# Global Climate Change, Technology Transfer and Trade with Complete Specialization

Vivekananda Mukherjee and Dirk T.G. Rübbelke

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Vivekananda Mukherjee, *Department of Economics, Jadavpur University, Calcutta, India*
Dirk T.G. Rübbelke, *Department of Economics, Chemnitz University of Technology, Chemnitz, Germany*

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# Global Climate Change, Technology Transfer and Trade with Complete Specialization


**Summary**

The paper develops a model in which a country with better technology for abatement of Green House Gas (GHG) emission (the North) commits to an international protocol to keep the global GHG emission within a specified limit while it helps the mitigation effort in the other country (the South) with unconditional transfer of abatement technology. It finds out in the autarkic ('no trade') equilibrium the technology transfer offer from the North is always accepted by the South. The North may offer either a partial or a complete technology transfer. If partial technology transfer is offered it finds out the determinants of the extent of technology transfer. Then it compares the autarkic equilibrium with equilibrium where trade with complete specialization occurs and finds out that trade limits the scope of technology transfer as an instrument for mitigation of global GHG emission.



**Keywords:** GHG Emission, Mitigation, Technology Transfer, Trade

**JEL Classification:** F18, F35, Q54, Q56

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*Address for correspondence*:

Dirk T.G. Rübbelke
Department of Economics
Chemnitz University of Technology
Reichenhainerstr. 39
09126 Chemnitz
Germany
Phone: +49 3715314212
Fax: +49 3715314372
E-mail: dru@hrz.tu-chemnitz.de

## 1. Introduction

Keeping global pollution within the limit has recently been a major cause of concern around the world. Global pollution is a public 'bad', which adversely affects all the countries around the world through incidents like global climate change with grave implications for their economies. So, the countries have been deliberating among themselves for quite sometimes now on the way to reduce the global pollution to prevent global climate change. The Kyoto protocol had been a landmark agreement in this initiative. The Protocol sets distinct GHG emission targets and tries - by means of its flexible mechanisms - to distribute the burden of GHG emission mitigation more equitably and efficiently among countries. The countries in the North with the history of high emissions along with high national income and high rank in the Human Development Index (HDI) are slated to make commitments to stabilize the global pollution at a particular level. The North can fulfil its commitment either by controlling its own emission level or by helping mitigation in the South. It is argued that transfers from the North to the South, which target mitigation serves the objective of equity as the transfer flows from the rich countries to the poor countries. It also serves the objective of efficiency. Since the south possesses relatively inefficient technology for abatement and the North is already in possession of a better technology for abatement, the North can abate relatively less on its own without sacrificing its production by exploiting cheaper abatement options in the South[2]. The Climate Convention also stresses on transfer from the North to the South to help the South to adapt with the reality of climate change. As a part of the adaptation funding,[3] a significant amount has already been spent in countries like India and China to make them aware of the danger of climate change. Consequently, though the countries in the South did not make any formal commitment in Kyoto, they have also joined the global effort in the GHG emission reduction by design of suitable regulations to control GHG emission and by formation of institutions like Pollution Control Boards.

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[2] See GTZ (2004) for details. For a theoretical model explaining the transfers with the objectives of equity and efficiency see Caplan, Cornes and Silva (2003).

[3] Here we refer to adaptation of climate friendly technologies to *mitigate* climate change. We therefore do not refer to adaptation to ongoing climate change.

Transfers from the North to the South play a major role in the global effort in GHG emission reduction. Transfers can take different forms: it can either be a financial transfer or a technology transfer. Schelling (1991) proposed a carbon tax in the North to finance abatement activities in the South. However, in this paper we focus on the issue of technology transfer, which in recent times became an important part of the international agreements defining the role of the North in the abatement effort in the South. Technology transfer from the North to the South played an important role in the talk about Clean Development Mechanism (CDM) as a part of Kyoto protocol. It also played an important role in the recent Asia-Pacific Partnership on Clean Development and Climate[4] signed by Australia, China, India, Japan, Republic of Korea and the United States in 2005. In this paper we focus on the role of technology transfer for abatement purpose in the reduction of GHG emission. Specifically, we explore the determinants of the extent of technology transfer where the North makes a commitment to stabilize the global GHG emission to a limit and South does not make any such explicit commitment. Then, we also ask the question if the trade in commodities restricts the role of technology transfer.

We construct a theoretical framework in this paper where first we consider the no-trade ("autarkic") situation and then we consider the trade in commodities, in which the country with better abatement technology (the North) specializes in production of the non-polluting commodity and the other country (the South) specializes in the production of the polluting commodity. We find in trade situation, there is a possibility that the North refuses to transfer its better technology at all as it fears an increase in global GHG emission as a result of the transfer. However, if it decides to transfer, it transfers the complete technology. This is unlike the autarkic situation in which it is always inclined to transfer the technology. However, in autarky it may decide to transfer only a part of its technology or an old

[4] On 28 July 2005 Australia, China, India, Japan, Republic of Korea and the United States announced the Asia-Pacific Partnership on Clean Development and Climate at an Association of South East Asian Nations (ASEAN) Regional Forum meeting. The Partnership was finally launched on January 12 2006 at the Partnership's inaugural Ministerial meeting in Sydney. The ministers agreed on a Charter, Communique and Work Plan that outline a new model to address climate change, energy security and air pollution. The members of this partnership account for more than 50% of the world's greenhouse gas emissions. Unlike the Kyoto Protocol, this agreement allows member countries to set their goals for reducing emissions individually, with no mandatory enforcement mechanism.

vintage of its stock of technologies. We find the determinants of equilibrium extent of technology transfer from the North. In trade situation, the South that always accepts the transfer offer in the autarkic situation may refuse to accept the offer. We argue this happens because it suffers from the adverse 'terms of trade' effect due to technology transfer. We find the precise condition under which the technology transfer takes place in trade situation. Here we observe that the commodity trade not only restricts the scope of technology transfer but also makes the fulfilment of the aim of stabilizing the global emission level uncertain even if the complete technology is transferred to the South.

The scope of this paper is somewhat unique in the literature and the results provide new insights. It deals with the issue of technology transfer and trade when the North commits to a defined limit of the global GHG emission and characterizes the equilibrium. There are some papers in the literature like Stranlund (1996), Scheffran and Pickl (2000) that deal with the issue of technology transfer from the North to the South, but they do not consider the commitment on the part of the North in keeping the GHG emission within a limit. They do not discuss the commodity trade equilibrium either. The paper by Yang (1999) is very close to our framework. Although it considers the mitigation effect of the technology transfer in the South, as it ignores the adaptation exercise in the South, it ignores an important effect generated by the transfer of abatement technology in the South i.e. the expansion of the polluting industry. This affects the results of the paper. We correct for this omission in our paper. Yang (1999) also does not consider the trade situation. There are papers in the trade theory which deal with trade and environment[5]. Copeland and Taylor (2005) analyze in a trading world the effects of commitment on the part of the North on global pollution level. It also discusses the effects of the pollution permit trading among the countries in the North on the same. It shows the conventional wisdom that existed in the context of the autarkic equilibrium change considerably as the possibility of trade is taken into account. But, though it considers trade flows between the countries, it does not consider any kind of transfer from the North to South as we do in this paper. Another set of papers in the literature restrict

[5] See Copeland and Taylor (2004) for a recent review.

themselves to the issue of technology transfer and trade; they do not deal with the issue of GHG emission. In particular, Beladi, Jones and Marjit (1997) use a very similar model as we develop in this paper. However, they find no conflict between technology transfer and commodity trade. In contrast to them, in our paper as we take into account the issue of the GHG emission we find out trade may restrict the scope of technology transfer. Therefore, this paper explores a new area in economic research and also makes important contribution in terms of the results it generates.

In the next section of the paper we lay out the model. The two subsections in it consider the “autarkic” and “trade” situations. The section following concludes.

## 2. The Model

### 2.1 Autarky

We consider two countries the North and the South. The North is denoted as the $i^{th}$ country and the South is denoted as the $j^{th}$ country. Both the countries have labor as their only factor of production. The endowments of labor in the North and the South are identical, given by L. The countries produce and consume two commodities 1 and 2, the amounts of which are denoted by $q_1$ and $q_2$. The commodity 1 does not have any pollution component associated with its production. However, commodity 2 is an “impure public good” that emits $CO_2$ in the production process that adversely affects global climate. In particular we assume 1 unit production of commodity 2 emits one unit of $CO_2$. The global climate change has a negative impact on the enjoyment of private utility (from the consumption of the commodities) in each of these countries. Therefore, each country tries to abate the pollution generated in her. But, the abatement technology has a limitation. It can abate only $\psi$ fraction of the 1 unit of $CO_2$ emitted in the production process. Therefore, it emits $\phi = 1 - \psi$ units of $CO_2$ per unit of production of commodity 2.

The countries differ in terms of their abatement technologies in the following way. Suppose, the amount of labor required to abate $\psi$ units of $CO_2$ is given by[6] $a_\psi$. We assume the North possesses more efficient technology for abatement than the South in the sense that $\psi_i > \psi_j$ and $a_{\psi i}\psi_i < a_{\psi j}\psi_j$. The fractions, $\phi_i$ and $\phi_j$ denote per unit emissions from the countries.

The countries have identical preferences. The utility function of the North is given by:

$$v_i = u(q_{1i}, q_{2i}) - \frac{1}{2} (\phi_i q_{2i} + \phi_j q_{2j})^2 \quad (1)$$

and the utility function of the South is given by:

$$v_j = u(q_{1j}, q_{2j}) - \frac{1}{2} (\phi_i q_{2i} + \phi_j q_{2j})^2 \quad (2)$$

where $u_1 > 0$, $u_2 - (\phi_i q_{2i} + \phi_j q_{2j}) \phi_i > 0$, $u_2 - (\phi_i q_{2i} + \phi_j q_{2j}) \phi_j > 0$, $u_{11} < 0$, $u_{22} < 0$, $u_{12} = u_{21} = 0$.

The countries have C.R.S technology in production of both the commodities. The production of 1 unit of commodity 1 in the North and the South requires respectively $a_{1i}$ and $a_{1j}$ units of labor. Similarly, the production of commodity 2 in them requires respectively $a_{2i}$ and $a_{2j}$ units of labor. We assume, $a_{1i} < a_{1j}$ and $a_{2i} < a_{2j}$ so that the North has absolute advantage in production of both the commodities. Since the countries internalize a part of the pollution cost associated with the production of commodity 2 through the costly abatement activity, its actual labor cost of production in the North and the South turns out to be[7] $(a_{2i} + a_{\psi i}\psi_i)$ and $(a_{2j} + a_{\psi j}\psi_j)$ respectively. Therefore, the production possibility frontier of the North can be written as:

$$L = a_{1i} q_{1i} + (a_{2i} + a_{\psi i}\psi_i) q_{2i}. \quad (3)$$

Similarly, the production possibility frontier of the South can be written as:

$$L = a_{1j} q_{1j} + (a_{2j} + a_{\psi j}\psi_j) q_{2j}. \quad (4)$$

[6] Such numbers reflect a mixture of technical knowledge (blueprints), climate and labor skills. In the question of technology transfer we consider reasonably only the transfer of the blueprint as in Beladi, Jones and Marjit (1997).

[7] In our model we assume $a_{\psi i}$ and $a_{\psi j}$ as parameters. The governments in individual countries being aware of the danger of GHG emission try their best to internalize the social cost of the emission from their own countries. There are papers in the literature, which treat them as strategic variables with the countries. See for examples the papers by Barrett (1994).

We also assume, the South has comparative advantage in production of commodity 2, which implies:

$$\frac{a_{1i}}{a_{2i} + a_{\psi i}\psi_i} < \frac{a_{1j}}{a_{2j} + a_{ij}\psi_j}. \tag{5}$$

Observe, the countries have strategic interdependence in their choice of $q_{2i}$ and $q_{2j}$. So it must be the case that at least a Nash equilibrium exists in this game. Suppose, the unique Nash equilibrium of the game is given by ($q_{2i}^* > 0$, $q_{2j}^* > 0$). Then it must satisfy the following pair of equations:

$$- u_1 \frac{a_{2i} + a_{\psi i}\psi_i}{a_{1i}} + u_2 = (\phi_i\, q_{2i} + \phi_j\, q_{2j})\, \phi_i \tag{6}$$

$$- u_1 \frac{a_{2j} + a_{\psi j}\psi_j}{a_{1j}} + u_2 = (\phi_i\, q_{2i} + \phi_j\, q_{2j})\, \phi_j. \tag{7}$$

While equation (6) represents the reaction function of the North, equation (7) represents the reaction function of the South. The equilibrium consumption of commodity 1 in the two countries $q_{1i}^*$ and $q_{1j}^*$ are determined from equations (3) and (4) as $q_{1i}^* = \frac{L - (a_{2i} + a_{\psi i}\psi_i) q_{2i}^*}{a_{1i}}$ and $q_{1j}^* = \frac{L - (a_{2j} + a_{\psi j}\psi_j) q_{2j}^*}{a_{1j}}$. We also check that at ($q_{2i}^* > 0$, $q_{2j}^* > 0$) the second order condition for utility maximization is satisfied for each of the countries. The stability condition for the Nash equilibrium is also satisfied. The global pollution level at the Nash equilibrium is given by:

$$\overline{R} = \phi_i\, q_{2i}^* + \phi_j\, q_{2j}^*. \tag{8}$$

Observe, at the equilibrium $q_{2i}^* > q_{2j}^*$. This must be true because owing to the assumption $\phi_i < \phi_j$ the marginal cost of production of $q_{2i}$ in the North which is given by $(\phi_i\, q_{2i} + \phi_j\, q_{2j})\, \phi_i$ is strictly less than the marginal cost of production of $q_{2j}$ in the South given by $(\phi_i\, q_{2i} + \phi_j\, q_{2j})\, \phi_j$.

Now, suppose the North with its better technology of abatement commits to an international agreement by which it contemplates transferring its technology for abatement to the South in order to restrict the global pollution level within the current limit. The South, which receives the technology, does not commit to any output restriction. We assume, the North can choose to transfer $\gamma \in [\frac{\psi_j}{\psi_i}, 1]$ proportion of its abatement technology $\psi_i$[8]. If $\gamma^*$ represents the choice $\gamma^* = \frac{\psi_j}{\psi_i}$ implies 'no technology transfer' (as the South's technology remains unchanged at $\psi_j$) and $\gamma^* = 1$ implies 'complete technology transfer' (as the South's technology changes to $\psi_i$) while $\gamma^*\psi_i$ represents a general case. We also assume, the technology is transferred free of cost. However, as the better abatement technology is transferred from the North to the South, the South's reaction to the North's pollution level changes that results in a change in the initial Nash equilibrium. The global pollution level also changes. Then, in this situation the North's commitment to the abovementioned international protocol would imply, it would choose its output level in such a way that at the new equilibrium ($q_{2i}'$, $q_{2j}'$) the following constraint holds:

$$\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}' \leq \overline{R}\,. \qquad (9)$$

As the North commits to technology transfer as well as to the above-mentioned international protocol the nature of the game played between the countries takes the form given below:

| t =1 | t = 2 | |
|---|---|---|
| The North choooses ($q_{2i}'$, $\gamma^*$) | The South observes ($q_{2i}'$, $\gamma^*$) and chooses $q_{2j}'$ | Payoffs are realized. |

Observe, in this situation $q_{2j}'$ depends on the choice of ($q_{2i}'$, $\gamma^*$) by the North. On the other hand the choice of ($q_{2i}'$, $\gamma^*$) depends on the way it affects $q_{2j}'$. We solve the game applying the method of backward induction. So, we first look at the reaction of the South to the change in the values of $q_{2i}'$ and $\gamma^*$.

[8] If the abatement technology was indivisible, the higher value of $\gamma$ would imply more updated vintage of the stock of technology in the North with greater abatement capacity.

**Lemma 1:** *(i) If* $\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}' = \overline{R}$ *, then* $\frac{\partial q_{2j}'}{\partial q_{2i}'} = 0$*. (ii) If* $\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}' < \overline{R}$ *, then* $\frac{\partial q_{2j}'}{\partial q_{2i}'} < 0$*.*

**Proof:** See the appendix.

**Lemma 2:** $\frac{\partial q_{2j}'}{\partial \gamma^*} > 0$*.*

**Proof:** See the appendix.

The North internalizes the behavior of the South as given by lemma 1 and 2 in its choice of ($q_{1i}'$, $q_{2i}'$, $\gamma^*$). The North solves the following problem: it maximizes,

$$v_i = u(q_{1i}, q_{2i}) - \frac{1}{2} (\phi_i\, q_{2i} + (1 - \gamma\psi_i)\, q_{2j})^2 \tag{10}$$

by choosing ($q_{1i}'$, $q_{2i}'$, $\gamma^*$) subject to the constraints given by equation (3), inequality (9), and the lemmas 1 and 2. Substituting $q_{1i}'$ from equation (3) into equation (10) the problem can be rewritten as: maximization of

$$v_i = u\left(\frac{L - (a_{2i} + a_{\psi i}\psi_i)q_{2i}}{a_{1i}}, q_{2i}\right) - \frac{1}{2} (\phi_i\, q_{2i} + (1 - \gamma\psi_i)\, q_{2j})^2 \tag{11}$$

by the choice of ($q_{2i}' > 0$, $\gamma^* > 0$) subject to the constraints:

$\phi_i\, q_{2i} + (1 - \gamma\psi_i)\, q_{2j} \leq \overline{R}$ (as in inequality (9))

$$\gamma \leq 1 \tag{12}$$

$$-\gamma \leq -\frac{\psi_j}{\psi_i} \tag{13}$$

and the behavior of the South given by lemmas 1 and 2. The equilibrium choice of $\gamma^*$ by the North and the global pollution level at the equilibrium are characterized by the first proposition of our model. Suppose, $\varepsilon = \frac{\gamma^*}{q_{2j}} \frac{dq_{2j}'}{d\gamma^*}$. Note, $\varepsilon > 0$ by virtue of lemma 2. Then, the proposition is stated as:

**Proposition 1:** *The following situations are possible at the equilibrium: (i) the North offers partial technology transfer when* $\gamma^* = \dfrac{\varepsilon}{\psi_i(1+\varepsilon)}$ *and* $\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}' \leq \overline{R}$. *(ii) It offers complete technology transfer when* $\varepsilon > \dfrac{\psi_i}{1-\psi_i}$ *and* $\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}' < \overline{R}$.

**Proof:** See the appendix.

As the North transfers the better technology of abatement to the South, the source of its benefit lies in the consequent reduction of the global pollution level. If the South receives the better technology its cost of abatement (and therefore the cost of production) falls. As a result the production of the polluting commodity in the South rises. Because of this, a possibility occurs such that the global pollution level increases as a whole with a threat of reducing welfare of country i, which has originally transferred the technology. However, if $\gamma^* = \dfrac{\varepsilon}{\psi_i(1+\varepsilon)}$, even if its production of the polluting commodity rises the South's contribution to the global pollution level remains unchanged. In this situation, depending on its preference for commodity 2 the North either can choose its output in such a way that the global pollution falls below the limit $\overline{R}$, which is the current pollution level or it can choose to maintain the pollution level at $\overline{R}$. On the other hand, if $\varepsilon > \dfrac{\psi_i}{1-\psi_i}$, as the technology is transferred the South emits more pollution in the air so that the global pollution level rises. Therefore, the North not only transfers its complete abatement technology but also reduces its own output of the polluting commodity to such an extent that the global pollution at the equilibrium falls below the limit $\overline{R}$.

In the next proposition we calculate the determinants of extent of technology transfer in the case of partial technology transfer is offered.

**Proposition 2:** *If the North offers partial technology transfer, as* $\psi_i$ *rises the extent of technology transfer falls. As* $\varepsilon$ *rises the extent of technology transfer rises.*

**Proof:** See the appendix.

As we have argued above when the North offers partial technology transfer $\gamma^* = \frac{\varepsilon}{\psi_i(1+\varepsilon)}$ the pollution emitted by the South remains constant as the technology is transferred. To maintain this feature of the equilibrium it is necessary for the North to reduce the extent of technology transfer at the equilibrium if it possesses a better technology at the initial situation. In other words, if the North possesses a better abatement technology it is sufficient for it to transfer a smaller part of it to keep the pollution emitted by the South unchanged at the initial level. If the South has higher $\varepsilon$ that implies if the technology is transferred to it to some extent, its output of the polluting commodity rises by a higher extent. As a result given the initial technology level of the country it adds more to the global pollution level. To counter this possibility and to keep the emission of the South fixed at the initial level, proposition 2 states, the North must transfer higher proportion of its better technology to the South.

It can also be argued that the South always accepts the technology transfer offer from the North. We note this as a separate proposition of the model as:

**Proposition 3:** *Whenever the South receives a technology transfer offer from the North it accepts the offer.*

**Proof:** See the appendix.

As the technology transfer is offered by the North, the South gains on two counts. First, as proposition 1 suggests, the global pollution level either falls or remains the same. Second, as the better abatement technology is transferred it produces more of the polluting commodity (from lemma 2). Since, as we assume in this paper there is a net gain in utility associated with production of commodity 2, the overall utility level of the country rises at the equilibrium. Therefore, proposition 1 and 3 together suggest whenever the North offers a technology transfer, the South readily accepts it.

Now, we consider the cases where at the initial equilibrium trade is opened up between the countries.

## 2.2 Trade: Complete specialization

We consider the countries are small enough and competitive in the world commodity markets for both the commodities. We denote the international terms of trade $\frac{p_2}{p_1}$ by p. We assume, at the trading equilibrium the following condition is satisfied: $\frac{a_{1i}}{a_{2i} + a_{\psi i}\Psi_i} < \frac{1}{p} < \frac{a_{1j}}{a_{2j} + a_{ij}\Psi_j}$. Since the North has comparative advantage in production of commodity 1 and the South has comparative advantage in commodity 2 (see the assumption in equation (5) above), as in the Ricardian models of trade, country 1 completely specializes in production of commodity 1 and country 2 completely specializes in production of commodity 2. It follows from equations (3) and (4), at the equilibrium the North produces ($\overline{q}_{1i} = \frac{L}{a_{1i}}$, $\overline{q}_{2i} = 0$) and the South produces ($\overline{q}_{1j} = 0$, $\overline{q}_{2j} = \frac{L}{a_{2j} + a_{\psi j}\Psi_j}$). However, both the countries consume both the commodities at the international prices $p_1$ and $p_2$. Suppose, $(\widetilde{q}_{1i}, \widetilde{q}_{2i})$ represent the consumption equilibrium at the North. Then it must satisfy the budget equation of the country:

$$\widetilde{q}_{1i} + \text{p}\ \widetilde{q}_{2i} = \frac{L}{a_{1i}}. \tag{14}$$

Similarly, the consumption equilibrium at the South, $(\widetilde{q}_{1j}, \widetilde{q}_{2j})$ must satisfy the budget equation of the South:

$$\widetilde{q}_{1j} + \text{p}\widetilde{q}_{2j} = \text{p}\frac{L}{a_{2j} + a_{\psi j}\Psi_j}. \tag{15}$$

We assume both the commodities are normal commodities in terms of their consumption. It follows: $\frac{d\widetilde{q}_{2i}}{dp} < 0$ and $\frac{d\widetilde{q}_{2j}}{dp} < 0$. As the trade opens up and both countries gain in terms of real income, it must also be true that $\widetilde{q}_{2i} > q_{2i}$* and $\widetilde{q}_{2j} >$ $q_{2j}$*.

The world market for commodity 2 must satisfy the following market clearing condition:

$$\tilde{q}_{2i}(\text{p}) + \tilde{q}_{2j}(\text{p}) = \frac{L}{a_{2j} + a_{\psi j}\Psi_j} \qquad (16)$$

which determines the international terms of trade p.

Since, now only the South produces the commodity emitting $CO_2$ in its production the global pollution level is given by:

$$\text{R} = \phi_j \, \bar{q}_{2j}. \qquad (17)$$

How does R compare with $\bar{R}$ ?

**Lemma 3:** R > $\bar{R}$ .

**Proof:** Since $\bar{q}_{2j} = \frac{L}{a_{2j} + a_{\psi j}\Psi_j}$, using equation (16) into equation (17) we have:

$$\text{R} = \phi_j \, (\tilde{q}_{2i} + \tilde{q}_{2j}). \qquad (18)$$

Since $\tilde{q}_{2i} > q_{2i}^*$, $\tilde{q}_{2j} > q_{2j}^*$ and $\phi_i < \phi_j$ the following must be true:

$\phi_j \, (\tilde{q}_{2i} + \tilde{q}_{2j}) > \phi_i \, q_{2i}^* + \phi_j \, q_{2j}^*$.

Therefore, from equations (8) and (18) the statement of the lemma follows. □

Since, now the North does not produce the polluting commodity, the commitment of the North to the international protocol to keep the global pollution level within $\bar{R}$ translates into the North's commitment to transfer the better abatement technology in such a way that the global pollution level remains within the limit. Now, the North chooses γ in an attempt to implement the following condition:

$$(1 - \gamma\psi_i) \, \bar{q}_{2j} \leq \bar{R}. \qquad (19)$$

Observe, since with trade and therefore unlike in the autarkic situation the North no longer produces the polluting commodity now it has only one instrument i.e. the choice of γ to implement the global pollution commitment given by equation (19). Here we are interested to know the choice of γ by the North. But, since it commits to satisfy equation (19) before making its choice it would like to know the way the South would like to react to its choice of γ. We denote the choice of γ by the North as $\tilde{\gamma}$. Unlike the autarkic situation here, as $\tilde{\gamma}$ changes the international terms of trade p changes. We call this 'terms-of-trade' effect. While taking its decision about of $\tilde{\gamma}$, the North also takes into account of the 'terms of trade' effect.

**Lemma 4:** $\frac{dp}{d\tilde{\gamma}} < 0$.

**Proof:** As the technology transfer takes place equation (16) can be written as:

$$\tilde{q}_{2i}(\text{p}) + \tilde{q}_{2j}(\text{p}) = \frac{L}{a_{2j} + \beta_j}. \tag{20}$$

From equation (15):

$$\frac{dp}{d\tilde{\gamma}} = - \frac{L}{(a_{2j} + \beta_j)^2 (\frac{d\tilde{q}_{2i}}{dp} + \frac{d\tilde{q}_{2j}}{dp})} \frac{d\beta_j}{d\tilde{\gamma}}. \tag{21}$$

Since by assumption $\frac{d\beta_j}{d\tilde{\gamma}} < 0$ and the commodities are the normal commodities, $\frac{dp}{d\tilde{\gamma}}$ $< 0$. □

**Lemma 5:** $\frac{d\bar{q}_{2j}}{d\tilde{\gamma}} > 0$.

**Proof:** We know, with trade $\bar{q}_{2j} = \frac{L}{a_{2j} + a_{\psi j}\Psi_j}$. With technology transfer $\bar{q}_{2j}$ becomes:

$$\bar{q}_{2j} = \frac{L}{a_{2j} + \beta_j}.$$

Therefore, $\frac{d\bar{q}_{2j}}{d\tilde{\gamma}} = - \frac{L}{(a_{2j} + \beta_j)^2} \frac{d\beta_j}{d\tilde{\gamma}}$.

Since, by assumption $\frac{d\beta_j}{d\tilde{\gamma}} < 0$, it follows $\frac{d\beta_j}{d\tilde{\gamma}} > 0$. □

Now, in view of the three lemmas derived above we look at the choice of $\tilde{\gamma}$ by the North. We also derive the condition under which the technology transfer offer is accepted by the South. We state the results in the following proposition of the model.

As we state the proposition we use the following definitions: $\eta = \frac{dp}{d\tilde{\gamma}}\frac{\tilde{\gamma}}{p}$ and $\xi = \frac{dR}{d\tilde{\gamma}}\frac{\tilde{\gamma}}{R}$.

**Proposition 4:** *The North refrains from technology transfer (chooses $\tilde{\gamma} = \frac{\psi_j}{\psi_i}$) if $\varepsilon \geq \frac{\psi_j}{1-\psi_j}$. If $\frac{1}{u_1}[\frac{R^2}{p\bar{q}_{2j}}\xi$ - $\frac{(\bar{q}_{2j}-\tilde{q}_{2j})}{\bar{q}_{2j}}\eta] < \varepsilon < \frac{\psi_j}{1-\psi_j}$, the North offers complete technology transfer (chooses $\tilde{\gamma}$ = 1) and the South accepts it.*

**Proof:**

Observe, compared to the autarkic situation now there is a possibility that the North refrains from technology transfer to the South. It does so if it contemplates that technology transfer is going to raise the global pollution level further. However, if it decides to transfer the technology at all, it opts for complete technology transfer. In the autarkic situation there is a possibility that the North goes for partial technology transfer, which vanishes with the trade situation. In the autarkic situation the South used to always gain from the technology transfer. So, whenever there was a technology transfer offer from the North, the South used to accept it. With trade this result changes. Now although the South benefits with the technology transfer as its production expands and the global pollution falls, but it loses as the international terms of trade moves against it. If ε is too low the 'terms of trade' effect dominates the other beneficial effects. Therefore, it refrains from accepting the technology transfer offer. Also observe, since in trade situation the North has one instrument less to commit to the global pollution constraint compared to the autarkic situation (it can choose only the extent of technology transfer, not the output of the polluting commodity), with trade there is no guarantee that the technology transfer can achieve the global pollution constraint given by equation (19). Unlike in the autarkic situation, despite technology transfer it may happen that the global pollution level exceeds $\bar{R}$.

## 3. Conclusions

The paper develops a model that tries to capture the possible impact of technology transfer in the purview of international agreements like Kyoto and Asia-Pacific Partnership on Clean Development and Climate on global climate change in which the North, the country with better abatement technology transfers its technology to the South such that the global GHG emission stabilizes within a defined limit. The paper considers both the no-trade ("autarkic") situation and the trade situation between the North and the South. It finds out in the autarkic situation even if the better abatement technology is transferred free of cost, at the equilibrium, the North will always like to transfer its technology to the South. However, the technology transfer can be either partial or complete. The South is always better off accepting the technology. The global pollution level always remains within the initially agreed limit. Next it introduces the possibility of trade in commodities between these countries and finds out the outcomes are different from the autarkic equilibrium. Because of trade, complete specialization in production occurs in both countries: the North completely specializes in production of the non-polluting commodity while the South specializes in the polluting commodity. In such a situation it becomes obvious that there is a possibility that the North is better off by not transferring its technology at all. However, if it decides to transfer the technology it transfers it completely. The partial transfer does not occur at the equilibrium. However, as the international terms of trade moves against the South, which receives the technology sometimes it is better off by refusing the transfer offer. The technology transfer in this case also cannot ensure the maintenance of the global pollution level within the initially agreed limit. Here we observe that the commodity trade not only restricts the scope of technology transfer but also makes the fulfilment of the aim of stabilizing the global emission level uncertain even if the complete technology is transferred to the South.

The model is based on a number of assumptions. It builds up on a carefully crafted example, which brings out the contrasting results in the autarkic and trade equilibria. Some of the assumptions we feel are realistic. Some of them are limiting, if relaxed offer possibilities of new research.

In this model we assume the country with better abatement technology also has a better production technology. The better abatement technology is not only able to abate more but also operates at lower cost. We think this assumption is realistic. The model also assumes a particular pattern of comparative advantage between the countries, which we again feel is realistic. The trade is modelled as a Ricardian model because that best captures the issue of technology transfer. Therefore, it uses only one factor of production, which is immobile between the countries. So, it fails to capture the effect of factor mobility between the countries on the equilibrium. The assumption of complete specialization in production is another limiting assumption of the model. If we allow for incomplete specialization in the country with better technology it is possible that the trade equilibrium can yield similar features as the autarkic equilibrium. In the model, we have assumed the technology transfer is free. Relaxing the assumption of free technology transfer eases the burden of fulfilling the commitment on the North, but it accentuates the possibility that there is no agreement between the countries on technology transfer and the effort to limit the global pollution suffers a setback. In this paper we have assumed the technology transfer takes place in a traded commodity. A possible extension of the paper can be introduction of a non-traded commodity (like power) in this model when the technology is transferred in this non-traded industry. However, our guess is that this new possibility, though interesting, is expected to yield similar results as in the current paper. Another interesting extension of this paper would be the introduction of strategic trade instead of the trade based on perfect competition. Here, we have not discussed if the transfer of abatement technology is the optimum strategy available for countries with better technology to keep the global pollution level within the limit. There could be other options like a transfer of the production technology or a combination of the abatement and the production technologies. We have not explored the possible answer to this question in this paper.

So, the paper brings out many interesting possibilities of research. Checking for these unexplored possibilities remain as our future research agenda.

**Appendix**

*Proof of lemma 1*. If $\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}' = \overline{R}$, at $(q_{1j}', q_{2j}')$ the objective function of the South as given in equation (2) can be written as:

$$v_j = u(q_{1j}', q_{2j}') - \frac{1}{2}\overline{R}^{\,2} \tag{1a}$$

From equation (4) it follows:

$$q_{1j}' = \frac{L - (a_{2j} + \beta_j)q_{2j}'}{a_{1j}} \tag{2a}$$

where $\beta_j$ is the new labor requirement in the South for the amount of abatement associated with per unit of production of commodity 2; $a_{\psi j}\psi_j \le \beta_j \le a_{\psi i}\psi_i$ and $\frac{d\beta_j}{d\gamma} <$ 0. Substituting the value of $q_{1j}'$ from equation (11) into equation (10) and maximizing with respect to $q_{2j}'$, we find $q_{2j}' > 0$ must satisfy the following first order condition for maximization:

$$- u_1 \frac{a_{2j} + \beta_j}{a_{1j}} + u_2 = 0. \tag{3a}$$

Since $q_{2j}'$ $(q_{2i}', \gamma^*)$ from equation (3a): $\frac{\partial q_{2j}'}{\partial q_{2i}'}$ = 0. Therefore, the first part of the statement of the lemma follows.

If $\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}' < \overline{R}$, at $(q_{1j}', q_{2j}')$ the objective function of the South as given in equation (2) can be written as:

$$v_j = u(q_{1j}', q_{2j}') - \frac{1}{2}(\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}')^2 . \tag{4a}$$

Substituting $q_{1j}'$ from equation (2a) into equation (4a) and maximizing with respect to $q_{2j}'$, we find $q_{2j}' > 0$ must satisfy the following first order condition for maximization:

$$- u_1 \frac{a_{2j} + \beta_j}{a_{1j}} + u_2 = (\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}')\,(1 - \gamma^*\psi_i). \tag{5a}$$

From (5a) we find:

$$\frac{\partial q_{2j}'}{\partial q_{2i}'} = \frac{\phi_i (1-\gamma *\psi_i)}{u_{11}(\frac{a_{2j}+\beta_j}{a_{1j}})^2 + u_{22} - (1-\gamma *\psi_i)^2}. \qquad (6a)$$

By the assumptions of the model $\gamma^*\psi_i < 1$. The second order condition of maximization implies the denominator of (6a) is negative. Therefore, from equation (6a) $\frac{\partial q_{2j}'}{\partial q_{2i}'} < 0$. Hence the statement of the second part of the lemma follows. □

*Proof of lemma 2.* If $\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}' = \overline{R}$, at ($q_{1j}'$, $q_{2j}'$) the objective function of the South as given in equation (1a). The objective function can be rewritten using equation (2a), which is maximized at $q_{2j}' > 0$. The first order condition given by equation (3a) is satisfied at the optimum. From equation (3a) we obtain:

$$\frac{\partial q_{2j}'}{\partial \gamma *} = \frac{\frac{1}{a_{1j}^2}\frac{d\beta_j}{d\gamma *}[a_{ij}u_1 - (a_{2j}+\beta_j)u_{11}q_{2j}']}{u_{11}(\frac{a_{2j}+\beta_j}{a_{1j}})^2 + u_{22}}. \qquad (7a)$$

The numerator of the term on the R.H.S of equation (7a) is negative as $u_1 > 0$, $\frac{d\beta_j}{d\gamma *} < 0$ and $u_{11} < 0$. The denominator is also negative by the second order condition of maximization, which is satisfied due to the assumptions $u_{11} < 0$, $u_{22} < 0$. Therefore, $\frac{\partial q_{2j}'}{\partial \gamma *} > 0$.

If $\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}' < \overline{R}$, at ($q_{1j}'$, $q_{2j}'$) the objective function of the South as given in equation (4a). Substituting $q_{1j}'$ from equation (2a) into equation (4a) and maximizing with respect to $q_{2j}'$, we find $q_{2j}' > 0$ must satisfy the first order condition for maximization given by (5a).

From (5a) we find:

$$\frac{\partial q_{2j}'}{\partial \gamma *} = \frac{\frac{1}{a_{1j}^2}\frac{d\beta_j}{d\gamma *}[a_{ij}u_1 - (a_{2j}+\beta_j)u_{11}q_{2j}'] - \psi_i R - (1-\gamma *\psi_i)\psi_i q_{2j}'}{u_{11}(\frac{a_{2j}+\beta_j}{a_{1j}})^2 + u_{22} - (1-\gamma *\psi_i)^2} \qquad (8a)$$

where, R = $\phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}'$. Given the assumptions of the model, it follows from equation (8a) $\frac{\partial q_{2j}'}{\partial \gamma^*} > 0$. Hence we prove the statement of the lemma. □

*Proof of Proposition 1.* Given the North's problem described above we can write the corresponding Lagrange function for optimization as:

$$Z = u\left(\frac{L-(a_{2i}+a_{\psi i}\psi_i)q_{2i}}{a_{1i}}, q_{2i}\right) - \frac{1}{2}(\phi_i q_{2i} + (1 - \gamma\psi_i) q_{2j})^2$$

$$+ \lambda_1 (\overline{R} - \phi_i q_{2i} - (1 - \gamma\psi_i) q_{2j}) + \lambda_2 (1 - \gamma) + \lambda_3 \left(- \frac{\psi_j}{\psi_i} + \gamma\right) \quad (9a)$$

which is maximized with respect to ($q_{2i}' > 0$, $\gamma^* > 0$, $\lambda_1^* \geq 0$, $\lambda_2^* \geq 0$ , $\lambda_3^* \geq 0$) where $\lambda_1$, $\lambda_2$ and $\lambda_3$ are Lagrange multipliers.

From equation (9a) we derive:

$$\frac{\partial Z}{\partial q_{2i}} = - u_1 \frac{a_{2i}+a_{\psi i}\psi_i}{a_{1i}} + u_2 - (\phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}')\left(\phi_i + (1 - \gamma^*\psi_i) \frac{\partial q_{2j}'}{\partial q_{1j}'}\right)$$

$$- \lambda_1^*\phi_i - \lambda_1^*(1 - \gamma^*\psi_i) \frac{\partial q_{2j}'}{\partial q_{1j}'} \quad (10a)$$

$$\frac{\partial Z}{\partial \gamma} = q_{2j}' \frac{(1-\gamma^*\psi_i)}{\gamma^*}\left(\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} - \varepsilon\right) (\phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}' + \lambda_1^*)$$

$$- \lambda_2^* + \lambda_3^* \quad (11a)$$

$$\frac{\partial Z}{\partial \lambda_1} = \overline{R} - \phi_i q_{2i}' - (1 - \gamma^*\psi_i) q_{2j}' \quad (12a)$$

$$\frac{\partial Z}{\partial \lambda_2} = 1 - \gamma^* \quad (13a)$$

$$\frac{\partial Z}{\partial \lambda_3} = - \frac{\psi_j}{\psi_i} + \gamma^*. \quad (14a)$$

Case 1: We assume, $\frac{\partial Z}{\partial \lambda_1} > 0$ i.e. $\overline{R} > \phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}'$ from equation (11a); $\frac{\partial Z}{\partial \lambda_2} > 0$ and $\frac{\partial Z}{\partial \lambda_3} > 0$ i.e. $\gamma^* \in (\frac{\psi_j}{\psi_i}, 1)$ from equations (13a) and (14a).

Then, complementary slackness implies it must be the case that $\lambda_1^* = \lambda_2^* = \lambda_3^* = 0$. This implies from equations (10a) and (11a) at ($q_{2i}' > 0$, $\gamma^* > 0$) the following equations must be satisfied:

$$-u_1 \frac{a_{2i} + a_{\psi i}\psi_i}{a_{1i}} + u_2 - (\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}')(\phi_i + (1 - \gamma^*\psi_i)\, \frac{\partial q_{2j}'}{\partial q_{1j}'}) = 0$$

and

$$q_{2j}'\, \frac{(1-\gamma^*\psi_i)}{\gamma^*} (\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} - \varepsilon)\, (\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}') = 0. \quad (15a)$$

From the assumptions of the model, equation (15a) implies: $\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} - \varepsilon = 0$, which in turn implies at the equilibrium it must be true that: $\gamma^* = \frac{\varepsilon}{\psi_i(1+\varepsilon)}$.

Case 2: We assume, $\frac{\partial Z}{\partial \lambda_1} = 0$ i.e. $\overline{R} = \phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}'$ from equation (11a); $\frac{\partial Z}{\partial \lambda_2} > 0$ and $\frac{\partial Z}{\partial \lambda_3} > 0$ i.e. $\gamma^* \in (\frac{\psi_j}{\psi_i}, 1)$ from equations (13a) and (14a).

Then, complementary slackness implies it must be the case that $\lambda_1^* > 0$ and $\lambda_2^* = \lambda_3^* = 0$.

We also know from lemma 1, $\frac{\partial q_{2j}'}{\partial q_{1j}'} = 0$ if $\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}' = \overline{R}$. These imply from equations (10a) and (11a) at ($q_{2i}' > 0$, $\gamma^* > 0$) the following equations must be satisfied:

$$-u_1 \frac{a_{2i} + a_{\psi i}\psi_i}{a_{1i}} + u_2 - (\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}')\phi_i - \lambda_1^*\phi_i = 0$$

and

$$q_{2j}' \frac{(1-\gamma^*\psi_i)}{\gamma^*}(\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} - \varepsilon)(\phi_i q_{2i}' + (1-\gamma^*\psi_i) q_{2j}' + \lambda_1^*) = 0. \quad (16a)$$

Equation (16a) is true for $\gamma^* = \frac{\varepsilon}{\psi_i(1+\varepsilon)}$.

We check at ($q_{2i}' > 0$, $\gamma^* > 0$) the constraint qualification condition: $\phi_i \, dq_{2i} \leq 0$ also holds.

Case 3: We assume, $\frac{\partial Z}{\partial \lambda_1} = 0$ i.e. $\overline{R} = \phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}'$ from equation (11a);

$\frac{\partial Z}{\partial \lambda_2} = 0$ and $\frac{\partial Z}{\partial \lambda_3} > 0$ i.e. $\frac{\psi_j}{\psi_i} < \gamma^* = 1$ from equations (13a) and (14a).

Then, complementary slackness implies it must be the case that $\lambda_1^* > 0$ and $\lambda_2^* > 0$ and $\lambda_3^* = 0$.

We also know from lemma 1, $\frac{\partial q_{2j}'}{\partial q_{1j}'} = 0$ if $\phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}' = \overline{R}$. These imply from equations (10a) and (11a) at ($q_{2i}' > 0$, $\gamma^* > 0$) the following equations must be satisfied:

$$-u_1 \frac{a_{2i} + a_{\psi i}\psi_i}{a_{1i}} + u_2 - (\phi_i q_{2i}' + (1-\gamma^*\psi_i) q_{2j}')\phi_i - \lambda_1^*\phi_i = 0$$

and

$$q_{2j}' \frac{(1-\gamma^*\psi_i)}{\gamma^*}(\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} - \varepsilon)(\phi_i q_{2i}' + (1-\gamma^*\psi_i) q_{2j}' + \lambda_1^*) - \lambda_2^* = 0. \quad (17a)$$

Equation (17a) is true for $\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} > \varepsilon$. Since in this case $\gamma^* = 1$, the condition turns out to be $\frac{\psi_i}{1-\psi_i} > \varepsilon$.

Here, the conditions for constraint qualifications are:

$\phi_i \, dq_{2i} + (1 - \psi_i) q_{2j}' (\varepsilon - \frac{\psi_i}{1-\psi_i}) d\gamma \leq 0$ and $d\gamma \leq 0$, which are not satisfied at ($q_{2j}' > 0$, $\gamma^* = 1$). Therefore, this case does not offer a solution to the North's maximization problem.

Case 4: We assume, $\frac{\partial Z}{\partial \lambda_1} = 0$ i.e. $\overline{R} = \phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}'$ from equation (11a); $\frac{\partial Z}{\partial \lambda_2} > 0$ and $\frac{\partial Z}{\partial \lambda_3} = 0$ i.e. $\frac{\psi_j}{\psi_i} = \gamma^* < 1$ from equations (13a) and (14a).

Then, complementary slackness implies it must be the case that $\lambda_1^* > 0$ and $\lambda_2^* = 0$ and $\lambda_3^* > 0$.

We also know from lemma 1, $\frac{\partial q_{2j}'}{\partial q_{1j}'} = 0$ if $\phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}' = \overline{R}$. These imply from equations (10a) and (11a) at $(q_{2i}' > 0, \gamma^* > 0)$ the following equations must be satisfied:

$$-u_1 \frac{a_{2i} + a_{\psi i}\psi_i}{a_{1i}} + u_2 - (\phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}')\phi_i - \lambda_1^*\phi_i = 0$$

and

$$q_{2j}' \frac{(1-\gamma^*\psi_i)}{\gamma^*} \left(\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} - \varepsilon\right) (\phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}' + \lambda_1^*) + \lambda_3^* = 0. \quad (18a)$$

Equation (18a) is true for $\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} < \varepsilon$. Since in this case $\gamma^* = \frac{\psi_j}{\psi_i}$, the condition turns out to be $\frac{\psi_j}{1-\psi_j} < \varepsilon$.

Here, the conditions for constraint qualifications are:

$\phi_i\, dq_{2i} + (1 - \psi_i) q_{2j}' (\varepsilon - \frac{\psi_j}{1-\psi_j})\, d\gamma \le 0$ and $d\gamma \le 0$, which are not satisfied at $(q_{2j}' > 0, \gamma^* = \frac{\psi_j}{\psi_i})$. Therefore, this case does not offer a solution to the North's maximization problem.

Case 5: We assume, $\frac{\partial Z}{\partial \lambda_1} > 0$ i.e. $\overline{R} > \phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}'$ from equation (11a); $\frac{\partial Z}{\partial \lambda_2} = 0$ and $\frac{\partial Z}{\partial \lambda_3} > 0$ i.e. $\frac{\psi_j}{\psi_i} < \gamma^* = 1$ from equations (13a) and (14a).

Then, complementary slackness implies it must be the case that $\lambda_1^* = 0$ and $\lambda_2^* > 0$ and $\lambda_3^* = 0$.

This implies from equations (10a) and (11a) at ($q_{2i}' > 0$, $\gamma^* > 0$) the following equations must be satisfied:

$$-u_1 \frac{a_{2i} + a_{\psi i}\psi_i}{a_{1i}} + u_2 - (\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}')\, (\phi_i + (1 - \gamma^*\psi_i) \frac{\partial q_{2j}'}{\partial q_{1j}'}) = 0$$

and

$$q_{2j}' \frac{(1-\gamma^*\psi_i)}{\gamma^*} (\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} - \varepsilon)\, (\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}') - \lambda_2^* = 0. \qquad (19a)$$

Equation (19a) is true for $\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} > \varepsilon$. Since in this case $\gamma^* = 1$, the condition turns out to be $\frac{\psi_i}{1-\psi_i} > \varepsilon$.

Here, the condition for constraint qualification is: $d\gamma \le 0$, which holds at ($q_{2j}' > 0$, $\gamma^* = 1$).

Case 6: We assume, $\frac{\partial Z}{\partial \lambda_1} > 0$ i.e. $\overline{R} > \phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}'$ from equation (11a); $\frac{\partial Z}{\partial \lambda_2} > 0$ and $\frac{\partial Z}{\partial \lambda_3} = 0$ i.e. $\frac{\psi_j}{\psi_i} = \gamma^* < 1$ from equations (13a) and (14a).

Then, complementary slackness implies it must be the case that $\lambda_1^* = \lambda_2^* = 0$ and $\lambda_3^* > 0$.

This implies from equations (10a) and (11a) at ($q_{2i}' > 0$, $\gamma^* > 0$) the following equations must be satisfied:

$$-u_1 \frac{a_{2i} + a_{\psi i}\psi_i}{a_{1i}} + u_2 - (\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}')\, (\phi_i + (1 - \gamma^*\psi_i) \frac{\partial q_{2j}'}{\partial q_{1j}'}) = 0$$

and

$$q_{2j}' \frac{(1-\gamma^*\psi_i)}{\gamma^*} (\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} - \varepsilon)\, (\phi_i\, q_{2i}' + (1 - \gamma^*\psi_i)\, q_{2j}') + \lambda_3^* = 0. \qquad (20a)$$

Equation (20a) is true for $\frac{\gamma^*\psi_i}{1-\gamma^*\psi_i} < \varepsilon$. Since in this case $\gamma^* = \frac{\psi_j}{\psi_i}$, the condition turns out to be $\frac{\psi_j}{1-\psi_j} < \varepsilon$.

Here, the condition for constraint qualification is: $d\gamma \le 0$. But, it does not hold at ($q_{2j}' > 0$, $\gamma^* = \frac{\psi_j}{\psi_i}$).

Hence, the statement of the proposition follows. □

*Proof of Proposition 2.* From proposition 1, if the North offers partial technology transfer the extent of technology transfer at the equilibrium is given by $\gamma^* = \frac{\varepsilon}{\psi_i(1+\varepsilon)}$. Clearly, $\frac{\partial\gamma^*}{\partial\psi_i} = -\frac{\varepsilon}{\psi_i^2(1+\varepsilon)} < 0$ since $\varepsilon > 0$ from lemma 2. Similarly, $\frac{\partial\gamma^*}{\partial\varepsilon} = \frac{1}{\psi_i(1+\varepsilon)^2} > 0$ since $\psi_i > 0$. Hence, the statement of the proposition follows. □

*Proof of Proposition 3*. From proposition 1 the following situations may occur at the equilibrium: (i) the North offers partial technology transfer when $\gamma^* = \frac{\varepsilon}{\psi_i(1+\varepsilon)}$ and $\phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}' \le \overline{R}$. (ii) It offers complete technology transfer when $\varepsilon > \frac{\psi_i}{1-\psi_i}$ and $\phi_i q_{2i}' + (1 - \gamma^*\psi_i) q_{2j}' < \overline{R}$.

If situation (i) occurs as the better abatement technology is offered the global pollution level either remains the same or falls. Therefore, it follows from equation (2), the South's utility either remains the same or improves from the pollution effect. The other part of the utility function is given by $u(\frac{L-(a_{2j}+\beta_j)q_{2j}'}{a_{1j}}, q_{2j}')$. It can be shown: $\frac{\partial u}{\partial\gamma^*} = \frac{dq_{2j}'}{d\gamma^*}[- u_1\frac{a_{2j}+\beta_j}{a_{1j}} + u_2] - u_1\frac{q_{2j}'}{q_{1j}'}\frac{d\beta_j}{d\gamma^*} > 0$ since $\frac{dq_{2j}'}{d\gamma^*} > 0$ from lemma 2, $[- u_1\frac{a_{2j}+\beta_j}{a_{1j}} + u_2] \ge 0$ from the first order conditions for $q_{2j}' > 0$ and $\frac{d\beta_j}{d\gamma^*}$

< 0. Similar arguments can be made if situation (ii) occurs at the equilibrium. Therefore, the South always accepts the offer for technology transfer. □

*Proof of Proposition 4*. As the North transfers the technology to the South, the global pollution level becomes:

$R = (1 - \gamma\psi_i)\ \bar{q}_{2j}$.

It follows, $\frac{dR}{d\gamma} = \psi_i\ \bar{q}_{2j}\,[\frac{1-\gamma\psi_i}{\gamma\psi_i}\varepsilon\ - 1]$.

At $\gamma = \frac{\psi_j}{\psi_i}$,

$$\frac{dR}{d\gamma} = \psi_i\ \bar{q}_{2j}\,[\frac{1-\psi_j}{\psi_j}\varepsilon\ - 1]. \tag{21a}$$

Since lemma 5 implies $\varepsilon > 0$ it follows from equation (21a) $\frac{dR}{d\gamma} \geq 0$ iff $\varepsilon \geq \frac{\psi_j}{1-\psi_j}$.

Therefore, if $\varepsilon \geq \frac{\psi_j}{1-\psi_j}$ since the North commits to constraint (19) it refrains from technology transfer (i.e. $\tilde{\gamma} = \frac{\psi_j}{\psi_i}$ is chosen). However, from equation (21a) $\frac{dR}{d\gamma} < 0$ iff $\varepsilon < \frac{\psi_j}{1-\psi_j}$. Then, the North offers technology transfer.

If $\varepsilon < \frac{\psi_j}{1-\psi_j}$, country i solves the following problem: it maximizes $v_i = u(\tilde{q}_{1i}, \tilde{q}_{2i}) - \frac{1}{2} R^2$ by choosing $(\tilde{q}_{1i}, \tilde{q}_{2i},)$ subject to the budget constraint given by equation (14). Using equation (14) the problem of the North can be restated as: maximization of $v_i = u(\frac{L}{a_{1i}} - p\ \tilde{q}_{2i}, \tilde{q}_{2i}) - \frac{1}{2} R^2$ with respect to $(\tilde{q}_{2i}, \tilde{\gamma})$.

For $\tilde{q}_{2i} > 0$, the first order condition implies:

$$\frac{\partial v_i}{\partial q_{2i}} = - pu_1 + u_2 = 0 \tag{22a}$$

On the other hand,

$$\frac{\partial v_i}{\partial \gamma} = \frac{dp}{d\gamma}[- u_1 \tilde{q}_{2i} + \frac{d\tilde{q}_{2i}}{dp}(- pu_1 + u_2)] - R\frac{dR}{d\gamma} > 0.$$

Since $(- pu_1 + u_2) = 0$ from equation (22a), $\frac{dp}{d\gamma} < 0$ from lemma 3 and $\frac{dR}{d\gamma} < 0$. Therefore, it is always $\gamma^* = 1$.

However, the South accepts the technology transfer offer if $\frac{dv_j}{d\gamma} > 0$. With technology transfer the South chooses $(\tilde{q}_{1j}, \tilde{q}_{2j})$ in such a way that it maximizes $v_j = u(\tilde{q}_{1j}, \tilde{q}_{2j}) - \frac{1}{2}R^2$ subject to the budget constraint given by equation (15):

$$\tilde{q}_{1j} + p\tilde{q}_{2j} = p\bar{q}_{2j}.$$

From the budget equation substituting $\tilde{q}_{1j} = p(\bar{q}_{2j} - \tilde{q}_{2j})$ into the objective function, we solve for the North's problem with respect to $\tilde{q}_{2j}$, which satisfies the following first order condition:

$$-p\, u_1 + u_2 = 0. \qquad (23a)$$

Observe, from (23a) $\tilde{q}_{2j}$ is a function of $\bar{q}_{2j}$ which in turn is a function of $\gamma$. Therefore,

$$\frac{\partial v_j}{\partial \gamma} = p\, u_1 \frac{d\bar{q}_{2j}}{d\gamma} + \frac{d\tilde{q}_{2j}}{d\bar{q}_{2j}} \frac{d\bar{q}_{2j}}{d\gamma}[-p\, u_1 + u_2] + [\bar{q}_{2j} - \tilde{q}_{2j}]\frac{dp}{d\gamma} - R\frac{dR}{d\gamma}. \qquad (24a)$$

Applying equation (23a) in equation (24a) we obtain:

$$\frac{\partial v_j}{\partial \gamma} = p\, u_1 \frac{d\bar{q}_{2j}}{d\gamma} + [\bar{q}_{2j} - \tilde{q}_{2j}]\frac{dp}{d\gamma} - R\frac{dR}{d\gamma}. \qquad (25a)$$

From equation (25a):

$$\frac{\partial v_j}{\partial \gamma} > 0 \text{ iff } [p\, u_1 \frac{d\bar{q}_{2j}}{d\gamma} + (\bar{q}_{2j} - \tilde{q}_{2j})\frac{dp}{d\gamma} - R\frac{dR}{d\gamma}] > 0.$$

The term $[p\, u_1 \frac{d\bar{q}_{2j}}{d\gamma} + (\bar{q}_{2j} - \tilde{q}_{2j})\frac{dp}{d\gamma} - R\frac{dR}{d\gamma}] > 0$ iff $\varepsilon > \frac{1}{u_1}[\frac{R^2}{p\bar{q}_{2j}}\xi - \frac{(\bar{q}_{2j} - \tilde{q}_{2j})}{\bar{q}_{2j}}\eta]$.

Therefore, the statement of the proposition follows. □

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