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Roles of Flexible Mechanisms in International Environmental Agreements*

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This paper focuses on the roles of flexible mechanisms in international environmental agreements (IEAs) and investigates the possibility of IEAs to achieve globally optimal transboundary pollution reduction. We first demonstrate that emission trading does not ensure the globally optimal outcome. Then, by introducing the investing schemes (Joint Implementation and Clean Development Mechanism) together with Emissions Trading, we also show that the global optimum can be achieved under a properly designed cost-sharing rule. Moreover, there exists an initial permit allocation with which every country can be better off through the flexible mechanisms. This finding implies that the countries can reach an agreement that can help achieve the globally optimal outcome.

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I. Introduction

Permit-trading schemes have attracted attention as effective instruments to resolve national and international environmental problems. Referring to a theoretical foundation based on Coase (1960), an efficient outcome can be achieved by bargaining between agents regardless of the initial allocation of property rights. The schemes have been adopted and developed by several international

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environmental agreements (IEAs), also known as flexible mechanisms.[1] The mechanisms are called "flexible" because they allow countries to cost-effectively achieve pollution reduction in other countries while reducing the overall cost of achieving abatement targets.

Compared with domestic mechanisms, the mechanisms in IEAs have a distinct feature in that trading schemes are not used independently but are often supplemented with some *investing* schemes.[2] In order to investigate the use of such additional schemes in IEAs, we examine the roles and limitations of the trading scheme in IEAs and explain how the additional investing schemes help to overcome the limitations. Then, we incorporate the key feature of each scheme into a standard IEA theory model, in order to analyze how flexible mechanisms work within the framework of IEAs. We focus on whether the global efficiency in the international environment problem can be achieved through market-based mechanisms (e.g., Emissions Trading in the Kyoto Protocol). We consider a model, in which the countries participating in an IEA simultaneously decide how much to reduce pollutant emissions.[3]

We show from the analysis that, assigning abatement obligations and allowing trade among countries are not sufficient for achieving the global optimum, especially if countries are significantly heterogeneous in their benefits and costs. Moreover, efficiency is lost in terms of global welfare even if countries succeed in reaching an agreement. The global optimum may not be desirable for some countries, but the global optimal outcome is attainable if the investment scheme is well designed to complement the trading scheme. Moreover, an initial permit allocation benefits every country through flexible mechanisms. This implies that all countries can reach an agreement to achieve the first-best outcome, and thus a

[1] Flexible mechanisms can be found in several recent international agreements, such as the Kyoto Protocol on Climate Change, the 1994 Oslo Protocol on Further Reduction of Sulfur Emissions, and the 1990 Revisions to the Montreal Protocol. See Pearce (1995) for more details.

[2] The Kyoto Protocol contains three flexible mechanisms. The first mechanism, Emissions Trading (ET), operates among countries with binding targets and meets their domestic targets by purchasing credits from other countries that have exceeded their targets. It resembles a typical domestic permit-trading scheme, except that the subjects are countries rather than firms or installations. The other two mechanisms, Clean Development Mechanism (CDM) and Joint Implementation (JI), are investing schemes that allow credits from investments in emission reduction projects in foreign countries to be used by countries with targets to meet their own commitments under the protocol. A key difference between CDM and JI is who hosts the investment. Host countries are those with binding targets for JI, whereas host countries are those without binding targets for CDM.

[3] Before negotiating an IEA, parties must first consider the asymmetric situation between developed and developing countries in terms of unilateral abatement efforts or historically cumulative emissions, especially when a study focuses on the IEA's establishment negotiations (see Dockner and Long, 1993; Zagonari, 1998; List and Mason, 2001; Aekapol and Hur, 2007). However, a simultaneous move game in the literature, which examines the efficiency of the IEA's operational mechanisms, is typically considered (e.g., Helm, 2003; Chander, 2003; Amato and Valentini, 2011), especially when the IEA itself has already been established, such as the Kyoto Mechanisms after the UNFCCC establishment.

trading scheme supplemented by an investing scheme is a highly effective mechanism for resolving the environmental problems caused by transboundary pollution.

The asymmetry in different countries' abatement benefits and costs makes the international environmental policy non-trivial compared with the domestic policy. Subjects in a domestic market mechanism are typically pure polluters who pay the costs, whereas those in an international one are beneficiaries for abatements and cost-payers. Therefore, this paper contributes to the literature on permit trading by discussing issues beyond cost efficiency. Most studies in the literature tend to focus on the conditions under which tradable permit markets can achieve efficiency gains in cost relative to policy alternatives, such as pollution tax or command and control, uncertainty (Weitzman, 1978), market structure (van Egteren and Weber, 1996; Lee, 2007), and transaction costs (Stavins, 1995). Cost efficiency is a key problem to solve when the subjects in the scheme are just cost-payers. However, the optimal scheme must be able to consider the benefit-dimension, especially when the subjects who enjoy direct benefits from mitigation are included in the scheme.

This paper contributes to the literature on IEAs by addressing whether and when the first-best IEAs are possible. Various approaches to improving international coordination have been suggested in the literature.[4] We reconsider the role of currently existing mechanisms in IEAs. Both non-cooperative and cooperative approaches have been used in the literature on IEAs, but the benefit heterogeneity issue has not been addressed sufficiently (Barrett, 1994; Hoel, 1992; Carraro and Siniscalco, 1993; Martimort and Sand-Zantman, 2013). Earlier studies have focused on cases where all nations are symmetric. In comparison, recent studies have shown flexibility regarding the assumption that marginal costs and benefits of abatement vary across countries (Helm, 2001, 2003; McGinty, 2007; Nagashima et al., 2009; Weikard, 2009; Gersbach and Winkler, 2011). A country does not care about the marginal benefit of its own abatement. Thus, these studies have focused on benefit heterogeneity only from the participation constraint aspect. However, we show how critical this assumption is and how problems associated with this assumption can be resolved through a mixture of flexible mechanisms in IEAs.

Finally, this paper provides a new way of understanding the role of flexible mechanisms in the architecture of IEAs. Many studies have considered the functions of the mechanisms separately or implicitly. Some studies on investment schemes have tackled issues about the schemes explicitly but not in an IEA context. They focus on problems of asymmetric information and strategic behaviors among potential hosts for foreign investment projects, and how to solve incentive problems between investors and hosts or between the Conference of the Parties and

[4] Examples include international carbon tax, international technology standards, and emissions trading. For more details, see Aldy *et al.* (2003).

investors/hosts through contracts for foreign investment projects or institutional arrangements (Hagem, 1996; Wirl et al., 1998; Breton et al., 2005). Other studies on IEAs consider issues about investment schemes with a broad perspective. For example, Barrett (1992) regards permit-trading schemes as a system of side-payments. Hoel (1992) and Carraro and Siniscalco (1993) show that transfers can increase participation when countries can commit to IEAs. Barrett (2001) highlights the incentives for high-benefit countries to induce participation by providing transfers to low-benefit countries, called "cooperation for sale." However, the manner in which investing schemes work with trading schemes in IEAs to produce a globally desirable outcome has not yet been addressed in the literature.

II. Basic Model

This section introduces the basic elements of our model. Let $N=\{1,\ldots,n\}$ be the set of countries. Each country emits global pollution, for example, greenhouse gas (GHG), which causes climate change. Although our model focuses on global pollution, it can be applied to highly generalized transboundary pollution problems without changing our main findings. Countries are aware of the detrimental effect of climate change and thus try to reduce GHG emissions. Let $a_i \geq 0$ be the level of abatement country i undertakes to ensure the reduction of GHG emissions.

Given a level of abatements $(a_k)_{k\in N}$, country i's payoff is expressed as

$$u_i(a_1,\ldots,a_n)=b_i\ln\left(\sum_{k\in N} a_k\right)-\frac{1}{2}c_i a_i^2, \tag{1}$$

where $b_i > 0$ and $c_i > 0$. The first term on the right-hand side represents country i's benefit from the aggregate abatement $A=\sum_{k\in N} a_k$. Country i's abatement increases the payoff of the other country even as it affects its own payoff. Thus, a positive externality exists in reducing GHG emissions. b_i captures the heterogeneity of countries in the benefit from the abatement of GHG emissions. A high b_i can be interpreted as country i considering the protection of the environment to be highly important or country i incurring great damage from climate change. The second term on the right-hand side represents the private costs incurred by country i to reduce GHG emissions. Here, c_i captures the heterogeneity of countries with regard to the cost of reducing GHG emissions. A low c_i can be interpreted as country i possessing highly advanced technology for reducing GHG emissions.

We first provide a condition for efficiency before analyzing the IEA. We refer to it as the Pareto efficiency.[5] We solve the problem to determine an efficient level of abatements. For $(\overline{u}_j)_{j \in N \setminus \{1\}}$,

$$\max_{(a_i)_{i \in N}} b_1 \ln\left(\sum_{k \in N} a_k\right) - \frac{1}{2} c_1 a_1^2$$

$$\text{is subject to} \quad b_j \ln\left(\sum_{k \in N} a_k\right) - \frac{1}{2} c_j a_j^2 \geq \overline{u}_j \quad \text{for} \quad j = 2, \ldots, n. \tag{2}$$

We solve this problem and find that an efficient level of abatements $(a_i^*)_{i \in N}$ must satisfy

$$\sum_{k \in N} a_k^* = \sum_{k \in N} \frac{b_k}{c_k a_k^*}. \tag{3}$$

We can see that, if country i increases GHG emissions, at least one of the other countries must reduce GHG emissions to sustain the efficiency.

Next, we consider the situation in which countries cannot reach an agreement on the abatement of GHG emissions. Each country i simultaneously decides its own abatement a_i to maximize its payoff given the level of abatements of the other countries. The outcome without agreement is achieved as a Nash equilibrium. Given an abatement $(a_k)_{k \in N \setminus \{i\}}$ of the other countries, each country i then chooses a_i that solves the problem

$$\max_{a_i} b_i \ln\left(\sum_{k \in N} a_k\right) - \frac{1}{2} c_i a_i^2. \tag{4}$$

We solve this problem for each i and obtain a Nash equilibrium as follows. For each i,

$$a_i^N = \frac{b_i}{c_i} \frac{1}{(\sum_{k \in N} b_k / c_k)^{1/2}}. \tag{5}$$

Moreover, the aggregate level of abatements in the Nash equilibrium is given by

[5] Efficiency is sometimes referred to as the maximization of global welfare. Every allocation that maximizes global welfare is Pareto efficient, but the converse is not true. However, Pareto efficiency is equivalent to the maximization of utilitarian global welfare if we allow monetary transfers among agents.

$$\sum_{k\in N} a_k^N = \left(\sum_{k\in N} \frac{b_k}{c_k}\right)^{1/2}. \tag{6}$$

The abatement a_i^N of each country i in the Nash equilibrium is proportional to b_i / c_i. The greater is the benefit from the abatement or the lower is the cost to reduce GHG emissions, and the more a country reduces GHG emissions in the equilibrium. For convenience, let $A^N = \sum_{k\in N} a_k^N$ be the aggregate level of abatements and $u_i^N = u_i(a_1^N, \ldots, a_n^N)$ be country i 's payoff at the Nash equilibrium.

The Nash equilibrium $(a_i^N)_{i\in N}$ is not Pareto efficient, which is trivial because

$$\sum_{k\in N} a_k^N = \left(\sum_{k\in N} \frac{b_k}{c_k}\right)^{1/2} < n\left(\sum_{k\in N} \frac{b_k}{c_k}\right)^{1/2} = \sum_{k\in N} \frac{b_k}{c_k a_k^N}. \tag{7}$$

Thus, $(a_i^N)_{i\in N}$ does not satisfy Equation (3). This finding implies that countries cannot achieve efficiency without cooperating with each other. This result coincides with the traditional argument on externality. Each country i 's abatement a_i generates a positive externality to the other countries. Thus, the individual decisions of countries with regards the level of abatement result in global inefficiency.

Countries cannot achieve efficiency without cooperating. Thus, they may seek to achieve efficiency by making an agreement on the level of abatement. A simple way to achieve efficiency is to define global welfare and maximize it. We refer to the level of abatement that maximizes global welfare as the global optimum. We consider global welfare SW as the sum of the country's payoffs. That is

$$SW = \sum_{j\in N} u_j(a_1, \ldots, a_n) = \sum_{j\in N}\left[b_j \ln\left(\sum_{k\in N} a_k\right) - \frac{1}{2} c_j a_j^2\right]. \tag{8}$$

We assume that each country's payoff is quasi-linear in terms of money.[6] Each country's welfare is measured in monetary units. Thus, the global welfare defined in Equation (8) means that global welfare is measured in terms of monetary units.[7]

Let $(a_i^M)_{i\in N}$ be the level of abatement that maximizes global welfare in Equation (8). A simple calibration yields that, for each i,

[6] This is clarified in Sections 3 and 4.

[7] Many previous studies define global welfare as the sum of the country's payoffs in the study of international environmental problems. Examples include Barrett (1994), Helm (2003), and Martimort and Sand–Zantman (2013).

$$a_i^M = \frac{1}{c_i}\frac{(\sum_{k\in N} b_k)^{1/2}}{(\sum_{k\in N} 1/c_k)^{1/2}}, \tag{9}$$

and

$$\sum_{k\in N} a_k^M = \left(\sum_{k\in N}\frac{1}{c_k}\right)^{1/2}\left(\sum_{k\in N} b_k\right)^{1/2}, \tag{10}$$

where a_i^M is proportional to $1/c_i$. To achieve the global optimum, a country that has incurred a low cost to reduce GHG emissions must exert more efforts to abate such emissions compared wih a country that has incurred a high cost to reduce GHG emissions. Moreover, each country i's marginal cost of abatement is the same, $c_i a_i^M = (\sum_{k\in N} b_k)^{1/2} / (\sum_{k\in N} 1/c_k)^{1/2}$. The aggregate cost to reduce GHG emissions should be minimized to achieve the global optimum. The different marginal costs to reduce GHG emissions across countries can reduce the aggregate cost by shifting the abatement from a country with high marginal cost to another country with low marginal cost. Equation (9) shows that a_i^M increases in $\sum_{k\in N} b_k$. Global welfare in Equation (8) depends on $\sum_{k\in N} b_k$ and not on b_i. Thus, a_i^M also depends on $\sum_{k\in N} b_k$. Here, $(a_i^M)_{i\in N}$ is efficient and satisfies Equation (3). Let $A^M = \sum_{k\in N} a_k^M$. We denote by u_i^M country i's payoff and the global welfare at $(a_i^M)_{i\in N}$ by SW^M. That is, $u_i^M = u_i(a_1^M,\ldots,a_n^M)$ and $SW^M = \sum_{k\in N} u_k^M$.

Next, we compare Equations (6) and (10), $\sum_{k\in N} a_k^M > \sum_{k\in N} a_k^N$. The globally optimal level of abatements is greater than the level of abatements at the Nash equilibrium, because each country i's abatement has a positive externality to the other countries. The level of abatement chosen by each country is lower than that at the global optimum.

The global optimum is desirable in terms of global welfare but achieving it is difficult due to multiple reasons. First, countries can reach an agreement, but enforcing them to abide by the agreement may not be fully possible. International agreements accept that a country has sovereignty to withdraw from an agreement if it is not favorable to its welfare. At the global optimum, each country does not maximize its payoff given the emission abatements of the other countries and has an incentive to increase GHG emissions for its own interests. Thus, an agreement to achieve the global optimum cannot be sustained by self-interested countries. Second, there might be a country whose payoff is worse at the global optimum compared with the non-cooperative outcome. This can happen for the country whose benefits from the abatement and cost to reduce GHG emissions are sufficiently small compared with other countries. Thus, country i with a relatively small c_i must make an excessive effort to reduce GHG emissions to achieve the global optimum even though this action is detrimental to itself. Moreover, the global optimum requires that a country i must exert some effort to reduce GHG emissions even if little benefit is received from the abatement.[8] Countries fail to reach an agreement to achieve the global optimum if $u_i^N > u_i^M$ for some country i.

Implementing a market-based system and allowing monetary transfers between countries are important steps to resolve these problems. ET, a well-known trading scheme for international environmental problems, is such an example. Monetary transfers under ET occur indirectly by assigning emission permits to each country and allowing countries to trade their permits. Moreover, ET is cost-efficient in reducing GHG emissions. We explore ET in the following section by focusing on its efficiency and the participation of countries to achieve the global optimum.

III. Trading Scheme without an Investing Scheme

This section considers ET as a trading scheme and examines its role in the agreement on GHG emissions. First, we modify the model where each country under ET is assigned a quota of permits to emit GHG. Each permit allows the country to emit one unit of GHG. Thus, each country is prohibited from emitting more GHG than allowed by their permits. A greater abatement means less GHG emissions. Thus, the assignment of permits can be interpreted as an assignment of the required abatement of GHG emissions. We denote by $\overline{a}_i$ the quota of required emission abatement for country i. Countries that need more or fewer emission permits can either buy or sell their permits in the market. The price of the permits is denoted by p. Under ET, the payoff for country i given a level of abatements $(a_k)_{k\in N}$ and a price p is expressed as

$$\begin{aligned} v_i(a_1,\ldots,a_n;p) &= u_i(a_1,\ldots,a_n) + p(a_i - \overline{a}_i) \\ &= b_i \ln\left(\sum_{k\in N} a_k\right) - \frac{1}{2}c_i a_i^2 + p(a_i - \overline{a}_i). \end{aligned} \tag{11}$$

If country i with quota $\overline{a}_i$ performs an abatement of emissions as $a_i > \overline{a}_i$, it must sell the remaining permits in the market. If country i with quota $\overline{a}_i$ wants to perform an abatement of emissions as $a_i < \overline{a}_i$, it must buy emission permits. The last term on the right-hand side in Equation (11) is a monetary transfer to country

[8] For a numerical example, let $N = \{1,2\}$. If $b_1 = b_2 = 1$ and $c_1 = 1$, $c_2 < 1/\ln 2 - 1 < 1$ implies $u_2^M < u_2^N$. If $b_1 = 1$ and $c_1 = c_2 = 1$, $b_2 < (1 - \ln 2 + \sqrt{(\ln 2)^2 + 2})/(2\ln 2 + 1) < 1$ implies $u_2^M < u_2^N$.

i, which is gained through trading emission permits. This term is positive if country i sells its permits and negative otherwise.

The outcome under ET is obtained as an equilibrium that consists of a level of abatements $(a_i^E)_{i\in N}$ and a price p^E that satisfy the following properties.

(E1) Each country i chooses a_i^E, which maximizes its payoff in Equation (11), given that other countries $j \neq i$ choose a_j^E and that the price of emission permits is p^E. That is,

$$a_i^E = \arg\max_{a_i} b_i \ln\left(\sum_{k\in N} a_k\right) - \frac{1}{2}c_i a_i^2 + p(a_i - \overline{a}_i)$$
$$\text{where } a_j = a_j^E \text{ for } j \neq i \text{ and } p = p^E. \tag{12}$$

(E2) The emission permit market is cleared. That is,

$$\sum_{i\in N} a_i^E = \sum_{i\in N} \overline{a}_i. \tag{13}$$

Countries do not treat the total emission $\sum_{k\in N} a_k$ as exogenously given when they choose their emission level. This is a typical approach in many economic analyses. For example, in a pure exchange economy, each individual does not consider the aggregate endowment, $\sum_{k\in N} \omega_k$, when they choose a commodity bundle to maximize their utility, where ω_k is individual k's endowment. Thus, an individual demand, x_k, and the aggregate demand, $\sum_{k\in N} x_k$, may exceed the aggregate endowment, $\sum_{k\in N} \omega_k$, although the aggregate demand equals the aggregate endowment in an equilibrium. Moreover, treating the total emission as endogenously may be more appropriate for flexible mechanisms in an international context. When the permit trading scheme is domestic, justifying that a polluter considers the total emission to be exogenously given is easier. This is because the government can effectively control the total emissions so that they will not exceed the permitted amount. However, the countries are less likely to consider the total emission to be fixed.

The market clearing condition in Equation (13) implies a zero aggregate monetary transfer in any equilibrium. That is, $\sum_{k\in N} p^E(a_k^E - \overline{a}_k) = 0$. The global welfare is defined as the sum of the country's payoffs. Thus, the global welfare at an equilibrium $((a_i^E)_{i\in N}, p^E)$ is expressed as

$$SW^E = \sum_{k\in N} u_k(a_1^E,\ldots,a_n^E) = \sum_{j\in N}\left[b_j \ln\left(\sum_{k\in N} a_k^E\right) - \frac{1}{2}c_j (a_j^E)^2 \right]. \tag{14}$$

The global welfare at an equilibrium $((a_i^E)_{i\in N}, p^E)$ depends only on the equilibrium abatement $(a_i^E)_{i\in N}$ and not on the equilibrium price p^E.

From the conditions in (12) and (13), we can calculate an equilibrium. The first-order necessary condition for the problem in Equation (12) implies that, for each i,

$$a_i^E = \frac{b_i}{c_i}\frac{1}{\sum_{k\in N} a_k^E} + \frac{1}{c_i} p^E. \tag{15}$$

We sum Equation (15) over $i \in N$, rearrange it, and obtain the equilibrium price

$$p^E = \frac{(\sum_{k\in N} \overline{a}_k)^2 - \sum_{k\in N} b_k / c_k}{(\sum_{k\in N} \overline{a}_k)(\sum_{k\in N} 1/c_k)}. \tag{16}$$

We plug this into Equation (15) and obtain the equilibrium abatement a_i^E for country i as

$$a_i^E = \frac{b_i \sum_{k\in N} 1/c_k + (\sum_{k\in N} \overline{a}_k)^2 - \sum_{k\in N} b_k / c_k}{c_i \sum_{k\in N} \overline{a}_k \sum_{k\in N} 1/c_k}. \tag{17}$$

If $\sum_{i\in N} \overline{a}_i$ is small enough, p^E in Equation (16) and a_i^E in Equation (17) can be negative, and the equilibrium is obtained as a corner solution. To avoid tedious arguments over corner solutions, we consider the target level of aggregate abatement $\sum_{i\in N} \overline{a}_i$ to be sufficiently high in order to satisfy

$$\sum_{k\in N} \overline{a}_k \geq \left(\sum_{k\in N} \frac{b_k}{c_k}\right)^{1/2}. \tag{18}$$

The condition in (18) ensures that $p^E \geq 0$ and $a_i^E > 0$ for each i. Since $\sum_{k\in N} a_k^N = (\sum_{k\in N} b_k / c_k)^{1/2}$ and ET aims to reduce GHG emissions compared with the non-cooperative situation, (18) is not so restrictive.

In addition, p^E in (16) is increasing in $\sum_{k\in N} \overline{a}_k$. Intuitively, an increase in $\sum_{k\in N} \overline{a}_k$ means that the countries are required to further reduce GHG emissions. Because the marginal cost of reducing GHG emissions increases with an increasing amount of emission abatement, the value of the emission permits also increases.

Notice that the equilibrium $((a_i^E)_{i\in N}, p^E)$ depends on the target level of aggregate abatement $\sum_{i\in N} \overline{a}_i$ and not on its distribution $(\overline{a}_i)_{i\in N}$ among the countries. Thus, $\sum_{i\in N} \overline{a}_i$ affects the global welfare in (14), but its distribution

$(\overline{a}_i)_{i \in N}$ does not. However, the distribution of the quotas $(\overline{a}_i)_{i \in N}$ affects each country's payoffs even when $\sum_{i \in N} \overline{a}_i$ is fixed. In addition, since p^E is determined with respect to $\sum_{i \in N} \overline{a}_i$, the payoffs of the countries are one-to-one transferable through the distribution of the quotas $(\overline{a}_i)_{i \in N}$ as long as $\sum_{i \in N} \overline{a}_i$ is unchanged. Given $\sum_{i \in N} \overline{a}_i$, a decrease in $\overline{a}_i$ improves the payoff of country i that hesitates to agree on the implementation of ET. Thus, countries' decision processes for deciding whether or not to implement ET can be separated into two parts. One is the decision regarding the target level of the aggregate abatement $\sum_{i \in N} \overline{a}_i$ concerning the optimum welfare. The other is the decision regarding the distribution $(\overline{a}_i)_{i \in N}$ of the target level of abatements concerning each country's payoffs, so that all countries agree on implementing ET.

Concerning global welfare, the first question raised is if it is possible to attain Pareto efficiency and the global optimum as an equilibrium under ET. Proposition 1 gives a negative answer to this question.[9]

Proposition 1 *Suppose that* $b_i \neq b_j$ *for some* i *and* j. *Then* $(a_i^M)_{i \in N}$ *cannot be obtained as an equilibrium under ET.*

Proof. Suppose that $(a_i^M)_{i \in N}$ is obtained as an equilibrium under a trading scheme. Then $\sum_{k \in N} a_k^E = \sum_{k \in N} \overline{a}_k = (\sum_{k \in N} 1/c_k)^{1/2} (\sum_{k \in N} b_k)^{1/2}$ should be satisfied. Plugging this into (17), we obtain

$$a_i^E = \frac{b_i \sum_{k \in N} 1/c_k + (\sum_{k \in N} 1/c_k)(\sum_{k \in N} b_k) - \sum_{k \in N} b_k / c_k}{c_i (\sum_{k \in N} \overline{a}_k)(\sum_{k \in N} 1/c_k)}$$

$$\neq \frac{1}{c_i} \frac{(\sum_{k \in N} b_k)^{1/2}}{(\sum_{k \in N} 1/c_k)^{1/2}} = a_i^M . \tag{19}$$

This completes the proof. ■

Proposition 1 states that the global optimum cannot be obtained under ET. In addition, letting $\sum_{i \in N} \overline{a}_i = \sum_{i \in N} a_i^M$, we can see that ET does not ensure Pareto efficiency. We note that Proposition 1 is based on the assumption that each country does not consider the level of aggregate abatement as a constant in maximizing its payoff, but does take into account the effect of its abatement effort on aggregate abatement. Indeed, the market clearing condition in (13) is a condition for equilibrium rather than a constraint for the countries to maximize their payoffs. If the countries consider the level of aggregate abatement as fixed at $\sum_{k \in N} a_k =$

[9] Proposition 1 comes from Suh et al. (2012), which is written in Korean. For the reader's convenience and the completeness of the paper, we include it in this paper.

$\sum_{k\in N}\overline{a}_k$ in maximizing their payoffs, the global optimum can be obtained as an equilibrium under ET.[10]

The failure of ET to attain the global optimum, as stated by Proposition 1, focuses attention on the second best that can be attained under ET. So, we will find $(\overline{a}_i)_{i\in N}$ that maximizes global welfare under ET. For convenience, let $\overline{A}=\sum_{i\in N}\overline{a}_i$ be the target level of aggregate abatement. As mentioned earlier, global welfare under ET depends on $\overline{A}$. Plugging (16) and (17) into (14), global welfare in the equilibrium is given by

$$SW^E(\overline{A})=\sum_{j\in N}\left[b_j\ln(\overline{A})-\frac{1}{2}c_j\left(\frac{b_j\sum_{k\in N}1/c_k+\overline{A}^2-\sum_{k\in N}b_k/c_k}{c_j\overline{A}(\sum_{k\in N}1/c_k)}\right)^2\right]. \tag{20}$$

We want to find $\overline{A}^*$ that maximizes $SW^E(\overline{A})$. The first order necessary condition for the maximization of $SW(\overline{A})$ is

$$\frac{dSW^E(\overline{A})}{d\overline{A}}=-\frac{1}{\overline{A}^3(\sum_{k\in N}1/c_k)}\left[\overline{A}^4-\overline{A}^2\left(\sum_{k\in N}b_k\right)\left(\sum_{k\in N}\frac{1}{c_k}\right)\right.$$
$$\left.-\left(\sum_{k\in N}\frac{1}{c_k}\right)\left(\sum_{k\in N}\frac{b_k^2}{c_k}\right)+\left(\sum_{k\in N}\frac{b_k}{c_k}\right)^2\right]=0. \tag{21}$$

Thus, we obtain $\overline{A}^*$ maximizing $SW^E(\overline{A})$ as follows:

$$\overline{A}^*=\frac{1}{\sqrt{2}}\left[\sum_{k\in N}b_k\sum_{k\in N}\frac{1}{c_k}\right.$$
$$\left.+\left(\left(\sum_{k\in N}b_k\sum_{k\in N}\frac{1}{c_k}\right)^2+4\sum_{k\in N}\frac{1}{c_k}\sum_{k\in N}\frac{b_k^2}{c_k}-4\left(\sum_{k\in N}\frac{b_k}{c_k}\right)^2\right)^{1/2}\right]^{1/2}. \tag{22}$$

Plugging this into (20), we find maximized global welfare $SW^E(\overline{A}^*)$ under ET. In Proposition 2, we compare $\overline{A}^*$ and A^M.

Proposition 2 *Suppose that* $b_i\neq b_j$ *for some* i *and* j. *Let* $A^M=\sum_{k\in N}a_k^M$. *Let*

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[10] This coincides with the well-known result of the Coase theorem. Helm (2003), Chander (2003), and Amato and Valentini (2011) also discuss the efficiency of ET under a model in which the countries consider the level of aggregate emission as fixed by the total emission permits.

$\overline{A}^*$ be the aggregate level of abatements that maximizes global welfare in (8) under ET. Then, $\overline{A}^* > A^M$ is satisfied.

Proof. Since $b_i \neq b_j$ for some i and j, the Cauchy-Schwarz inequality implies

$$\left(\sum_{k\in N}\frac{1}{c_k}\right)\left(\sum_{k\in N}\frac{b_k^2}{c_k}\right) > \left(\sum_{k\in N}\frac{b_k}{c_k}\right)^2. \tag{23}$$

Then, from (10) and (22), we have

$$\begin{aligned}&(\overline{A}^*)^2 - (A^M)^2\\ &= \frac{1}{2}\left[\left(\left(\sum_{k\in N} b_k \sum_{k\in N}\frac{1}{c_k}\right)^2 + 4\sum_{k\in N}\frac{1}{c_k}\sum_{k\in N}\frac{b_k^2}{c_k} - 4\left(\sum_{k\in N}\frac{b_k}{c_k}\right)^2\right)^{1/2} - \sum_{k\in N} b_k \sum_{k\in N}\frac{1}{c_k}\right]\\ &> 0\end{aligned} \tag{24}$$

Since $\overline{A}^* > 0$ and $A^M > 0$, we complete the proof. ■

Proposition 2 states that, if there is heterogeneity of countries with regard to the benefit from emission abatement, the target level of aggregate abatement under ET should be higher than the global optimum level of aggregate abatement in order to improve global welfare. For intuition, suppose that $\overline{A} = A^M$. As mentioned earlier, in the presence of heterogeneity of benefits from abatements, the marginal costs of countries are not equalized at equilibrium. Since the global marginal benefit is not affected by the distribution $(\overline{a}_i)_{i\in N}$ of $\overline{A}$, there is a country whose marginal cost of abatement is lower than the global marginal benefit. This implies that the optimum marginal benefit from the abatement is greater than the global marginal cost to abate GHG emissions. Hence, global welfare can be improved by increasing $\overline{A}$ from A^M.

Proposition 2 also implies that ET can improve global welfare compared with the non-cooperative outcome. Although ET is desirable in terms of global welfare, it does not ensure that every country is better off. If there is a country that prefers the non-cooperative outcome to the equilibrium under ET, an agreement on ET implementation cannot be achieved. However, Proposition 3 shows that it is possible for such countries to reach an agreement on ET implementation.

Proposition 3 *Suppose that $\overline{A} > \sum_{k\in N} a_k^N$ and $SW^E(\overline{A}) > \sum_{k\in N} u_k^N$. Then, there exists $(\overline{a}_i)_{i\in N}$ such that $\sum_{k\in N} \overline{a}_k = \overline{A}$ and, for each i, the equilibrium payoff*

$v_i(a_1^E,\ldots,a_n^E;p^E)$ *under ET satisfies* $v_i(a_1^E,\ldots,a_n^E;p^E) > u_i^N$.

Proof. Given $\sum_{k\in N}\bar{a}_k = \bar{A}$, the equilibrium payoff of country i is maximized when $\bar{a}_i = 0$. The maximized payoff of country i is denoted by $\bar{v}_i^E(\bar{A})$. From (16) and (17), we can see that

$$\bar{v}_i^E(\bar{A}) = b_i\ln(\bar{A}) - \frac{1}{2}c_i(a_i^E)^2 + p^E a_i^E$$
$$= b_i\ln(\bar{A}) - \frac{1}{2}\frac{1}{c_i\bar{A}^2(\sum_{k\in N}1/c_k)^2}\left(b_i^2\left(\sum_{k\in N}\frac{1}{c_k}\right)^2 - \left(\bar{A}^2 - \sum_{k\in N}\frac{b_k}{c_k}\right)^2\right) \quad (25)$$

Suppose that $\bar{A} = \sum_{k\in N}a_k^N$. Then, we can see from (5) and (17) that

$$a_i^E = \frac{b_i\sum_{k\in N}1/c_k + \sum_{k\in N}b_k/c_k - \sum_{k\in N}b_k/c_k}{c_i(\sum_{k\in N}b_k/c_k)^{1/2}(\sum_{k\in N}1/c_k)} = \frac{b_i}{c_i}\frac{1}{(\sum_{k\in N}b_k/c_k)^{1/2}} = a_i^N \quad (26)$$

and $p^E = 0$. Thus, we have

$$\bar{v}_i^E\left(\sum_{k\in N}a_k^N\right) = b_i\ln\left(\sum_{k\in N}a_k^N\right) - \frac{1}{2}c_i(a_i^N)^2 + p_i^E a_i^N \geq u_i^N . \quad (27)$$

In addition, we can see that, for any $\bar{A} > \sum_{k\in N}a_k^N = (\sum_{k\in N}b_k/c_k)^{1/2}$,

$$\frac{d\bar{v}_i^E(\bar{A})}{d\bar{A}} = \frac{b_i}{\bar{A}} + \frac{1}{c_i\bar{A}^3(\sum_{k\in N}1/c_k)^2}\left(b_i^2\left(\sum_{k\in N}\frac{1}{c_k}\right)^2 + \bar{A}^4 - \left(\sum_{k\in N}\frac{b_k}{c_k}\right)^2\right) > 0 \quad (28)$$

holds. This implies that $\bar{v}_i^E(\bar{A}) > u_i^N$ for all $\bar{A} > \sum_{k\in N}a_k^N$. Given $(\bar{a}_i)_{i\in N}$, let $v_i^E = v_i(a_1^E,\ldots,a_n^E;p^E)$ be an equilibrium payoff of country i. Note that $v_i^E = \bar{v}_i^E(\bar{A}) - p^E\bar{a}_i$ and $\sum_{i\in N}v_i^E = SW(\bar{A})$. Let

$$\alpha = \frac{p^E\bar{A}}{\sum_{i\in N}\bar{v}_i^E(\bar{A}) - \sum_{i\in N}u_i^N} . \quad (29)$$

Since $\sum_{i\in N}u_i^N < \sum_{i\in N}\bar{v}_i^E(\bar{A}) - p^E\bar{A} = SW^E(\bar{A})$ holds, $0 < \alpha < 1$ is satisfied. For each i, let

$$\overline{a}_i = \alpha\left(\frac{\overline{v}_i^E(\overline{A}) - u_i^N}{p^E}\right). \tag{30}$$

Since $0 < \alpha < 1$, (30) implies that $p^E \overline{a}_i = \alpha(\overline{v}_i^E(\overline{A}) - u_i^N) < \overline{v}_i^E(\overline{A}) - u_i^N$. Thus, we have $v_i^E = \overline{v}_i^E(\overline{A}) - p^E \overline{a}_i > u_i^N$.[11] ■

Proposition 3 implies that countries can improve their payoffs by implementing ET with an appropriate $(\overline{a}_i)_{i\in N}$. Thus, it may be possible to reach an agreement on adopting ET without harming any country. In the proof of Proposition 3, country i's payoff that is maximized under ET with $\overline{A} = \sum_{k\in N} \overline{a}_k$ increases from u_i^N as $\overline{A}$ increases from A^N. Then, as in the proof of Proposition 3, it can be shown that, if $\overline{A}$ and $\overline{A}'$ satisfy $A^N < \overline{A} < \overline{A}'$ and $SW^E(\overline{A}) < SW^E(\overline{A}')$, for any equilibrium payoff $(v_1^E, \ldots, v_n^E)$ under ET with $\overline{A}$, there exists an equilibrium payoff $(v_1'^E, \ldots, v_n'^E)$ satisfying $v_i'^E > v_i^E$ for each i under ET with $\overline{A}'$. This implies that ET with $\overline{A}^*$ is the most desirable in the sense that Pareto improvement is not possible through ET. However, as we mentioned earlier, ET does not ensure Pareto efficiency or the global optimum, and so mechanisms other than ET might be required to achieve the global optimum.

IV. Trading Scheme Supplemented with Investing Schemes

In this section, we apply an investing scheme to the trading scheme and investigate the attainability of the global optimum. Through the investing scheme, each country can reduce GHG emissions in any other country as an alternative to reducing emissions domestically. Under the investing scheme in our model, denoted by *JI/CDM*, each country can implement mitigation projects in other countries at the marginal abatement cost of the hosting country rather than the investing country. Let a_{ik} be the amount of emission abatement that country i performs in country k. The total amount of emission abatement that country i performs is $\sum_{k\in N} a_{ik}$, and the total emission abatement that is performed in country k is $\sum_{j\in N} a_{jk}$. We assume that the cost to reduce GHG emissions in country k is shared by countries according to the proportion of their abatements. Let $\overline{a}_i$ be a quota of required emission abatement for country i. When the price of the emission permits is p and the abatement of countries is $((a_{ik})_{k\in N})_{i\in N}$, country i's payoff is given by

[11] We note that $(v_i^E)_{i\in N}$ here is the Kalai-Smorodinsky solution in TU bargaining games. Of course, this is not the unique payoff that satisfies $v_i^E > u_i^N$ for each i.

$$\begin{aligned} & v_i(((a_{jk})_{k\in N})_{j\in N};p) \\ & = u_i(((a_{jk})_{k\in N})_{j\in N}) + p\left(\sum_{k\in N} a_{ik} - \overline{a}_i\right) \\ & = b_i \ln\left(\sum_{j\in N}\sum_{k\in N} a_{jk}\right) - \sum_{k\in N}\left(\frac{1}{2}c_k\left(\sum_{j\in N} a_{jk}\right)^2 \frac{a_{ik}}{\sum_{j\in N} a_{jk}}\right) + p\left(\sum_{k\in N} a_{ik} - \overline{a}_i\right) \end{aligned} \tag{31}$$

Because country i's abatement in any country is admitted as a domestic abatement of GHG emissions, the amount of emission permits that country i sells or buys is $\sum_{k\in N} a_{ik} - \overline{a}_i$.

We can define an equilibrium under ET with JI/CDM as in Section 3. An equilibrium consists of a level of abatements $((a^J_{ik})_{k\in N})_{i\in N}$ and a price p^J satisfying the following properties.

(J1) Each country i chooses $(a^J_{ik})_{k\in N}$ that maximizes its payoff in (31) given that the other countries $j \neq i$ choose $(a^J_{jk})_{k\in N}$ and the price of emission permits is p^J. That is,

$$\begin{aligned} (a^J_{ik})_{k\in N} = \arg\max_{(a_{ik})_{k\in N}} & \, b_i \ln\left(\sum_{j\in N}\sum_{k\in N} a_{jk}\right) \\ & - \sum_{k\in N}\left(\frac{1}{2}c_k\left(\sum_{j\in N} a_{jk}\right)^2 \frac{a_{ik}}{\sum_{j\in N} a_{jk}}\right) + p\left(\sum_{k\in N} a_{ik} - \overline{a}_i\right) \end{aligned}$$

where $(a_{jk})_{k\in N} = (a^J_{jk})_{k\in N}$ for $j \neq i$ and $p = p^J$. (32)

(J2) The emission permit market is cleared. That is,

$$\sum_{i\in N}\sum_{k\in N} a^J_{ik} = \sum_{i\in N} \overline{a}_i . \tag{33}$$

Due to the market clearing condition in (33), global welfare, defined as a sum of the country's payoffs, is given by

$$SW^J = \sum_{k\in N} u_k(((a^J_{jk})_{k\in N})_{j\in N}) = \sum_{k\in N}\left[b_k \ln\left(\sum_{j\in N}\sum_{k\in N} a^J_{jk}\right) - \frac{1}{2}c_k\left(\sum_{j\in N} a^J_{jk}\right)^2\right]. \tag{34}$$

From the conditions in (32) and (33), we can explicitly calculate an equilibrium. The first order necessary conditions for the problem in (32) imply that, for each i and each k,

$$a_{ik}^J = 2b_i \frac{1}{c_k \sum_{j\in N}\sum_{k\in N} a_{jk}^J} - \sum_{j\in N} a_{jk}^J + 2\frac{1}{c_k} p^J . \tag{35}$$

Summing (35) over $i \in N$ and rearranging the equation, we have

$$\sum_{i\in N} a_{ik}^J = \frac{2}{n+1}\frac{\sum_{i\in N} b_i}{c_k \sum_{j\in N}\sum_{k\in N} a_{jk}^J} + \frac{2n}{n+1}\frac{1}{c_k} p^J . \tag{36}$$

Since the market clearing condition in (33) should be satisfied in the equilibrium, summing (35) over i and rearranging the equation, we can find the equilibrium price p^J as follows:

$$p^J = \frac{(n+1)\overline{A}^2 - 2\sum_{k\in N} b_k \sum_{k\in N} 1/c_k}{2n\overline{A}\sum_{k\in N} 1/c_k}, \tag{37}$$

where $\overline{A} = \sum_{i\in N}\sum_{k\in N} a_{ik}^J$. In addition, plugging (37) into (35) and (36) and rearranging the equation, we obtain each country i's abatement in country k at equilibrium as follows:

$$a_{ik}^J = \frac{\overline{A}^2 + 2nb_i \sum_{j\in N} 1/c_j - 2\sum_{j\in N} b_j \sum_{j\in N} 1/c_j}{nc_k \overline{A}\sum_{j\in N} 1/c_j}. \tag{38}$$

As in the equilibrium in Section 3, the equilibrium $(((a_{ik}^J)_{k\in N})_{i\in N}, p^J)$ and the global welfare SW^J in the equilibrium depend on the target level of aggregate abatement $\overline{A}$.

Notice that, for any $\overline{A} \geq A^M$, p^J is always positive. In this section, we focus on the possibility of attaining the global optimum as an equilibrium under ET with JI/CDM. Thus, we restrict our attention to the case of $\overline{A} \geq A^M$. Although this restriction ensures that the equilibrium price is positive, it does not ensure that equilibrium abatement is non-negative. Indeed, even when $\overline{A} \geq A^M$, a_{ik}^J in (38) can be negative if the difference of b_i is sufficiently great across countries. To avoid tedious arguments for corner solutions, we assume that, for each i, $b_i \geq \sum_{k\in N} b_k / (2n)$ unless otherwise noted. In other words, the difference of the benefits from emission abatement is not so great across countries. This assumption, together with the restriction of $\overline{A} \geq A^M$, ensures that equilibrium is obtained as an interior solution.

From (38), we can determine the amount of abatement that country i performs as follows:

$$\sum_{k \in N} a_{ik}^J = \frac{\overline{A}^2 + 2nb_i \sum_{k \in N} 1/c_k - 2\sum_{k \in N} b_k \sum_{k \in N} 1/c_k}{n\overline{A}}. \tag{39}$$

The amount of abatement that is performed in country k is

$$\sum_{i \in N} a_{ik}^J = \frac{1}{c_k} \frac{\overline{A}}{\sum_{i \in N} 1/c_i}. \tag{40}$$

Country i, which enjoys more benefits from emissions abatement, reduces GHG emissions to a greater extent. In addition, greater abatement of GHG emissions is undertaken in country k, whose cost to reduce emissions is relatively low. Since countries share the cost of emission abatement through JI/CDM, the amount of abatement that country i undertakes depends on $\sum_{k \in N} 1/c_k$ and not on its own cost c_i.

In Section 3, we showed that the global optimum cannot be attained as an equilibrium through ET. However, Proposition 4 shows that, if JI/CDM is adopted under ET, it is possible to achieve the global optimum as an equilibrium.

Proposition 4 *Let* $\overline{A} = \sum_{k \in N} a_k^M$. *Then, the equilibrium under ET with JI/CDM attains the global optimum.*

Proof. For the proof, it is enough to show that, for each k, $\sum_{i \in N} a_{ik}^J = a_k^M$ holds. Plugging $\overline{A} = \sum_{k \in N} a_k^M$ into (40), we have the result. ■

For intuition, consider the equilibrium in Section 3. Here, the marginal cost of abatement in country k is $c_k a_k^E$ and depends on b_k as well as the equilibrium price p^E. This implies that the marginal cost of abatement differs across countries, and so it fails to achieve the global optimum. However, under ET with JI/CDM, the cost of abatement in country k is shared by all countries. Thus, although the marginal cost of abatement for country i in country k depends on b_i, the marginal cost of abatement in country k for global society depends on $\sum_{i \in N} b_i$.[12] This implies that the marginal cost of abatement is equalized across countries. Note that equalizing the marginal cost of abatement in each country is necessary to

[12] Note that the marginal cost of abatement in country k for global society is $c_k \sum_{i \in N} a_{ik}^J$.

achieve the global optimum.

In addition, under ET with JI/CDM, country i's abatement in country k depends on the cost c_k of the abatement in country k and not on the cost c_i in country i as long as $\sum_{k\in N} 1/c_k$ is given. This implies that the aggregate abatement $\sum_{i\in N} a_{ik}^J$ in country k depends on c_k. Indeed, $\sum_{i\in N} a_{ik}^J$ in (40) is proportional to $1/c_k$ as is a_k^M in (9). Thus, when $\overline{A} = \sum_{k\in N} a_k^M$, the abatement $\sum_{i\in N} a_{ik}^J$ in country k should be equal to a_k^M.[13]

Although the global optimum can be attained under ET with JI/CDM, it does not ensure that all countries can reach an agreement on implementing ET with JI/CDM. If a country will not be better off compared with the non-cooperative outcome irrespective of the allocation of target abatement, it will not sign the agreement on implementing ET and JI/CDM. However, Proposition 5 states that every country can be better off through ET with JI/CDM.

Proposition 5 *Let* $\overline{A} = \sum_{k\in N} a_k^M$. *Then, there exists* $(\overline{a}_i)_{i\in N}$ *such that* $\sum_{k\in N} \overline{a}_k = \overline{A}$ *is satisfied and, for each* i, *the equilibrium payoff* $v_i(((a_{ik}^J)_{k\in N})_{i\in N}; p^J)$ *under ET with JI/CDM satisfies* $v_i(((a_{ik}^J)_{k\in N})_{i\in N}; p^J) > u_i^N$.

Proof. See the Appendix. ■

The proof of Proposition 5 contains a tedious calculation and is therefore presented in the Appendix. In the proof, it is shown that, for each i, $\overline{v}_i^J(\overline{A}) > u_i^N$ is satisfied. Here, $\overline{v}_i^J(\overline{A})$ is the maximized payoff of country i that can be obtained as an equilibrium under ET with JI/CDM. Then, the arguments similar to the proof of Proposition 3 can be applied for the result.

Propositions 5 and 4 imply that the difficulties in making an agreement to

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[13] Regarding the possibility of a global optimum through JI/CDM without ET, each country i chooses $(a_{ik})_{k\in N}$ to maximize

$$u_i(((a_{jk})_{k\in N})_{j\in N}) = b_i \ln\left(\sum_{j\in N}\sum_{k\in N} a_{jk}\right) - \sum_{k\in N}\left(\frac{1}{2}c_k\left(\sum_{j\in N} a_{jk}\right)^2 \frac{a_{ik}}{\sum_{j\in N} a_{jk}}\right)$$

given the abatements $((a_{jk})_{k\in N})_{j\in N\setminus\{i\}}$ of the other countries. The outcome is obtained as a Nash equilibrium $((a_{jk}^C)_{k\in N})_{j\in N}$. In this setting, we can show that

$$\sum_{j\in N} a_{jk}^C = \frac{\sqrt{2}}{\sqrt{n+1}}\frac{1}{c_i}\frac{(\sum_{j\in N} b_j)^{1/2}}{(\sum_{j\in N} 1/c_j)^{1/2}} = \frac{\sqrt{2}}{\sqrt{n+1}} a_k^M .$$

This implies that the global optimum cannot be attained through JI/CDM without ET.

achieve the global optimum can be resolved by implementing ET with JI/CDM.[14] As discussed in Section 2, difficulties arise in making an agreement to achieve the global optimum without monetary transfers. Due to the absence of an international institution that can enforce countries to abide by the agreement, countries may have an incentive to deviate from the agreement on achieving the global optimum. In addition, one country may be worse off at the global optimum and thus may not sign the agreement. Because each country maximizes its payoff given the price and the abatements of other countries, the equilibrium under ET with JI/CDM is self-enforcing. Thus, the global optimum can be attained by self-interested countries without an international institution that enforces them to abide by the agreement. In addition, as seen in Proposition 5, each country's payoff can be improved through ET and JI/CDM. This implies that countries can reach an agreement to implement ET and JI/CDM to achieve the global optimum.

In reality, how to allocate quotas of emission permits is an important issue in implementing ET. Indeed, Proposition 5 does not explain how to allocate quotas for countries to reach an agreement on implementing ET with JI/CDM. However, an example of such allocations can be found in the proof. In the example, each country's quota is determined proportionally to its maximum gain (i.e., $\overline{v}_i^J(\overline{A}) - u_i^N$). That is, for each country i ,

$$\overline{a}_i = \frac{\overline{v}_i^J(\overline{A}) - u_i^N}{\sum_{k \in N}(\overline{v}_k^J(\overline{A}) - u_k^N)}\overline{A}\,. \tag{41}$$

This means that the amount of required abatement is smaller for countries with less incentive to participate in the agreement. One might think that it is more realistic that the countries in the negotiation determine the allocation of quotas based on the level of abatements prior to the negotiation. A simple example of such an allocation of quotas is that each country's quota is proportional to the amount of abatement at the non-cooperative outcome. That is, for each country i ,

[14] Another advantage of ET with JI/CDM is worth mentioning. Note that information on c_i for each i as well as on $\sum_{i \in N} b_i$ should be shared by the countries in order to achieve the global optimum as in (9). Without joining the abatement in country i , the countries may not know about c_i , and so country i may have an incentive not to truthfully reveal information on c_i . This makes it difficult to achieve the global optimum through an agreement. However, under ET with JI/CDM, each country may be able to acquire information on c_j by performing abatement in other country j . Thus, once the aggregate level A^M of abatements at the global optimum is known to the countries, the global optimum can be attained under ET with JI/CDM without the incentive problem for countries to truthfully reveal their private information.

$$\overline{a}_i = \frac{a_i^N}{\sum_{k \in N} a_k^N} \overline{A} . \quad (42)$$

However, given the allocation of quotas in (42), it is possible that a country becomes worse off after flexible mechanisms are implemented. For example, when $n = 2$, if b_1 / b_2 is large enough and c_1 / c_2 is small enough, country 1 is worse off under ET with JI/CDM compared with the non-cooperative outcome. This implies that the allocation of quotas should be carefully decided in order to encourage countries to participate in the international environmental agreement.[15]

Besides monetary transfer, technological transfer is also an important issue in international environmental agreements. However, we do not explicitly consider the technological transfers in this paper for the following reasons. First, the aim of this paper is to discuss the role of flexible mechanisms in an international environmental problem. In particular, this paper focuses on the possibility of achieving the global optimum through monetary transfers (ET) with direct transfers of pollutant abatement (JI/CDM), not through technological transfers between countries. Secondly, in reality, the Kyoto mechanism introduced in 1997 is designed to induce the indirect transfer of finance and technology. After the Kyoto mechanism, developing counties constantly demanded direct transfer of finance and technology from developed countries. Such requests came to a close with the introduction of the Green Climate Fund (GCF) and the Climate Technology Centre and Network (CTCN) through the Cancun agreement in 2010. Based on these facts, we think that it is more realistic for the market mechanism itself to be designed without considering direct transfer of technology. In addition, we consider the indirect spillover of technology through FDI under CDM as a secondary part of this study.

V. Concluding Remarks

The difficulties of international environmental negotiation arise from the negative externality of transboundary pollution. This creates an incentive for countries to free-ride on other countries' abatement efforts instead of working toward an agreement requiring their cooperative effort. To resolve this problem,

[15] In the Kyoto Protocol, the reduction targets for each country were set at -5% based on the specific year (1990), and then flexibly set from -8% to +10% considering the economic situation of each country. The reason for considering up to +10% here is to encourage the participation of transition economies and to ensure that the condition for entry into force of the agreement is satisfied. This shows that meeting participation is a crucial consideration factor when setting the quota allocation rule.

most negotiations in IEAs have focused on how to assign an abatement obligation to each country. For example, the Kyoto Protocol contains a list for assigning each country's obligation to abate GHG emissions. To ensure more countries participate in the agreement, it has been often argued that some transfers are required. If direct monetary transfer is fully available, it is not difficult to reach an agreement on the global optimum or to compensate those countries that are worse off under the global optimum. However, forcing sovereign countries to provide monetary transfer as stipulated in the agreement is not a realistic solution. This is one of the reasons why market-based mechanisms have attracted significant attention as an alternative.

Permit trading is recognized as a concrete solution to address environmental externality because the difference in abatement costs between pollutants allow for gains from trade in permits. In an international context, this property helps signatories to reduce the incentive to deviate from an IEA. However, a permit-trading scheme may not be sufficient when asymmetry also applies to the benefits. For example, a developing country with a heavy emphasis on economic growth may have a smaller marginal abatement benefit than its developed counterpart that values environmental quality. In this situation, ensuring efficiency with trading schemes only is difficult, though it is achievable if the cost difference is the only heterogeneity between countries. Our results show that, if countries are significantly heterogeneous in their benefits and costs, assigning abatement obligations and allowing trade among countries is not sufficient for an agreement to achieve the global optimum. Even if countries succeed in reaching an agreement, they may suffer efficiency loss in terms of global welfare. In addition, the global optimum may not be desirable for some countries. Consequently, some additional supplementary mechanisms are required in IEAs.

In our investigation of the role and limitations of flexible mechanisms, we conclude that the first-best is achievable if the IEA allows its signatories to use trading schemes supplemented with investing schemes. Moreover, such an IEA can satisfy the individual rationality condition and thus ensure that all countries come to an agreement once initial allowances are properly allocated to countries. One thing we need to remember is that our results hold when the degree of heterogeneity in benefits among countries is not sufficiently high. When the heterogeneity across countries is large enough, international negotiations aimed at the first-best will be negotiated toward an unachievable objective, even in theory. This may explain, besides mitigation, why financial and technology transfers are important components in IEAs.

Appendix

Proof of Proposition 5. Given $\overline{A} = \sum_{k\in N} a_k^M = \sum_{k\in N} \overline{a}_i$, the equilibrium payoff of country i is maximized when $\overline{a}_i = 0$. Denote this maximized payoff of country i by $\overline{v}_i^J(\overline{A})$. For convenience, for each i, let $d_i = 1/c_i$. From (37) and (38), we can see that

$$\overline{v}_i^J(\overline{A}) - u_i^N = \frac{1}{2}b_i\left[\ln\left(\frac{\sum_{k\in N} b_k \sum_{k\in N} 1/c_k}{\sum_{k\in N} b_k/c_k}\right) - \frac{2nb_i - \sum_{k\in N} b_k}{n^2 b_i} + \frac{b_i/c_i}{\sum_{k\in N} b_k/c_k}\right]$$
$$= \frac{1}{2}b_i\left[\ln\left(\frac{\sum_{k\in N} b_k \sum_{k\in N} d_k}{\sum_{k\in N} b_k d_k}\right) + \frac{b_i d_i}{\sum_{k\in N} b_k d_k} + \frac{\sum_{k\in N} b_k}{n^2 b_i} - \frac{2}{n}\right]. \tag{43}$$

Let

$$R((b_i, d_i)_{i\in N}) = \ln\left(\frac{\sum_{k\in N} b_k \sum_{k\in N} d_k}{\sum_{k\in N} b_k d_k}\right) + \frac{b_i d_i}{\sum_{k\in N} b_k d_k} + \frac{\sum_{k\in N} b_k}{n^2 b_i} - \frac{2}{n}. \tag{44}$$

Note that $R((b_i, d_i)_{i\in N})$ is homogeneous of degree zero in $(b_i)_{i\in N}$ and $(d_i)_{i\in N}$. Thus, to show that $\overline{v}_i^J(\overline{A}) - u_i^N$ is positive, it is enough to show that a lower bound of $R((b_i, d_i)_{i\in N})$ is positive given that $\sum_{k\in N} b_k = 1$ and $\sum_{k\in N} d_k = 1$ hold. Letting $\sum_{k\in N} b_k = 1$ and $\sum_{k\in N} d_k = 1$, we have

$$\begin{aligned}
&R((b_i, d_i)_{i\in N}) \\
&= \ln\left(\frac{1}{\sum_{k\in N} b_k d_k}\right) + \frac{b_i d_i}{\sum_{k\in N} b_k d_k} + \frac{1}{n^2 b_i} - \frac{2}{n} \\
&= \ln\left(\frac{1}{b_i d_i + \sum_{k\in N\setminus\{i\}} b_k d_k}\right) + \frac{b_i d_i}{b_i d_i + \sum_{k\in N\setminus\{i\}} b_k d_k} + \frac{1}{n^2 b_i} - \frac{2}{n} \\
&\geq \ln\left(\frac{1}{b_i d_i + \sum_{k\in N\setminus\{i\}} b_k \sum_{k\in N\setminus\{i\}} d_k}\right) + \frac{b_i d_i}{b_i d_i + \sum_{k\in N\setminus\{i\}} b_k \sum_{k\in N\setminus\{i\}} d_k} + \frac{1}{n^2 b_i} - \frac{2}{n} \\
&= \ln\left(\frac{1}{b_i d_i + (1-b_i)(1-d_i)}\right) + \frac{b_i d_i}{b_i d_i + (1-b_i)(1-d_i)} + \frac{1}{n^2 b_i} - \frac{2}{n} \\
&\equiv H(b_i, d_i; n),
\end{aligned} \tag{45}$$

where $0 \leq b_i \leq 1$ and $0 \leq d_i \leq 1$. Since $H(b_i, d_i; n)$ is continuous in (b_i, d_i) and bounded below, there exists (b_i^*, d_i^*) in $[0,1]\times[0,1]$ that minimizes $H(\cdot;n)$. Note that

$$\frac{dH(b_i,d_i;n)}{db_i}=\frac{2d_i-1}{b_i+d_i-2b_id_i-1}+\frac{(1-d_i)d_i}{(b_i+d_i-2b_id_i-1)^2}-\frac{1}{n^2b_i^2}\text{, and} \tag{46}$$

$$\frac{dH(b_i,d_i;n)}{dd_i}=\frac{2b_i-1}{b_i+d_i-2b_id_i-1}+\frac{(1-b_i)b_i}{(b_i+d_i-2b_id_i-1)^2}. \tag{47}$$

Suppose that $0<d_i^*<1$. The first order necessary condition for d_i^*, $dH(b_i^*,d_i^*)/dd_i=0$, implies $d_i^*=(b_i^*-1)^2/(2b_i^*-1)^2$. Plugging this into the second order necessary condition, we that $d^2H(b_i^*,d_i^*)/dd_i^2=-(2b_i^*-1)^4/(b_i^{*2}(b_i^*-1))^2\geq 0$. Thus, $b_i^*=1/2$ should hold. However, this contradicts $0<d_i^*=(b_i^*-1)^2/(2b_i^*-1)^2<1$.

Suppose that $d_i^*=1$. The first order necessary condition for d_i^*, $dH(b_i^*, d_i^*;n)/dd_i\leq 0$, implies $b_i^*\geq 2/3$. Then, since $dH(b_i^*,d_i^*;n)/db_i=-b_i^{*2}(n^2b_i^*+1)/(n^2b_i^{*4})<0$ is satisfied, the first order necessary condition for b_i implies $b_i^*=1$. Then, we can see that, for all $n\geq 2$, $H(b_i^*,d_i^*;n)=\ln(1)+1+1/n^2-2/n>0$.

Suppose that $d_i^*=0$. Since the first order necessary condition for d_i is $dH(b_i^*,d_i^*)/dd_i=1\geq 0$ and the first order necessary condition for b_i is

$$\frac{dH(b_i^*,d_i^*;n)}{db_i}=\frac{n^2b_i^{*2}-(1-b_i^*)}{(1-b_i^*)n^2b_i^{*2}}\begin{cases}\leq 0 & \text{if } b_i^*=0\\ =0 & \text{if } 0<b_i^*<1\\ \geq 0 & \text{if } b_i^*=1,\end{cases} \tag{48}$$

it should be satisfied that $b_i^*=(\sqrt{4n^2+1}-1)/(2n^2)$. Plugging $d_i^*=0$ and $b_i^*=(\sqrt{4n^2+1}-1)/(2n^2)$ into $H(b_i,d_i;n)$ and letting $x=\sqrt{4n^2+1}$, we have

$$\begin{aligned}H(b_i^*,d_i^*;n)&=\ln\left(\frac{2n^2}{2n^2-\sqrt{4n^2+1}+1}\right)+\frac{2}{\sqrt{4n^2+1}-1}-\frac{2}{n}\\ &=\ln\left(\frac{x+1}{x-1}\right)+\frac{2}{x-1}-\frac{4}{\sqrt{x^2-1}}\equiv\tilde{H}(x)\end{aligned} \tag{49}$$

with $x>1$. Note that $\lim_{x\to\infty}\tilde{H}(x)=0$ and, for $x>1$,

$$\frac{d\tilde{H}(x)}{dx}=-4x\frac{(x+1)^{1/2}-(x-1)^{1/2}}{(x+1)^{3/2}(x-1)^2}<0. \tag{50}$$

Thus, for all $x > 1$, $\tilde{H}(x) > 0$ holds. This means that $H(b_i^*, d_i^*; n) > 0$ for all $n \geq 2$.

Therefore, for any $n \geq 2$, the lower bound of $H(b_i, d_i; n)$ is greater than zero. This implies that $\overline{v}_i^J(\overline{A}) > u_i^N$ for each i. Then, applying the same arguments as in the proof of Proposition 3, we complete the proof.

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