2006) examined unilateral emission regulations. Their analysis shows that emissions trading is introduced only in the North. Ishikawa et al. (2012) consider the welfare and environmental effects when implementing domestic or international emissions trading, given that the countries are engaged in free international trade in goods. Ishikawa et al. (2020) extended the analysis of Ishikawa et al. (2012) and obtained more general results for international emissions trading. However, none of the studies above deals with technology transfer.

Greaker and Hagem (2014) and Helm and Pichler (2015) theoretically investigated the technology's role in the presence of international emissions trading. Greaker and Hagem (2014) dealt with the R&D of GHG emission abatement technologies, and Helm and Pichler (2015) considered technology transfer from the North to the South. Greaker and Hagem (2014) showed that the North benefits from investing in reducing abatement costs in the South because such investments reduce the future permit price. Helm and Pichler (2015) concluded that the North's motivation to subsidize international technology transfers is to reduce the permit price, given that the North is a permit buyer. Unlike these studies, we explicitly consider both goods and emissions trading and show that international technology transfer can increase the permit price. This result implies that emissions trading can reduce incentives for the North to transfer technology to the South since it imports permits from the South.

We also show that sectors and trade regimes matter for the effects of technology transfer on national welfare and the global environment. Under international trade in goods only, technology transfer from the North to the South in the less emissions-intensive sector can lead to a larger reduction in global GHG emissions than in the more emissions-intensive sector. Technology transfer in the more emissions-intensive sector can benefit both the North and the South. The North gains from the improved terms of trade in goods and reduced global GHG emissions. The South also benefits if environmental and technological gains are greater than the

[10] For example, Copeland and Taylor (1994,1995,2005), Ishikawa and Kiyono (2006), Ishikawa, Kiyono, and Yomogida (2012, 2020) follow this idea.

loss from a deterioration in terms of trade in goods. If trade in permits and goods is liberalized, technology transfers in either sector may not reduce global GHG emissions. This may, however, reduce the incentive for the North to engage in technology transfers in addition to the negative welfare impact of an increase in the permit price.

The rest of this paper is organized as follows. In Section 2, we develop the basic model with domestic emissions trading and free trade in goods. Section 3 examines whether international technology transfers lead to economic and environmental benefits under free trade in goods. Section 4 extends the basic model by introducing international emissions trading and analyzes the effects of international technology transfers. Section 5 concludes the paper.

2 The Basic Model

Two goods (X and Y) are initially produced with a single factor (labor) under constant returns-to-scale technology and consumed by households. Whereas producing good Y leads to no GHG emissions, producing good X does.[11] GHG emissions worsen global warming and harm households. We describe the production technology for each good below.

2.1 Production Technology

Following 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, unregulated, and socially overused production factor. Thus, environmental regulation internalizes the social opportunity cost of such resources for the private evaluation of costs and benefits. For simplicity of exposition, we refer to this environmental resource input as emissions. Specifically, we assume that the government enforces a total emission quota in the form of a tradeable emission permit in the domestic market. Thus, the emission price given below is also the emission permit price.

Producing one unit of good Y requires a_Y units of labor, whereas 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; however, this has a limit, given by (a_{XR}, e_{XR}), where a_{XR} is the minimum labor input and e_{XR} is the maximum GHG emissions to produce one unit of good X. A unit isoquant of good X is illustrated in Figure 1. Subustituting labor inputs for GHG emissions is possible only in the region above a_{XR}. Without any environmental regulation, firms would choose a_{XR} units of labor to produce one unit of good X.

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

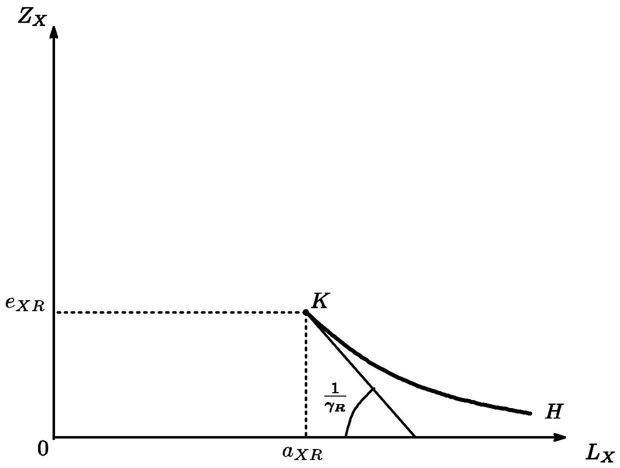

Figure 1: Technical substitution between labor inputs and emissions

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 is 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 will be

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

Let γ denote the relative emission price, r/w, and γ_R denote the critical relative emission price above which the emissions regulation is effective, promoting 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 producing good X. The critical emission intensity for γ_R is denoted by z_{XR} ($:= e_{XR}/a_{XR}$). The relationship between γ and z can be visualized by the downward-sloping curve shown in Figure 2.

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

Assumption 1 *The government imposes a 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 remain for the production of good Y, and the country would completely specialize in good X. The associated relative emission price is represented by γ_D, depending on the per capita emission quota. We express this relationship 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 γ_R, a substitution would occur between labor and emissions along segment DK. However, if the relative emission price is equal to or lower than γ_R, the substitution ceases and the emission intensity becomes constant at the critical value z_{XR}.

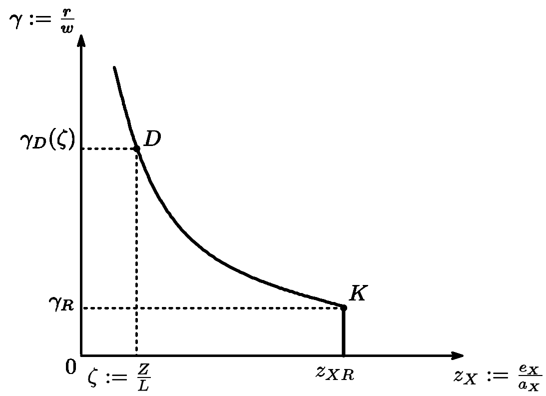

Figure 2: Substitution between labor inputs and emissions

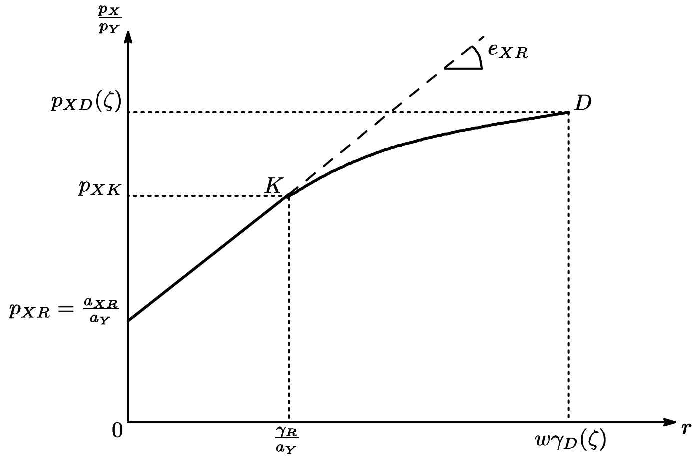

Figure 3: The relation between the relative price of good X and the emission price

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 relationship between the relative and emission prices 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 of the relative price curve is equal to the emission coefficient $e_X(ra_Y)$. A higher emission price promotes substitution of

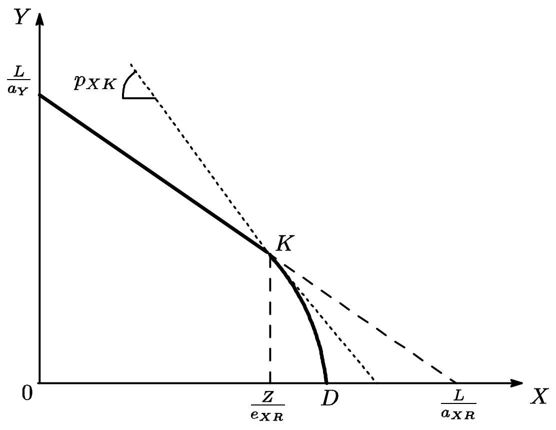

Figure 4: The production possibility frontier

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 ζ (see Figure 2). We also found that the country fully specializes in 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 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

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

Before introducing the emission quotas, the producers of good X did not incur GHG emission costs, with the unit cost of producing good X equal to 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 restricts the capacity to produce good X.

Thus, 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

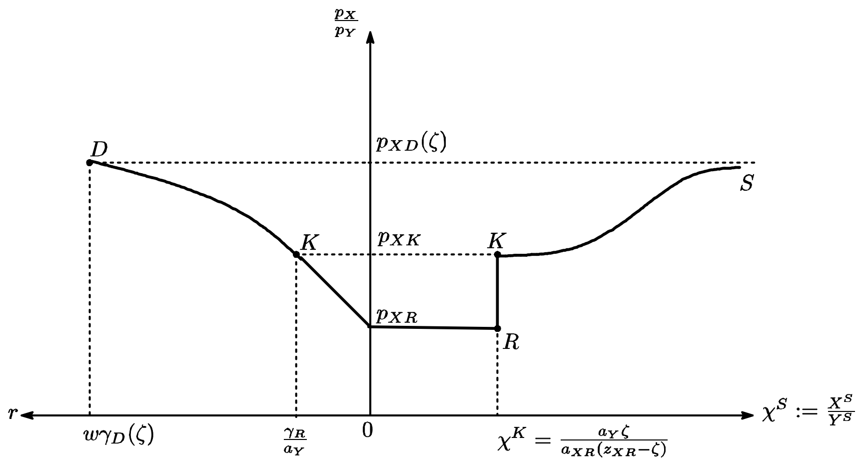

Figure 5: The relative supply curve

γ_R/a_Y, making the emission intensity constant at z_{XR}. Moreover, the outputs remain constant until the permit price equals zero because the economy is at the point K along the production possibility frontier. Once permits are free, the economy will be only Ricardian, and the resulting relative price remains at $p_{XR} := a_{XR}/a_Y$. When the price of good X is less than p_{XR}, the economy specializes in good Y and stops 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 and labor constraints 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 increasing the production of good X results in 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 $p_{XR} = a_{XR}/a_Y$, the emission constraint will not bind, and the relative supply curve will be similar to that in the Ricardian case. For $p \in (p_{XR}, p_{XK})$, the supply of good X relative to good Y is fixed because production occurs at kinky point K on the production possibility frontier. With factor constraints, we can derive the relative output of good X to good Y as follows:

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

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

If $p_X \in (p_{XK}, p_{XD})$, then the substitution between labor and emissions takes places, and the competitive conditions, $p_X = c_X(w, r)$ and $1 = wa_Y$, 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 relative price p_X because $r'_D(p_X) > 0$.[12]

2.3 National Welfare

A country's national welfare 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 subutility function, and Z^W are global GHG emissions. We 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 subutility* 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*

$$\text{(v)} \lim_{\chi^C \to +0} \frac{\partial u(\chi^C, 1)/\partial X^c}{\partial u(\chi^C, 1)/\partial Y^c} = +\infty \text{ and } \lim_{\chi^C \to +\infty} \frac{\partial u(\chi^C, 1)/\partial X^c}{\partial u(\chi^C, 1)/\partial Y^c} = 0$$

where $\chi^C := X^c/Y^c$.

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

2.4 Free trade in goods

The autarky equilibrium 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. The downward sloping curve D describes this relative demand. There are possible equilibria, that is A_i ($i = 1, 2, 3$) for each

[12] We can rewrite χ^S as $\chi^S = a_Y\zeta/(e_X(r_D a_Y) - a_X(r_D a_Y)\zeta)$. Since $e_X(r/w)' < 0$ and $a_X(r/w)' > 0$, an increase in p_X leads to an increasae in χ^S.

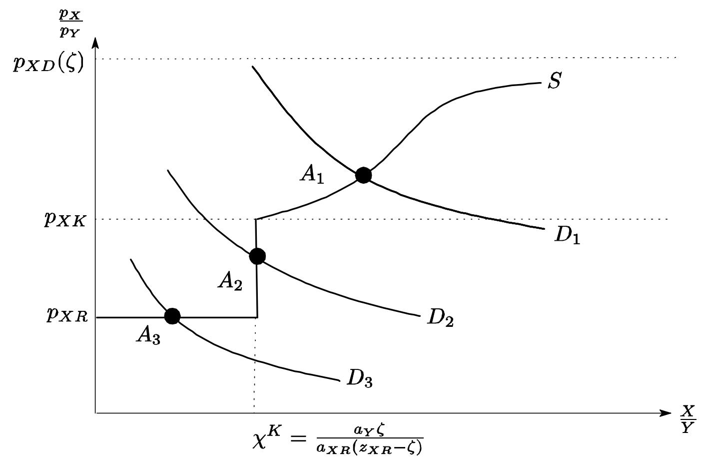

Figure 6: Autarky equilibrium

relative demand curve D_i ($i = 1, 2, 3$). The emission quota is strictly binding at A_1, strictly unbinding at A_3, and just binding at A_2.

We now introduce the international trade in goods between two countries that have already implemented domestic emission quotas. We consider the case in which the two countries differ in evaluating external damage from global warming. This difference in the perception of environmental damage leads to distinct emission quotas for the two countries. We assume that the per capita emission quota of the home country (the North) is less than that of the foreign country (the South),

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

We also assume that the production technology for good X in the foreign country is given by

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

We assume that $\lambda_X > 1$, which indicates that the home country has a Hicks-neutral technical advantage to produce good X over the foreign country. As in the home country, producers of good X in the foreign country have a minimum level of abatement up to which they can reduce labor for abatement by using emissions. For a unit output of good X, the abatement constraint is given by $(\lambda_X a_{XR}, \lambda_X e_{XR})$, where the maximum emission intensity to produce 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 the countries is λ_i ($i = X$,Y). We assume that $\lambda_X = \lambda_Y$ holds without international technology transfers, i.e., the technology gaps between the sectors are uniform. This assumption simplifies the exposition.

When $\lambda_X = \lambda_Y$ holds, technological differences do not lead to a comparative advantage in the production of goods. Thus, with $\lambda_X = \lambda_Y$, trade could arise from the comparative advantage based on the difference in per-capita emission quotas between the countries.

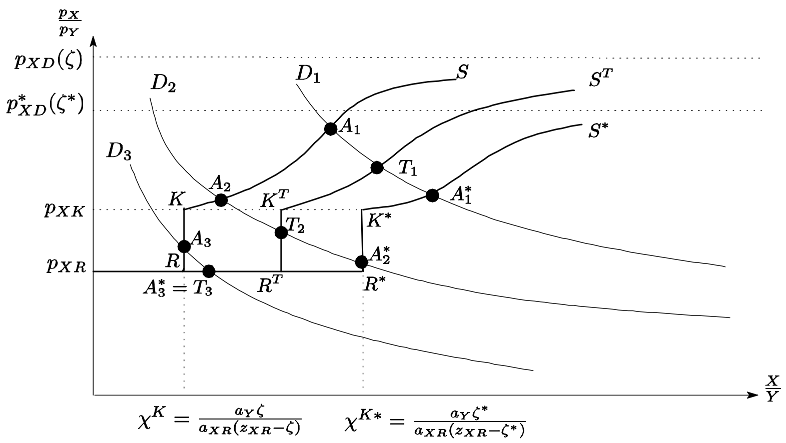

Figure 7: Free commodity-trade equilibrium under $\lambda_X = \lambda_Y$

Figure 7 shows the global trading equilibrium when the two countries liberalize their trade in commodities, given the emission quotas in autarky.[13] Figure 7 illustrates the home country's relative supply curve by $p_{XR}RKS$, the foreign country's by $p_{XR}R^*K^*S^*$, and the global 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 and the world.[14]

We examine each equilibrium associated with the relative demand curve D_i $(i = 1, 2, 3)$ in more detail. In Figure 7, point A_i $(i = 1, 2, 3)$ shows the autarky equilibrium for the home country, while A_i^* is the foreign counterpart. Point T_i then shows the global trading equilibrium. Note that for each possible case, the foreign country has a comparative advantage in producing good X.

When the relative demand curve is given by D_1, the two countries face binding emission quotas at both the autarky and commodity-trading equilibria, because they are incompletely specialized. 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 in autarky. After commodity trade liberalization, each country is incompletely specialized and produces at its kinky point on its production possibility frontier. Thus, their emission quotas are binding for both countries.

If the relative demand curve is D_3, the situation varies slightly. Following free trade in commodities, the home country produces both goods or specializes in good Y, while the foreign country produces 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 global production of good X and increase GHG emissions globally. This is because the foreign producers using less efficient technology would expand their production of good X under its unbinding emission quota.

In the following sections, we examine the effects of technology transfers under situations

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

[14] Each relative supply curve coincides with the vertical axis for $p_X < p_{XR}$. In addition, the global 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.

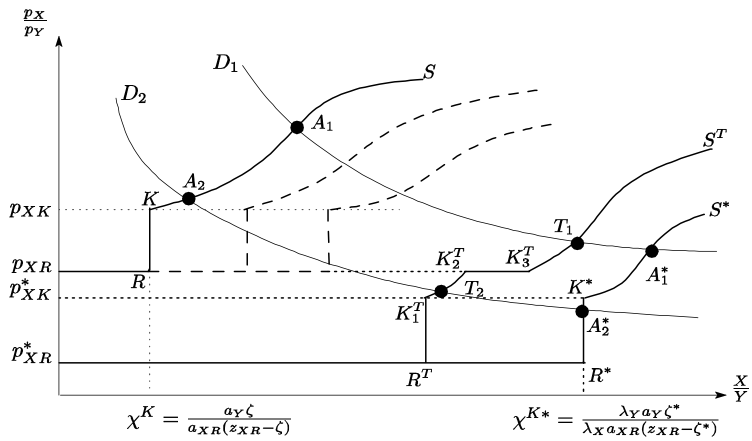

Figure 8: The effects of the technology transfer in home country's import-competing sector X

where emission quotas are binding in both countries. For this purpose, we focus on the case where the relative demand curve is given by D_1 or D_2 in Figure 7.

3 Technology Transfer under Free Trade in Goods

In this section, we examine the effects of technology transfers from the home country to the foreign country when the countries engage in free trade in goods. We assume that technology transfers reflected by reductions of the technology gap parameters, λ_i $(i = X, Y)$, are free of charge. We first consider technology transfer in the home country's import-competing sector X and turn to the export sector Y. We show that both countries gain from technology transfers in the import-competing sector X. We also show that the impacts of technology transfers on global GHG emissions depend on the initial allocation of total emission quotas between the countries.

3.1 Technology Transfer in the Import-Competing Sector

Figure 8 illustrates the effects of technology transfer in the import-competing sector X. In the foreign country, the relative cost of good X declines due to the technology transfer. Since λ_X becomes smaller relative to λ_Y, both $p^*_{XR} = p_{XR}\lambda_X/\lambda_Y$ and $p^*_{XK} = p_{XK}\lambda_X/\lambda_Y$ decrease.[15] Additionally, the relative output of good X increases in the foreign country with the binding emission quota because its effective emissions quota expands. Therefore, after the technology transfer, the relative supply curve of the foreign country is illustrated as $p^*_{XR}R^*K^*S^*$ and the world's relative supply curve as $p^*_{XR}R^TK_1^TK_2^TK_3^TS^T$ in Figure 8. In this situation, global emissions may decline due to the technology transfer. Suppose that the relative demand curve is D_2. Before the technology transfer, both countries were incompletely specialized in production and their emissions quotas were binding. In contrast, after the technology transfer, the home

[15]The reduction of p^*_{XK} is larger than that of p^*_{XR}. See Appendix A for details.

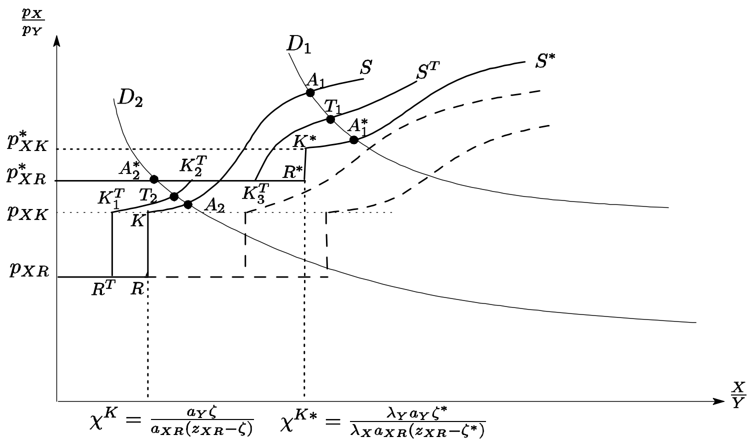

Figure 9: The effects of the technology transfer in home country's export sector Y

country specializes in producing good Y, and its emission quota is no longer binding. In the foreign country, the production pattern does not change, and its emission quota continues to be binding. Thus, global emissions decrease due to the technology transfer. Note that the technology transfer is not necessarily beneficial for the global environment. If the relative demand is D_1, global emissions would remain the same because the emission quotas are binding for both countries before and after the technology transfer.

The above results suggest that the welfare implications of technology transfer should be modified if we consider its impact on the global environment. It is well-known that technology transfers may hurt a country when its terms of trade deteriorate. In the above case, technology transfer in sector X improves the home country's terms of trade but deteriorates those of the foreign country. The foreign country would lose if the negative effect of its worsening terms of trade dominates the positive effect of an increase in its production capacity in sector X. In our analysis, we also need to consider the environmental effects of the technology transfer. If the relative demand is D_2, the technology transfer improves the global environment, positively affecting welfare. However, if the relative demand is D_1, the technology transfer does not affect the global environment.

We can summarize the results in the following proposition.

Proposition 1 *Suppose that the home country transfers its superior technology in the import-competing sector X to the foreign country when the countries engage in free trade in goods under the binding emissions quotas. Then, the technology transfer can improve the global environment. The home country gains from the technology transfer. The foreign country gains if the environmental and technology gains exceed the loss from the worsening in its terms of trade.*

3.2 Technology Transfer in the Export Sector

Next, we consider the case in which the home country transfers its superior technology in export sector Y to the foreign country. In contrast to the previous case, the technology transfer raises the relative cost of good X in the foreign country. Since λ_Y becomes smaller relative to

λ_X, both $p^*_{XR} = p_{XR}\lambda_X/\lambda_Y$ and $p^*_{XK} = p_{XK}\lambda_X/\lambda_Y$ increase.[16] After the technology transfer, the foreign country's relative supply curve is illustrated as $p^*_{XR}R^*K^*S^*$ and the global relative supply curve as $p_{XR}R^TK^T_1K^T_2K^T_3S^T$ in Figure 9.[17] As before, the effects of the technology transfer depend on the relative demand size. If the relative demand curve is D_1, global GHG emissions are not affected because emissions quotas are binding for both countries before and after the technology transfer; however, if the relative demand curve is D_2, then the technology transfer would reduce global GHG emissions. The foreign country is induced to specialize in good Y due to the technology transfer; consequently, its emissions decline to zero. The home country gains its comparative advantage in good X and its emission quota remains binding. Therefore, the technology transfer is beneficial for the global environment.

If the relative demand curve is D_1, the home country loses due to its deteriorating terms of trade, whereas the foreign country gains because of its improving terms of trade and increased production capacity in sector Y. If the relative demand curve is D_2, the welfare effects of the technology transfer are ambiguous because the trade pattern is reversed; that is, it is unclear whether the terms of trade improve or worsen for each country.

Proposition 2 *Suppose that the home country transfers its superior technology in the export sector Y to the foreign country when the countries engage in free trade in goods. Global emissions can decrease due to the technology transfer. When global emissions decrease, the welfare effects are unclear because the terms of trade effects are ambiguous as a consequence of the trade pattern reversal.*

Note that the environmental effects of the technology transfers may depend on the initial allocation of emission quotas when they are initially binding for both countries. Suppose the relative demand is D_2 in Figure 8 and 9. While the technology transfer in the import-competing sector X induces the home country to reduce its emissions to zero, that in the export sector Y induces the foreign country to do so. If the total emission quota for the foreign country, Z^*, is larger than that for the home country, Z, then technology transfer in the sector Y would result in a greater reduction in global emissions than in the sector X. Otherwise, the opposite result is obtained.

Proposition 3 *Suppose that emission quotas initially are binding for both countries. If the emission quota of the foreign country, Z^*, is larger than that of the home country, Z, then the technology transfer in the home country's export sector Y can lead to a greater reduction in global GHG emissions than that in its import-competing sector X.*

[16] The increase of p^*_{XK} is larger than that of p^*_{XR}.

[17] χ^*_K may become smaller than χ_K. Figure 9 illustrates the case in which the difference in per-capita emission quota, $\zeta^* - \zeta$, is large so that χ^*_K is still larger than χ_K even after the technology transfer. We show that the following results continue to hold if χ^*_K becomes smaller than χ_K due to the technology transfer.

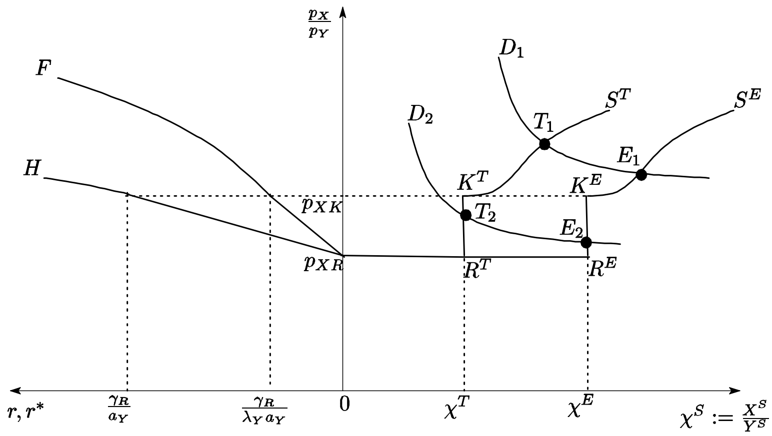

Figure 10: The effects of emissions trading under free trade in goods

4 Technology Transfer under Free Trade in Goods and International Emissions Trading

In this section, we investigate the effects of technology transfers from the home country to the foreign country under international emissions trading. We first examine the effects of trade liberalization in emission permits and then analyze the technology transfer effects under free trade in emission permits and commodities. We show that technology transfers in either sector increase the permit price. We also show that technology transfers do not necessarily generate more preferable effects on reducing global emissions under international emissions trading compared with those under international goods trade only.

4.1 International Emissions Trading Equilibrium

Figure 10 shows the effects of emissions trading when the countries engage in free trade in goods. The first quadrant in Figure 10 replicates the free trade equilibrium in Figure 7 with the relative demand curve, D_i, and the world's relative supply curve, $p_{XR}R^TK^TS^T$. The second quadrant in Figure 10 shows the relationship between the relative price of good X and the emission permit price in the home country, $p_{XR}H$, and 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 in the foreign country, r^*, because the home producers have a technical advantage in producing good X. This suggests that the home country would buy emission permits from the foreign country under free trade in permits and commodities.

When international emissions trading is liberalized, the global relative supply curve is illustrated as $p_{XR}R^EK^ES^E$ in the first quadrant of Figure 10.[18] This situation arises under the assumption that each country's labor endowment is sufficiently large to absorb the total world emission permits,

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

[18]See Appendix B for details.

where $Z^W = Z + Z^*$. The condition (4) implies that the emission quota can be binding even if all permits are allocated to either country.

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 are necessarily binding in both countries. Similarly, when the relative demand is D_2, international emissions trading would reverse the trade pattern and not affect total emissions. In both cases, the trade pattern is reversed; thus, it is ambiguous whether emissions trading benefits or hurts each country.[19]

Note that even if emissions quotas are binding in both countries before international emissions trading, emissions quotas may not be binding and the permit price zero. In Figure 10, this is the case if D_2 intersects with the relative supply curve on the horizontal segment, $R^T R^E$, and equilibrium, E_2, is determined on the segment. In this case, free trade in emissions permits improves global production efficiency so that the global demand for emission permits is smaller than the global supply. This result suggests that international emissions trading can benefit the global environment.

Proposition 4 *Suppose that the emissions quotas are binding in both countries under free commodity trade. If international trading in emission permits is liberalized, then some permits may not be used at equilibrium due to the increase in global production efficiency. Then, both countries may benefit from emissions trading because of the reduction of global emissions.*

4.2 Technology Transfer under Emissions Trading

In this subsection, we consider technology transfers under free trade in emission permits and commodities. We first examine the effects of technology transfers in sector X and then turn to those in sector Y. We focus on the case with relative demand D_2 in the following.

Figure 11 shows the effects of technology transfers in sector X from the home country to the foreign country. In the first quadrant of Figure 11, point E_2 replicates the emissions trading equilibrium illustrated in Figure 10. Due to the technology transfer, the relative cost curve of the foreign country shifts downward. First, suppose that it shifts down to $p^*_{XR}F$ in Figure 11. At the initial equilibrium, E_2, the foreign country offers a higher permit price than the home country. Note that the foreign country still lags behind the home country in production technologies, and its emissions coefficient is higher than that of the home country. However, it can offer a higher return for emission permits than the home country. The reason is that technology transfers reduce the relative labor cost in the foreign production of good X, p^*_{XR}. The comparative advantage in labor costs allows foreign producers to offer the higher return

[19] Grossman (1984) showed that a country engaging in free trade in goods gains from international factor movements if its terms of trade improve.

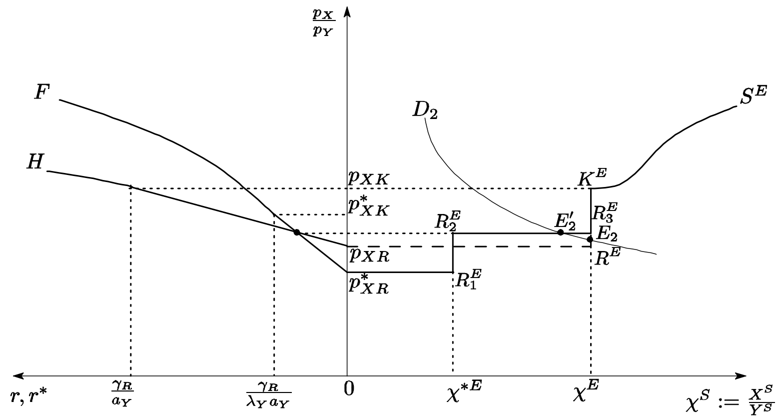

Figure 11: The effects of the technology transfer in sector X under emissions trading

to permits than their home counterparts.[20]

After the technology transfer, the relative supply cure can be illustrated as follows: $p^*_{XR}R_1^E R_2^E R_3^E K^E S^E$ in Figure 11. The vertical segment of the global relative supply curve, $R_1^E R_2^E$, indicates the global relative output of good X, χ^{*E}, when the foreign country uses all permits. Note that χ^{*E} is smaller than χ^E, the global relative output of good X under the home country's use of all permits. If permits move from the home country to the foreign country, the global production of good X decreases because home producers still use technology superior to that of their foreign counterparts. At the same time, the global output of good Y expands because home producers with more efficient technology increase the production of good Y relative to their foreign counterparts.[21] Thus, the global relative output of good X decreases if permits move from the home to the foreign country.

The new equilibrium is determined at E_2' in which emissions prices are equalized between the countries and both countries are incompletely specialized under binding emission quotas. Trade patterns may be reversed due to technology transfers. Suppose that the patterns of trade in goods and permits remain the same, i.e., the home country exports good X and imports permits. Due to the technology transfer, both the price of good X and the return to emissions permits increase. For the home country, the terms of trade in goods improve but those of permits worsen. Because the home country buys permits, the increase in the permit price negatively affects the home country's welfare, weakening the incentive to transfer technology in good X to the foreign country.[22] For the foreign country, its terms of trade in goods deteriorate but its terms of trade in permits improve. In addition to directly benefiting from an increase

[20] Jones (1980) shows that comparative and absolute advantages play a role in determining the direction of international factor movements.

[21] See Appendix B for details.

[22] The welfare effect of a change in the permit price was based on the results derived from Jones (1967), which examined an optimal policy in tariffs and capital taxes under commodity trade and capital movements between countries. According to Jones (1967), a change in national welfare can be decomposed into the terms of trade effect in goods and capital. An increase in the return on capital negatively affects the welfare of a country that imports capital and positively affects the welfare of a country that exports capital. Jones (1967) used the Heckscher Ohlin model. Jones (2000) showed that the same welfare decomposition can be derived with the specific factor model.

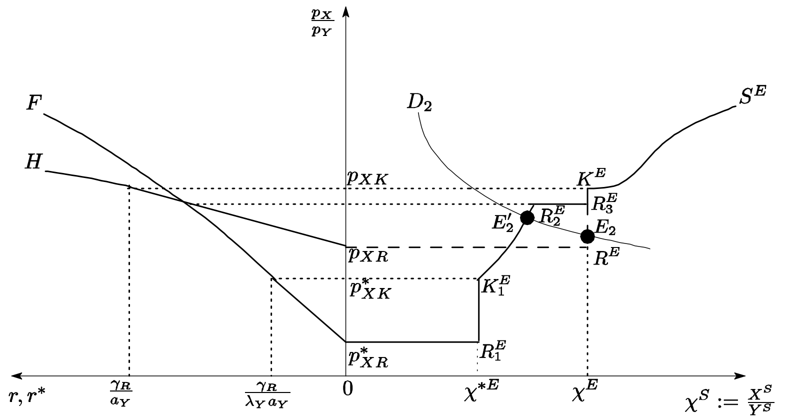

Figure 12: The effects of the technology transfer in sector X under emissions trading in the case with a large magnitude of the technology transfer

in its production capacity in sector X, the foreign country gains from a permit price increase because it sells permits.

Note that even if the home country transfers its superior technology in sector X to the foreign country, the home country may continue to import all permits from the foreign county. This case occurs when the relative demand curve intersects with the relative supply curve on segment $R_3^E K^E S^E$ in Figure 11. Then, the technology transfer has no effect because the foreign country has no opportunity to use the transferred technology. Technology transfers have effects only if the foreign country starts producing good X.

Next suppose that the magnitude of the technology transfer is so large that the unit relative cost curve of the foreign country shifts downward further as in Figure 12. Compared to the small magnitude of the technology transfer, the foreign country can offer a much higher return on permits, leading to a reversal in the pattern of trade in permits, i.e., the home country becomes an exporter of permits to the foreign country. Then, the world's relative supply curve of good X is illustrated as $p_{XR}^* R_1^E K_1^E R_2^E R_3^E K^E S^E$. The equilibrium shifts to E_2' from E_2.

At equilibrium, E_2', the home country is specialized in good Y because it exports all permits to the foreign country. The foreign country produces both goods under the binding emission quota, implying that the global GHG emissions are unaffected. Due to the technology transfer, the global relative output of good X declines, increasing the relative price of good X and permit price. Welfare effects of the technology transfer are ambiguous because the trade patterns are reversed.

Proposition 5 *Suppose that the home country transfers its superior technology in sector X to the foreign country under free trade in emissions permits and goods, given that the emissions quotas bind for both countries. Due to technology transfers, both the relative price of good X and the permit price increase. The welfare effects of technology transfers are ambiguous for both countries. If the trade patterns remain the same, i.e., the home country exports good X and imports permits, a higher permit price weakens incentives for the home country to transfer the technology.*

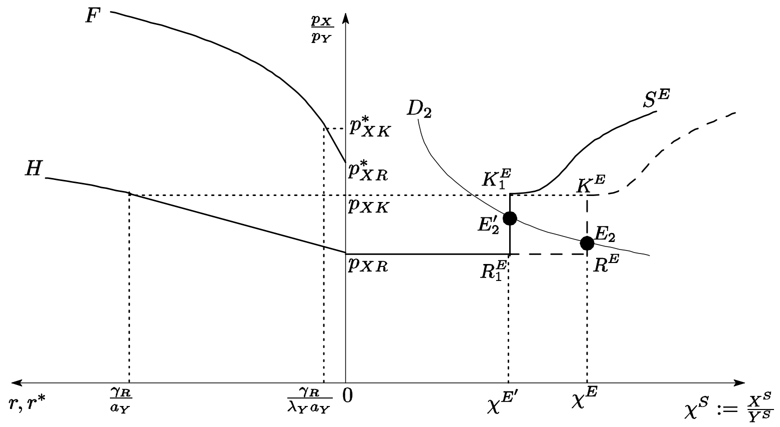

Figure 13: The effects of technology transfer in sector Y under emissions trading

Finally, let us turn to technology transfers in sector Y from the home country to the foreign country. The second quadrant of Figure 13 shows that technology transfers in sector Y shift the relative cost curve of the foreign country upward to $p^*_{XR}F$. The home country continues to offer a higher permit price and uses all permits. The world's relative supply curve of good X can be illustrated as $p_{XR}R_1^E K_1^E S^E$ in the first quadrant of Figure 13. Since the technology transfer increases the output of good Y in the foreign country, the vertical segment of the world's relative supply curve necessarily shifts left.[23]

The equilibrium shifts to E_2' from E_2 due to the technology transfer. At equilibrium, E_2', the home country is incompletely specialized and the foreign country is completely specialized in good Y. The trade patterns do not change; the home country exports good X and imports emissions permits. Technology transfer increases both the relative price of good X and the permit price. For the home country, the terms of trade in goods improve, but terms of trade in permits deteriorate. For the foreign country, while there is a benefit from an increase in its production capacity in sector Y, its terms of trade in goods deteriorate and in permits improve. Because the emissions quotas are binding before and after the technology transfer, there is no change in global emissions.

Proposition 6 *Suppose that the home country transfers its superior technology in sector Y to the foreign country under free trade in emissions permits and goods, given that the emissions quotas are binding for both countries. Due to technology transfer, the relative price of good X and the permit price increase. The increase in the permit price leads to a negative effect on the incentive for the home country to transfer the technology but it also results in a benefit for the foreign country.*

In Proposition 5 and 6, we have shown that technology transfers in either sector increase the permit price, negatively affecting the home country's welfare because it buys permits. If countries engage in goods trade only and produce under binding emission quotas, technology transfers in sector X benefit the home country (see Proposition 2). These results suggest that

[23] See Appendix B for details.

	Effects on global emissions
TT in sector X under goods trade	$-$
TT in sector X under goods and permits trade	0
TT in sector Y under goods trade	$-$
TT in sector Y under goods and permits trade	0

Table 1: The effects of the technology transfers on global emissions under the relative demand, D_2.

emissions trading may weaken incentives for the home country to transfer its technologies to the foreign country.

Table 1 summarizes the effects of technology transfers on the global environment in the case where emission quotas are binding before technology transfers, and the relative demand is D_2. First, we can compare the effects between sectors. In either industry, technology transfers improve the global environment when the countries engage only in goods trade. In addition, technology transfers in the less emissions-intensive sector reduce global emissions more than in the more emissions-intensive sector (see Proposition 3). Second, we can compare the effects under different regimes of trade in goods and permits. Technology transfers under goods trade alone lead global emissions to be less than or equal to those under trade for both goods and permits. When international emissions trading is not allowed, one country with excess demand for permits cannot import them, and the other country with excess supply of permits is induced to decrease its use of them. As a result, global emissions can decrease due to technology transfers. However, under international trade in emissions permits, one country with excess demand for permits can increase its emissions by importing permits from the other country with excess supply of them. Therefore, technology transfers do not lead to reductions in global emissions under international emissions trading.

5 Conclusion

We examined the effects of technology transfers on global warming and welfare under international commodity and emissions trading in a two-country, two-good, general equilibrium model with both Ricardian and Heckscher-Ohlin features. We have specifically considered the situation in which the home country has superior technologies in both sectors and a comparative advantage in the less emissions-intensive goods under free trade in goods.

The total welfare effect of technology transfers can be decomposed into four effects: efficiency gains from technology transfers, gains or losses from changes in terms of trade in goods and changes in terms of trade in emission permits, and social benefits or costs from changes in global emissions. Under international trade in goods only, both countries can benefit from technology transfers. If emissions trading and goods trade are allowed between countries, the permit price increases due to technology transfers in either sector. This may benefit the foreign country since it gains from improved terms of trade in permits. The permit price increase, however, may reduce the incentive for technology transfer in either sector because a deterioration in its terms of trade in permits may negatively affect the welfare of the home country.

Sectors and trade regimes may matter for the effects of technology transfers on the global environment. Under international trade in goods only, technology transfer in the less emissions-intensive sector can significantly reduce global GHG emissions than in the emissions-intensive sector. Such an improvement in the global environment is more likely to arise under goods trade only rather than goods and permits trade. Technology transfers change the composition of production sectors, resulting in an unbinding emission quota in either country. If the countries engage in only goods trade, unused permits are held in a country with an unbinding emission quota. However, under emissions trading, those permits can be exported to a country that offers a higher permit price and used for production in the emissions-intensive sector. Therefore, technology transfers that reduce global emissions under goods trade only do not necessarily do so under emissions trading and goods trade. This result suggests that international emissions trading may weaken the incentive to engage in technology transfers because there is no environmental benefit and a negative welfare effect of an increase in the permit price.

We examined the effects of technology transfers that occur after countries liberalize international trade in goods and emissions permits. It is also interesting to analyze the consequences of liberalizing international emission trading after technology transfers occurs under international trading in goods. In the latter case, some of our results could be modified. Unlike the former case, international emissions trading could result in increases in global emissions regardless of the sector in which technology transfers occurred. Technology transfer could induce one country to specialize in the less emissions-intensive sector and make its emissions quota unbinding under domestic emissions trading. Liberalizing international emissions trading allows the country to export its emissions permits, expanding the global output of emissions-intensive goods and increasing global emissions of GHG.

Appendix A: Relationship between Technology Gaps and Relative Unit Costs

We examine the relationship between technology gaps and relative unit costs. For the home country, competitive conditions for production under incomplete specialization and an unbinding 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,

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

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

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

Note that γ_R denotes the critical ratio of the emission price to the wage rate above which emission regulation induces producers to abate their emissions using labor. Under a 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 $\lambda_X \gtreqless \lambda_Y$. In addition, we can easily confirm that $p_{XK} - p^*_{XK} \lesseqgtr p_{XR} - p^*_{XR}$ if and only if $\lambda_X \gtreqless \lambda_Y$.

Appendix B: The Global Relative Supply of Good X

We derive the world's relative supply of good X under goods trade and international emissions trading. First, we show how international emissions trading affects the global relative supply of good X. Before the international emissions trading is allowed, the world's 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

$$\begin{aligned} X + X^* &= Z^W/e_X(\gamma) - [1/e_X(\gamma) - 1/\lambda_X e_X(\gamma^*)]Z^*, \\ Y + Y^* &= L/a_Y + L^*/\lambda_Y a_Y - a_X(\gamma)Z^W/a_Y e_X(\gamma) \\ &\quad + [a_X(\gamma)/a_Y e_X(\gamma) - a_X(\gamma^*)/\lambda_Y a_Y e_X(\gamma^*)]Z^*. \end{aligned}$$

Suppose that the comparative advantage is based only on the difference in per capita emission quotas. 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 $\lambda_X = \lambda_Y > 1$, χ^S decreases with Z^*. Thus, the movement of emission permits from the foreign to home country would raise the global 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 effects of technology transfers in sector X under emissions trading, given that the emissions quotas are binding for both countries. Before the technology transfer, the home country uses all permits by importing permits from the foreign country, which specializes in producing good Y. The global relative supply of good X is derived as

$$\chi_1^S = \frac{Z^W / e_X(\gamma)}{L/a_Y + L^*/\lambda_Y a_Y - a_X(\gamma) Z^W / a_Y e_X(\gamma)}. \tag{6}$$

If the home country produces at point K on its production possibility frontier, then $e_X(\gamma) = e_{XR}$ and $a_X(\gamma) = a_{XR}$ and $\chi_1^S = \chi^E$ in Figure 11 and 12. After the technology transfer, there is a case in which the foreign country's permit price is higher than that in the home country. Then, if the foreign country produces both goods and the home country specializes in producing good Y, the global relative supply of good X is derived as follows:

$$\chi_2^S = \frac{Z^W / \lambda_X e_X(\gamma^*)}{L/a_Y + L^*/\lambda_Y a_Y - a_X(\gamma^*) Z^W / \lambda_Y a_Y e_X(\gamma^*)}. \tag{7}$$

If the foreign country produces at the kinky point of its production possibility frontier, then $e_X(\gamma^*) = e_{XR}$ and $a_X(\gamma^*) = a_{XR}$ and $\chi_2^S = \chi^{*E}$ in Figure 11 and 12. Using (6) and (7), we can show that $\chi^E = \chi_1^S > \chi_2^S = \chi^{*E}$ if $e_X(\gamma) = e_X(\gamma^*) = e_{XR}$, $a_X(\gamma) = a_X(\gamma^*) = a_{XR}$, and $1 < \lambda_X < \lambda_Y$.

Finally, we show how the global relative supply of good X is affected by the technology transfer in sector Y under emissions trading, given that the emissions quotas are binding for both countries. The world's relative supply of good X is given by (6). Since the technology transfer reduces λ_Y, χ_1^S becomes smaller. When the home country produces at point K on its production possibility frontier, $e_X(\gamma) = e_X(\gamma^*) = e_{XR}$ and $a_X(\gamma) = a_X(\gamma^*) = a_{XR}$ hold. Thus, a reduction in λ_Y implies that $\chi^{E\prime} < \chi^E$ in Figure 13.

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