# Self-Enforcing International Environmental Agreements among Asymmetric Countries and Welfare *

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**Abstract**

Theoretical analyses of self-enforcing international environmental agreements (IEAs) have adopted the assumption of identical countries. In this paper, we assume that countries are asymmetric in terms of abatement technologies. By examining the IEA formation and total welfare, we show that i) the asymmetry leads to multiple sizes of self-enforcing IEAs, which corresponds to the multiple equilibria of a coalition formation game Maruta and Okada (2005); ii) technology transfer can lead to a smaller size of self-enforcing IEA, resulting in welfare loss. We also examine the rule of IEA and discuss that the unanimity rule plays an important role in IEA formation.

## 1 Introduction

International environmental agreements (IEAs) provide internationally organized treatment for solving multiregional environmental problems such as ozone depletion and climate change. The absence of a supranational authority means that IEAs are supported

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by voluntary participation, which is captured as *self-enforcement* in the theoretical literature on IEAs. Self-enforcement is a concept of coalition stability which was first developed by d'Aspremont, Jacquemin, Gabszewicz and Weymark (1983) and applied to IEA analysis by Barrett (1994). In a self-enforcing IEA, all member countries have no incentive to unilaterally withdraw (*internal stability*) and all non-member countries have no incentive to unilaterally join (*external stability*). After Barrett (1994), studies of self-enforcing IEAs have concluded pessimistic results: only a small-sized IEA can be self-enforcing (Hoel (1992); Carraro and Siniscalco (1993); Barrett (1994)).[1]

Earlier studies of self-enforcing IEAs share the assumption of identical countries. Although it provides tractability, this specification fails to describe the effects of country-specific factors on IEA formation. For example, let us consider an IEA requiring pollution abatement. The countries would differ from each other in features affecting their decision whether to join an IEA, such as productivity of abatement technology, population, and economic scale. Identical countries models ignore the difference among these characteristics determining IEA formation.

The purpose of this paper is to investigate the effect of asymmetry among countries on IEA formation and welfare. There are several studies examining IEA formation among asymmetric countries. Barrett (2001) differentiates countries into two types according to the preference for the environment. He shows that strong asymmetry can reduce the free-rider problem and side-payments among member countries can increase the size of IEA. Furusawa and Konishi (2011) analyze a "free-riding-proof IEA," which is equivalent to a self-enforcing IEA in this paper. In their model, countries are different from each other in economic scale and abatement technology. They show that coalitions become more stable under transferable utility regime such as emission

[1] There exists a significant amount of game theoretic literature on IEAs, which can be roughly classified into two types according to the framework adopted: the cooperative approach and the non-cooperative approach (see Missfeldt (1999) and Wagner (2001) for a survey). Unlike the non-cooperative approach, the cooperative approach gives relatively optimistic results that a grand coalition can be sustained (Chander and Tulkens (1995), Chander and Tulkens (1997)). In this paper, in order to consider self-enforcing IEAs, we adopt the non-cooperative framework. The non-cooperative approach enables us to examine the participation decision, whereas a cooperative framework focuses on a grand coalition where all countries have already joined.

permit trading.

This paper is closely related to Maruta and Okada (2005), which studies collective action games among $n$ persons in prisoners' dilemma situation. In their model, each person's payoff is determined by own cooperation decision and the number of cooperators. Countries are differentiated by *threshold of cooperation*, which is the number of cooperators required for each country's cooperation. A coalition in the strict Nash equilibrium in their model is equivalent to a self-enforcing IEA. They show that there always exists at least one strict Nash equilibrium and, furthermore, multiple equilibria can be the case.

Our model is a simplification of Maruta and Okada (2005) where we introduce a specific welfare function according to IEA literature. We differentiate countries by abatement cost, which determines the each country's welfare. Under this modification, the threshold of cooperation for country $i$ can be represented by its abatement technology and the distribution of abatement technology plays an important role to determine the IEA formation. Our simplification provides a reasonable interpretation of Maruta and Okada (2005), which is consistent with the environmental problem.

This modification also enables us to examine the effect of asymmetry of technologies on welfare. In asymmetric countries model, the total welfare is determined by the size of IEA and the distribution of abatement technologies, whereas only the size determines the welfare in symmetric model. We find that even if the asymmetry results in a smaller IEA, the total welfare can increase, and vice versa.[2]

We can discuss the effect of technology transfer using analogies of welfare analysis. We show that technology transfer may result in welfare loss even if it improves the average productivity of abatement because technology transfer affects the distribution of technology which might lead to a smaller size of IEA.

The rest of this paper proceeds as follows. First, we construct a model of self-

[2]McEvoy and Stranlund (2009) also examine the welfare with a self-enforcing IEA. In their model, the perfect compliance of member countries requires costly monitoring by IEA committee, which is incurred by member countries. They show that although the cost of monitoring increases the size of IEA, it may lead to welfare loss if the total number of countries is small enough.

enforcing IEA among asymmetry countries, where we provide a definition of a self-enforcement with asymmetric countries. Results in Maruta and Okada (2005) are confirmed to hold in our setting. Then welfare analysis examining the effect of asymmetry on the total welfare is to be presented. Lastly we discuss the technology transfer resulting in welfare loss.

# 2 The Model

## 2.1 A Basic Model of Self-Enforcing IEA

There are $n$ symmetric countries emitting pollutants. The set of countries is denoted by $N = \{1, 2, \cdots, n\}$. Each country makes a discrete abatement choice: Abate ($q_i = 1$) and Emit ($q_i = 0$).[3] Country $i$'s welfare is determined by own choice and aggregate choice:

$$u_i = \sum_{j \in N} q_j - a q_i,$$

where $a$ is the common abatement cost for all countries.[4] We focus on the case of $1 < a < n$. $1 < a$ means that Emit ($q_i = 0$: noncooperation) is the dominant strategy for all $i \in N$ without agreements. $a < n$ means that aggregate welfare is maximized when all countries choose Abate ($q_i = 1$: cooperation). Therefore the economic environment can be summarized as a prisoners' dilemma with incentive to form an IEA.

We describe the IEA formation game as a three-stage game, following Kosfeld et al. (2009) as follows.[5]

[3] We adopt discrete choice structure following previous studies such as Ulph (2004), Kolstad (2007), McEvoy and Stranlund (2009). Furusawa and Konishi (2011) adopt continuous abatement choice.

[4] Linear payoff functions are also adopted in many papers. See Ulph (2004), Kolstad (2007), McEvoy and Stranlund (2009), Kosfeld, Okada and Riedl (2009), for example. Linearity of welfare function brings perfect consistency with the applied game theoretic literature on coalition formation such as Maruta and Okada (2005), Okada (1993).

[5] In earlier studies, IEA formation game is usually described as two-stage game consisting of Participation Stage and Abatement Stage with an assumption that in Abatement Stage, countries must chose an abatement level maximizing the joint welfare of the IEA if they choose to join in the

1 Participation Stage

– Each country decides whether to join a single IEA.

2 Implementation Stage

– Member countries simultaneously and independently vote whether to agree on cooperation ($q_i = 1$) under the unanimity rule, knowing who participated in the Participation stage. The IEA is implemented if all member countries accept cooperation.

3 Abatement Stage

– Each member and nonmember country makes an abatement choice $q_i$. If the IEA is implemented, each member country $i$ is forced to choose $q_i = 1$, whereas each nonmember country $j$ can choose $q_j$ freely, i.e., it chooses $q_j = 0$. If the IEA is not implemented, all countries $i$ can choose $q_i$ freely, i.e., they choose $q_i = 0$.

An IEA is denoted by $S \subset N$ where $|S|$ means the number of members in $S$. We call $|S|$ as *size* of the IEA. Let us consider the IEA $S$ with $|S| = s$ formed in the Participation Stage agrees to cooperate in the Implementation Stage.[6] Then, in the Abatement Stage, the welfare for member countries denoted as $u^m(S)$ and nonmember countries denoted as $u^{nm}(S)$ are realized as follows

$$u^m(S) = s - a$$
$$u^{nm}(S) = s$$

because each member country $i$ and nonmember country $j$ chooses $q_i = 1$ and $q_j = 0$, respectively.

Participation Stage. In this paper, we adopt three-stage game by introducing Implementation Stage between Participation and Abatement Stage. This modification allows us to examine IEA formation without assuming joint-welfare maximizing IEA.

[6]Such an IEA is called as an *effective IEA* (McEvoy and Stranlund (2009)), or *successful group* (Maruta and Okada (2005)).

In the Implementation Stage, all member countries agree to cooperate when the following condition holds:[7]

$$u^m(S) \geq u^{nm}(\emptyset) \Leftrightarrow s \geq a.$$

This means that an IEA reaches cooperation in the Implementation Stage if the its size is greater than $a$. We call this condition as *implementation condition*.

It is useful to introduce the following notation:

**Definition 1.** For $x \in \mathbb{R}$, define $x^*$ as the minimum integer which is greater than or equal to $x$. In other words, $x^* = \min\{y \in \mathbb{Z} | y \geq x\}$.

Because $s$ is an integer, the implementation condition can be reduced to

$$s \geq a^*.$$

We focus on the case where an IEA in this game is self-enforcing. According to the definition provided in d'Aspremont et al. (1983) and Barrett (1994), a self-enforcing IEA can be defined as follows:

**Definition 2.** An IEA $S$ is self-enforcing if and only if:

$(i)$ $u^m(S) \geq u^{nm}(S \backslash \{i\})$ for $s \geq a^* + 1$, for all $i \in S$
$u^m(S) \geq u^{nm}(\emptyset)$ for $s < a^* + 1$

$(ii)$ $u^{nm}(S) \geq u^m(S \cup \{i\})$, for all $i \in N \backslash S$

Condition $(i)$ is called *internal stability*, which means that no member country has incentive to withdraw from the IEA. Condition $(ii)$ is called *external stability*, which means that nonmember countries cannot gain by joining the IEA.

Under these conditions, we obtain the following well-known result (Ulph (2004), Kolstad (2007), McEvoy and Stranlund (2009)):

[7] An IEA satisfying this condition is equivalent to a *profitable IEA* in McEvoy and Stranlund (2009).

**Result 1.** The size of a self-enforcing IEA is $a^*$.

An IEA $S$ with $s < a^*$ is not self-enforcing because the implementation condition is not satisfied. Also, $S$ with $s > a^*$ is not self-enforcing because the internal stability condition is not satisfied. In this case, there exists at least one member country that can gain by withdrawing from the IEA since the IEA $S \backslash \{i\}$ can be implemented.

Therefore, $s = a^*$ is the only one size of self-enforcing IEAs.[8] In self-enforcing IEAs, all member countries are pivotal in the sense that the IEA cannot be implemented without participation of each country.

By Definition 1, we obtain that $2 \leq a^* \leq n$ because of the assumption of $1 < a < n$. This means that the smallest possible size of self-enforcing IEA is two and the full cooperation is also reached by self-enforcing IEA. The size is always $a^*$, regardless of the total number of countries, $n$. The full cooperation is realized only if $a^* = n$.

## 2.2 A Self-Enforcing IEA among Asymmetric Countries

In this subsection, we introduce the asymmetry among countries into the model in 2.1. The asymmetry is captured by country-dependent abatement cost $a_i$.[9] Lower $a_i$ means that country $i$ has relatively more efficient technology. Then the welfare function for country $i$ can be written as follows:

$$u_i = \sum_{j \in N} q_j - a_i q_i.$$

We assume that $1 < a_i < n$ for all $i \in N$ for the same reason in 2.1.

The model in this subsection is basically a simplification of Maruta and Okada (2005). Our contribution here would be objectification of the welfare function, which provides practical interpretation for the result of the model. Also, it enables us to examine the effect IEA formation on welfare.

[8] This does not mean there is only one self-enforcing IEA. Any IEAs satisfying $s = a^*$ are self-enforcing. More concretely, there are $\binom{n}{a^*}$ self-enforcing IEAs.

[9] We assume complete information so that $a_i$ is common knowledge for all countries.

In the same manner as 2.1, let us consider an implemented IEA $S$ with $|S| = s$. The welfare for member countries and nonmember countries are given by

$$u_i^m(S) = s - a_i$$
$$u_i^{nm}(S) = s.$$

The IEA is implemented when all member countries accept cooperation:

$$u_i^m(S) \geq u_i^{nm}(\emptyset) \quad \text{for all} \quad i \in S.$$

This implies $s \geq a_i^*$ for all $i \in S$ because $s$ is an integer. We call $s \geq a_i^*$ as *implementation condition for country $i$.*

Maruta and Okada (2005) assume that each player $i$ has value $s_i$, called *threshold of cooperation*, which determine the number of cooperators profitable for player $i$ when he cooperates. In our modification, threshold of cooperation for country $i$ can be determined by its abatement cost.

A self-enforcing IEA in this case is defined as follows:

**Definition 3.** An IEA $S$ among asymmetric countries is self-enforcing if and only if:

$(i)$ $u_i^m(S) \geq u_i^{nm}(S \backslash \{i\})$ for $s \geq (\max_{j \in S \backslash \{i\}} a_j)^* + 1$, for all $i \in S$
$u_i^m(S) \geq u_i^{nm}(\emptyset)$ for $s < (\max_{j \in S \backslash \{i\}} a_j)^* + 1$, for all $i \in S$

$(ii)$ $u_i^{nm}(S) \geq u_i^m(S \cup \{i\})$ for all $i \in N \backslash S$

The external stability condition $(ii)$ is exactly the same as that in the symmetric countries case, which always holds. The first condition of the internal stability $(i)$ demonstrates the situation where the IEA $S \backslash \{i\}$ is implemented after a unilateral deviation by member country $i$. The second condition is that a withdrawal of country $i$ leads to non-implementation of IEA formed by the remaining member countries. It depends on the highest abatement cost among remaining countries whether country

$i$'s withdrawal leads to break-down of IEA or not. Applying the same argument as before, we obtain the following proposition:

**Proposition 1.** *An IEA $S$ is self-enforcing if and only if it satisfies:*

$$a_i \leq s < (\max_{j \in S \setminus \{i\}} a_j)^* + 1 \quad \textit{for all} \quad i \in S^{10}$$

All proofs are given in Appendix. Let us characterize a self-enforcing IEA among asymmetric countries in more detail. First, we have the following proposition with respect to the size. Let us denote $a_h = \max_{i \in S} a_i$, i.e., country $h$ has the highest $a_i$ among the IEA.[11]

**Lemma 1.** If an IEA $S$ with $|S| = s$ is self-enforcing, then we have $s = a_h^*$.

$s < a_h^*$ is not sufficient for self-enforcing IEA because it breaks the implementation condition for country $h$. Country $h$ requires the highest number of participants, or highest level of environmental improvement, in order to recover the highest cost for cooperation. Also, an IEA $S$ with $s > a_h^*$ is not self-enforcing because it does not satisfy the internal stability, i.e., there is at least one member country that benefits from its withdrawal. This proposition shows that the size of IEA must be sufficiently large so that the member country with the most inefficient technology finds it beneficial to implement the IEA; however, it must also be small enough to hold the internal stability.

We have another necessary condition for self-enforcement as follows:

**Lemma 2.** If an IEA $S$ with $|S| = s$ is self-enforcing, then we have $(\max_{i \in S \setminus \{h\}} a_i)^* = a_h^*$.

The definition of the self-enforcement reminds us that the IEA is no longer implemented after withdrawal of each country. In other words, the withdrawal always leads to the breaking of the implementation condition for some of the remaining countries.

[10]Notice that the symmetric case is the special case of the asymmetric case where $a_i^* = (\max_{j \in S \setminus \{i\}} a_j)^* = a^*$, which implies $s = a^*$ in a self-enforcing IEA.

[11]If the number of countries with highest $a_i$ is greater than one, we randomly choose one of them as highest.

According to Lemma 1, country $i \in S$ with $a_i < a_h$ has no incentive to deviate because its deviation results in breakdown of the implementation condition for country $h$. This proposition ensures that country $h$ also has no incentive to withdraw because it always breaks the implementation condition for a country with the second highest cost.

The necessary conditions provided in Lemma 1 and Lemma 2 are also the sufficient conditions for a self-enforcing IEA:

**Proposition 2.** *The IEA $S$ is self-enforcing if and only if $s = a_h^* = (\max_{i \in S \setminus \{h\}} a_i)^*$.*

This proposition corresponds to Therem 3.2 in Maruta and Okada (2005), characterizing a strict Nash equilibrium of the group formation game. They also shows that there always exists at least one strict Nash equilibrium in the group formation game. In our setting, we obtain the same proposition stating that there always exists an IEA satisfying Proposition 2:[12]

**Proposition 3.** *There exists at least one self-enforcing IEA among asymmetric countries.*

Furthermore, in the asymmetric situation, the size of self-enforcing IEA can be multiple as shown in Example 1.

**Example 1.** Consider a set of six countries: $N = \{1, \cdots, 6\}$. Assume that the distribution of $a_i$ is given by $\{a_i\}_{i \in N} = \{1.2, 2.1, 2.8, 3, 4.2, 4.6\}$ in ascending order. Then we obtain the set of $a_i^*$ as $\{a_i^*\}_{i \in N} = \{2, 3, 3, 3, 5, 5\}$. According to Proposition 2, there are two sizes of the self-enforcing IEA: 3 and 5 (multiple sizes).[13]

Generally, the size of a self-enforcing IEA can be found by plotting $a_i^*$ in ascending order and examining the height of the horizontal area below 45-degree line (including the boundary).[14] The horizontal area corresponds to the candidates for country $h$

[12] In the symmetric case, there always exist single size of self-enforcing IEA because Proposition 2 is satisfied by $s = a_h^* = (\max_{i \in S \setminus \{h\}} a_i)^* = a^*$.

[13] In this example, we can observe that the following eight IEAs are self-enforcing: $\{1,2,3\}$, $\{1,2,4\}$, $\{1,3,4\}$, $\{2,3,4\}$, $\{1,2,3,5,6\}$, $\{1,2,4,5,6\}$, $\{2,3,4,5,6\}$, and $\{1,3,4,5,6\}$.

[14] Refer to the Proof of Proposition 2 in Appendix. Notice that this method can be applied to the case of symmetric countries.

and the second highest cost country; the area below 45-degree line ensures that the number of participants is sufficiently large. In the Example 1, we obtain 3 and 5 this way (Figure 1). The size of a self-enforcing IEA deeply depends on the distribution of countries' $a_i^*$.

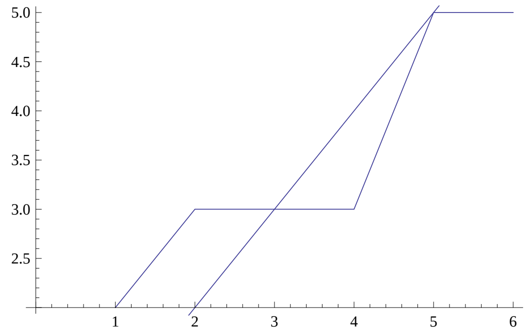



Figure 1: The Distribution of $a_i^*$

**Remark 1** (Comparison among multiple sizes)**.** In Example 1, we have two self-enforcing IEA sizes: 5 and 3. From the viewpoint of the aggregate welfare, size 5 is preferred to size 3 because we have the following welfare relations:

| Size | Aggregate Welfare |
|---|---|
| 3 | 11.9 at most[15] |
| 5 | 13.3 at least[16] |

In Example 1, a bigger IEA always results in a greater welfare. In general, however, this is not always the case as shown in Example 2.

**Example 2.** Consider a set of fourteen countries: $N = \{1, \cdots, 14\}$. For simplicity, assume that $a_i$ is an integer for all $i \in N$. The distribution of $a_i$ and $a_i^*$ are given by $\{a_i\}_{i \in N} = \{a_i^*\}_{i \in N} = \{4, 6, 6, 6, 6, 6, 8, 8, 8, 8, 8, 8, 8, 8\}$ in ascending order. According to Proposition 5, there are two sizes of self-enforcing IEAs: 6 and 8. Let us compare the aggregate welfare under an IEA $S_1 = \{1, 2, 3, 4, 5, 6\}$ with $\{a_i^*\}_{i \in S_1} = \{4, 6, 6, 6, 6, 6\}$ and an IEA $S_2 = \{7, 8, 9, 10, 11, 12, 13, 14\}$ with $\{a_i^*\}_{\in S_2} = \{8, 8, 8, 8, 8, 8, 8, 8\}$. The aggregate welfare for each situation is given as follows:

[16]Consider an IEA $\{1, 2, 3\}$
[16]Consider an IEA $\{2, 3, 4, 5, 6\}$

| Size (IEA) | Aggregate Welfare |
|---|---|
| 6 ($S_1$) | 50 |
| 8 ($S_2$) | 48 |

This result shows that a larger size of an IEA may lead to smaller aggregate welfare. The aggregate welfare is consisted of two parts: the gain from the environmental quality and the total cost of abatement. Although the bigger IEA brings us higher quality of environment, the total welfare may not improve if the cost of supporting the environmental quality is too expensive. This aspect cannot be captured by symmetric model because it is created by the difference in abatement technology.

**Remark 2** (Voting rule: the unanimity rule v.s. the majority rule)**.** In the Implementation Stage, we assume that member countries vote under the unanimity rule. In this Remark, we discuss the choice of voting rule greatly affects the IEA formation. The Example 3 shows that the unanimity rule plays significant role in supporting self-enforcing IEAs.

**Example 3.** Consider a set of six countries: $N = \{1, \cdots, 5\}$. Assume that the distribution of $a_i$ is given by $\{a_i\}_{i \in N} = \{1.3, 2.8, 3.5, 4.1, 4.7\}$ in ascending order. Then we obtain the set of $a_i^*$ as $\{a_i^*\}_{i \in N} = \{2, 3, 4, 5, 5\}$. According to Proposition 2, the grand coalition (size 5) is self-enforcing under the unanimity rule.

Let us examine the IEA formation under the majority rule in the Implementation Stage. Under the majority rule, an IEA is implemented if the majority (six out of ten) of members vote to agree on cooperation. Once the IEA is implemented, each member country $i$ is forced to choose $q_i = 1$ even if it does not vote to agree. As a result, the grand coalition is no longer self-enforcing because country 4 and country 5 have an incentive to withdraw. Under the unanimity rule, country 5 cannot withdraw from the grand coalition because its withdrawal leads to the breakdown of the implementation condition for country 4, which results in the breakdown of IEA. Under the majority rule, however, even if the country 4 vote not to agree after the withdrawal of country 5, the remaining three countries still agree and their approval is enough for implementation of the IEA. Thus the grand coalition is not stable under the majority rule.

In the Example 3, the self-enforcing IEA does not exist, which means that the existence theorem by Maruta and Okada (2005) does not hold under the majority rule. Although we focus on the case of the majority rule, we can show that an IEA supported by the unanimity rule is not always supported under the other voting rules such as the two-thirds majority rule by the same logic. Intuitively, the bigger-scale cooperation seems to be more supported by the majority rule rather than the unanimity rule because less approval is required for the agreement under the majority rule. However, the unanimity rule, which seems to be relatively strict to achieve an agreement, is important to support a stable IEA.

# 3 Welfare Analysis

Let us investigate the effect of asymmetry of countries on IEA formation on welfare. In this section, we provide the general conditions that asymmetry of countries leads to an increase in total welfare. Furthermore, we discuss the effect of technology transfer by examining the effect of adjusting the degree of asymmetry.

As shown in the previous section, the size of a self-enforcing IEA is determined by Proposition 2. By adjusting the distribution of $a_i^*$ to hold Proposition 2, any size $s$ with $2 \leq s \leq n$ can be self-enforcing. The following figures describe distributions of $a_i^*$ leading to the smallest and largest sizes of self-enforcing IEAs among six countries, respectively.

Because asymmetry may result in any size of self-enforcing IEA, we first need a criterion determining how to compare symmetry and asymmetry. In this paper, we adopt the following criterion:

**Criterion 1.** The total number of countries $n$ and the average level of $a_i$ are fixed in both symmetric and asymmetric conditions.

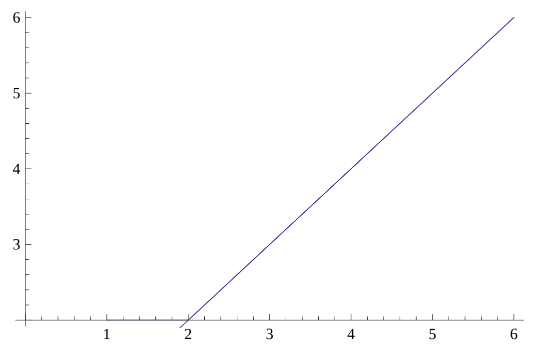



Figure 2: The Smallest Size: Two

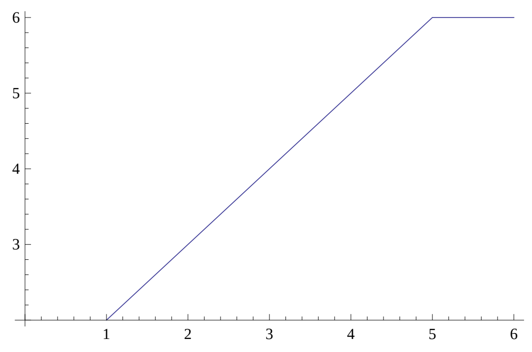



Figure 3: The Largest Size: Six

Criterion 1 requires that a distribution of $a_i$ with asymmetry is a mean-preserving spread of a distribution of $a_i$ under symmetry. This enables two situations to have the same aggregate welfare from full cooperation. The idea here is to compare the situations with the same potential source of cooperation, i.e., the same amount of total welfare would be reached in the ideal world.

The following example would be helpful to understand what we are addressing:

**Example 4.** Consider a set of six symmetric countries $N = \{1, \cdots, 6\}$ with common abatement cost 3.5. Let us introduce asymmetry among countries into this situations and compare the total welfare. According to Criterion 1, $\{a_i\}_{i \in N} = \{1.2, 2.1, 2.6, 4.3, 4.9, 5.9\}$ is one candidate to be compared in this analysis because the average $a_i$ of these countries is 3.5. The relation between distributions of $a_i$ is described in Figure 4 where the horizontal line is $\{3.5, 3.5, 3.5, 3.5, 3.5, 3.5\}$, demonstrating for symmetric countries, and the line graph is $\{1.2, 2.1, 2.6, 4.3, 4.9, 5.9\}$, demonstrating for asymmetric countries. The full cooperation leads to the aggregate welfare of 15 in both situations. In this example, the distributions of $a_i^*$ are $\{a_i^*\}_{i \in N} = \{4, 4, 4, 4, 4, 4\}$ for symmetry and $\{a_i^*\}_{i \in N} = \{2, 3, 3, 5, 5, 6\}$ for asymmetry, demonstrated in Figure 5. From the intersections between a 45-degree line and the horizontal parts of distributions, we can see that the size of a self-enforcing IEA among symmetric countries is 4. Also, we obtain that the size of a self-enforcing IEA among asymmetric countries is either 3 or 5. The aggregate welfare for each case is summarized as follows:

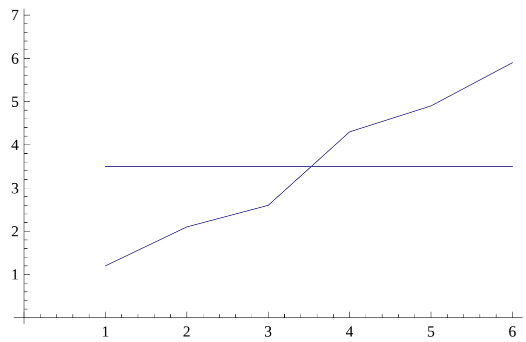



Figure 4: Distributions of $a_i$ to be Compared

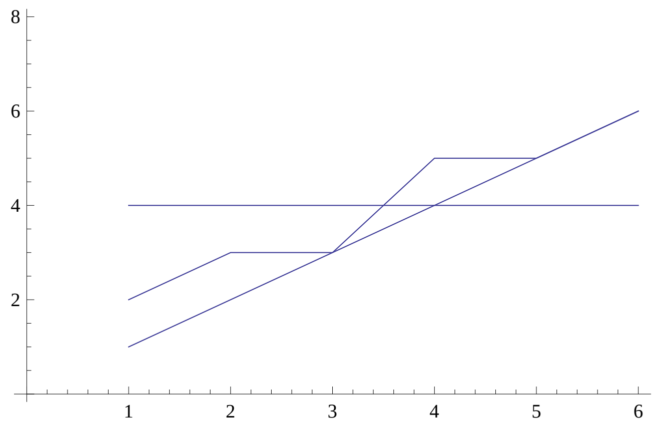



Figure 5: Distributions of $a_i^*$ to be Compared

| | Size | Aggregate Welfare |
|---|---|---|
| Symmetry | 4 | 10 |
| Asymmetry | 3 | 12.1 |
| | 5 | 14.9 |

In this example, asymmetry among countries always results in welfare improvement. Notice that asymmetry increases aggregate welfare even if the size of the self-enforcing IEA decreases.[17]

Here, we have a general proposition about the welfare consequences of introducing asymmetry among countries.

**Proposition 4.** *Asymmetry of countries results in an increase in aggregate welfare with a self-enforcing IEA if and only if the following holds:*

$$n(a_h^* - a^*) > \sum_{i \in \tilde{S}} a_i - \sum_{i \in \bar{S}} a,$$

*where* $\bar{S}$ *is a self-enforcing IEA with symmetric countries with* $|\bar{S}| = a^*$*,* $\tilde{S}$ *is a self-enforcing IEA with* $|\tilde{S}| = a_h^*$*.*

Proposition 4 shows that asymmetry among countries could result in welfare gain. The left-hand side $n(a_h^* - a^*)$ measures the increment of the total benefit from environmental improvement. The right-hand side $(\sum_{i \in \tilde{S}} a_i - \sum_{i \in \bar{S}} a^*)$ demonstrates the increment of the total cost to realize the environmental quality.

$a_h^* > a^*$ means that asymmetry leads to the positive externality because more countries become to engage in cooperation. However, this could also mean an increase in the total abatement cost. Even in that case, if $n$ is large enough, the total gain from the positive externality exceeds the loss from the increment of abatement cost.[18]

[17] An increase in size of a self-enforcing IEA does not always lead to welfare improvement. Notice that the distribution of $a_i$ in Example 2 is a mean-preserving spread of a symmetric distribution of $\{a_i\}_{i \in N} = \{7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7\}$. We can verify that the aggregate welfare under an IEA among asymmetric countries with size 8 is less than the one under an IEA among symmetric countries with size 7.

[18] Notice that even if asymmetry results in the bigger IEA, it may lead to welfare loss with small $n$. (Refer to the footnote 16.)

Similarly, $a_h^* < a^*$ results in an increase in negative externality because the number of cooperating countries decreases. However, this would have a positive effect on welfare if it reduces the total abatement cost. Therefore, even if asymmetry makes the IEA smaller, it may increase the total welfare when the gain from saving abatement cost exceeds the loss from smaller size of IEA. (The basic logic is the same as Remark 1.)

The change of $a_i$ can be interpreted as a change in abatement technology. We can discuss the effect of technology transfer on welfare by considering the change in distribution of $a_i$ to be induced by technology transfer among countries.[19] Let us consider ODAs, FDI and other movements inducing technology transfer, resulting in the improvement of average productivity of abatement technology. Such technology transfer, however, may lead to welfare loss as shown in the following example.

**Example 5.** Let us consider six countries $N = \{1, \cdots, 6\}$ with a distribution of $a_i$: $\{a_i\}_{i\in N} = \{1.6, 2.5, 2.8, 4.5, 4.9, 5.9\}$. Let us denote $N_s = \{1, 2, 3\}$ with $\{a_i\}_{i\in N_s} = \{1.6, 2.5, 2.8\}$ as "south" and $N_n = \{4, 5, 6\}$ with $\{a_i\}_{i\in N_n} = \{4.5, 4.9, 5.9\}$ as "north". The distribution of $a_i^*$ is $\{a^*\}_{i\in N} = \{2, 3, 3, 5, 5, 6\}$, leading to the two candidates for the size of self-enforcing IEA: 3 and 5 by Proposition 5.

Assume that technological transfer happens from north to south and it reduces the southern abatement cost by 0.5, resulting in $\{a_i\}_{i\in N} = \{1.6, 2.5, 2.8, 4, 4.4, 5.4\}$. The distribution of $a^*$ changes to $\{a^*\}_{i\in N} = \{2, 3, 3, 4, 5, 6\}$, achieving the size of self-enforcing IEA, 3. If the coalition size is 5 before technological transfer, then the aggregate welfare is 13.7, whereas it is 11.1 after technological transfer.

Although the technology transfer improves average productivity of abatement technology, it might reduce the size of self-enforcing IEA, resulting in welfare loss. We can also apply this discussion to technology innovation. Although innovation improves average productivity of the abatement technology, it might decrease the total welfare.

[19] Proposition 4 can be interpreted as a result of technology transfer. Let us call such technology transfer as "mean-preserving technology transfer" because the mean of $a_i$ is unchanged before and after the transfer. As examples of mean-preserving technology transfer, we can consider the relocation of factories or transfer of human capital. According to Proposition 4, this type of technology transfer may lead to welfare loss.

## 4 Conclusion

In this paper, we have analyzed the effect of countries' asymmetry on self-enforcing IEA formation and total welfare. The asymmetry among countries is captured by country-dependent abatement cost. The model is a simplification of a group formation game in Maruta and Okada (2005) with a specific welfare function adopted in much of IEA literature. According to the definition, self-enforcement requires that all member countries are pivotal in the sense that a withdrawal of each country lead to break-down of the implementation condition. In our model, IEA formation depends deeply on the distribution of abatement technologies because abatement cost plays an important role in determining the country's choice whether to implement an IEA. As Barrett (2001) and Maruta and Okada (2005) show, asymmetry among countries may imply multiple sizes of self-enforcing IEAs, while identical countries leads only to a single size of self-enforcing IEA.

We have investigated the welfare effect of countries' asymmetry by comparing the total welfares of symmetric and asymmetric situations sharing the potential gain from full cooperation. As a result, compared with symmetric situation, we find that asymmetry might result in welfare gain (loss) even if the size of coalition became smaller (bigger). This is because the total welfare is determined by not only *how large the IEA is* but also *who joins and who does not join the IEA* in the asymmetric situation.

The welfare analysis has an important implication of technology transfer. We find that technology transfer can lead to welfare loss even if it improved the average technology of abatement. This is because technology transfer can result in a smaller size of self-enforcing IEA. While the dominance of the scale effect on the technique effect demonstrates the pollution-increasing technological change (Copeland and Taylor (2003)), change in the IEA formation offers a new channel to explain welfare loss caused by technology transfer. Technology transfer would basically benefit us because it expands potential abatement capacity in the world. Actually, the Kyoto Protocol adopts Clean Development Mechanism (CDM) that encourage environmental technology transfer. However, according to our results, we need to consider its effect on the size of IEA that might result in deterioration of the environment.

# Appendix

## Proof of Proposition 1

*Proof.* We can easily check that the external stability holds for any $S$. $u_i^m(S) \geq u_i^{nm}(S \backslash \{i\})$ does not hold because it violates the assumption of $1 < a_i$ for all $i \in N$. $u_i^m(S) \geq u_i^{nm}(\emptyset)$ implies $s \geq a_i$. From the condition of $s < (\max_{j \in S \backslash \{i\}} a_j)^* + 1$, the $S$ satisfying the internal condition is $a_i \leq s < (\max_{j \in S \backslash \{i\}} a_j)^* + 1$ for all $i \in S$. □

## Proof of Lemma 1

*Proof.* Assume on the contrary that $S$ is a self-enforcing IEA with $s > a_h^*$ or $s < a_h^*$.

If we have $s > a_h^*$, then we have $s \geq a_h^* + 1$ since $s$ is an integer. Using this result, we have $a_h^* + 1 \leq s < \max_{j \in S \backslash \{h\}} a_j + 1$ from the internal stability condition for country $h$, which implies $a_h^* < \max_{j \in S \backslash \{h\}} a_j$. This is a contradiction because $a_h^*$ is defined as $a_h^* = \max_{i \in S} a_j$.

If we have $s < a_h^*$, then we have $a_h \leq s < a_h^*$ because of the internal stability condition for country $h$. If $a_h$ is an integer, then we have $a_h < a_h$ which is a contradiction. If $a_h$ is not an integer, then there does not exist an integer $s$ that satisfies $a_h \leq s < a_h^*$.

Therefore, we have $s = a_h^*$ if an IEA $S$ is self-enforcing. □

## Proof of Lemma 2

*Proof.* Assume that $S$ is self-enforcing. In case of $\max_{j \in S \backslash \{h\}} a_j = a_h$, we have the result directly.

Assume that $\max_{j \in S \backslash \{h\}} a_j < a_h$. Then we have $a_h^* < \max_{j \in S \backslash \{h\}} a_j + 1$ because of $s = a_h^*$ (from Lemma 1) and the internal stability for country $h$. These two equations and $a_h \leq a_h^*$ imply $a_h^* - 1 < \max_{j \in S \setminus \{h\}} a_j < a_h^*$. Because $a_h^*$ is an integer, this implies that $(\max_{j \in S \setminus \{h\}} a_j)^* = a_h^*$. □

## Proof of Proposition 2

*Proof.* The necessary conditions are directly derived from the results of Lemma 1 and Lemma 2. We show the sufficient conditions for a self-enforcing IEA.

We want to show that $s = a_h^* = (max_{j \in S \setminus \{h\}} a_j)^*$ implies $a_i \leq s < \max_{j \in S \setminus \{i\}} a_j + 1$ for all $i \in S$.

First, we obviously have that $a_i \leq a_h^*$ for all $i \in S$. Because of $s = a_h^*$, we have $a_i \leq s$ for all $j \in S$.

Next, we show that we have $s < \max_{j \in S \setminus \{i\}} a_j + 1$ for all $i \in S$. For country $h$, we show that $a_h^* < \max_{i \in S \setminus \{h\}} a_i + 1$. From the definition of $\cdot^*$, we have $(\max_{i \in S \setminus \{h\}} a_i)^* - 1 < \max_{i \in S \setminus \{h\}} a_i$. Because we have $a_h^* = (\max_{i \in S \setminus \{h\}} a_i)^*$ from the assumption, we have $a_h^* - 1 < \max_{i \in S \setminus \{h\}} a_i$, which implies $a_h^* < \max_{i \in S \setminus \{h\}} a_i + 1$. Therefore, the condition to be shown holds for country $h$.

For other countries $i \in S \setminus \{h\}$, we check that $a_h^* < \max_{j \in S \setminus \{i\}} a_j + 1$. Because $\max_{j \in S \setminus \{i\}} a_j = a_h$, this equation always holds due to the definition of $\cdot^*$.

Therefore, we have $a_i \leq s < \max_{j \in S \setminus \{i\}} a_j + 1$ if we have $s = a_h^* = (max_{i \in S \setminus \{h\}} a_i)^*$.

□

## Proof of Proposition 3

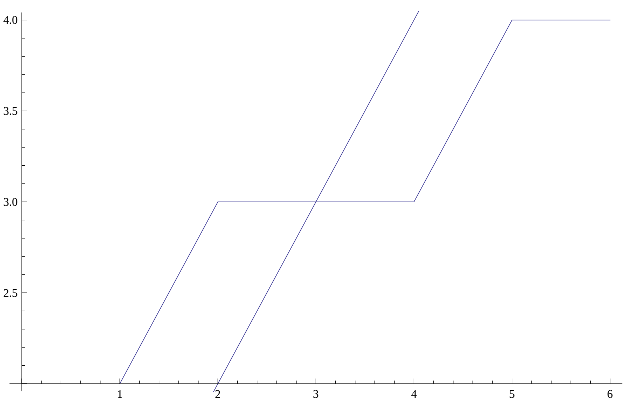
*Proof.* By Proposition 2, it is enough to show that there always exists at least one coalition $S$ which satisfies that $s = a_h^* = (max_{i \in S \setminus \{h\}} a_i)^*$.

First we show that there always at least two countries $i$ and $j$ with $a_i^* = a_j^*$. The assumption that $1 < a_i < n$ for every $i \in N$ implies that $2 \leq a_i^* \leq n$ for all $i \in N$. Because we have $n$ integers on $[2, n]$, at least two of them must have the same number. Therefore, there always exit at least two countries $i$ and $j$ with $a_i^* = a_j^*$.

Next we show there always exists $S$ which contains two countries $i$, $j$ with $a_i^* =$

$a_j^* = (\max_{k \in S} a_k)^*$, where $s = a_i^* = a_j^*$ holds. Let us define $i$ and $j$ as countries with highest $a_i^* = a_j^*$. Denote an integer $l$ as $l = a_i^* = a_j^*$. Let us introduce a set $\bar{S}$ such that $\bar{S} = \{k \neq i, j | a_k^* \leq a_i^* = a_j^*\} \cup \{i\} \cup \{j\}$. ($\{k | a_k^* \leq a_i^* = a_j^*\}$ can be $\emptyset$.) It is enough to show that $|\bar{S}| \geq a_i^* = a_j^*$. Assume on the contrary that $|\bar{S}| < l$. Then there are more than $n - l$ countries whose $a_i^*$ is in $[l+1, n]$. This implies that there are at least two countries of $n - l$ countries must share their $a_i^*$, which is a contradiction to the assumption of $l$ is the largest integer that satisfies $l = a_i^* = a_j^*$. Therefore, we have $|\bar{S}| \geq a_i^* = a_j^*$.

We can check this proof graphically analogue to the fixed point theorem. Let us arrange all $a_i^*$ in ascending order. (Assume the set of countries is $N = \{1, \cdots, 6\}$) The




linear line is 45-degree line and the line graph is plotting $\{a_i\}_{i \in N} = \{2, 3, 3, 3, 4, 4\}$. We know that if line graph has a horizontal part in the area below 45-degree line (including boundary), there exists $\bar{S}$ that satisfies $|\bar{S}| \geq a_i^* = a_j^*$ with $i, j \in \bar{S}$. From the first step of this proof, the line graph has at least one horizontal part. From the second step of the proof, there are at least one intersection between the two graphs. Therefore, there exists a horizontal part below or on the 45-degree line, implying that $\bar{S}$ with $|\bar{S}| \geq a_i^* = a_j^*$ with $i, j \in \bar{S}$ always exists. □

## Proof of Proposition 4

*Proof.* Denote the common average of $a_i$ as $a$. $\bar{S}$ is a self-enforcing IEA with symmetric countries with $|\bar{S}| = a^*$, $\tilde{S}$ is a self-enforcing IEA with asymmetric countries with

$|\tilde{S}| = a_h^*$.

We want to show that asymmetry of countries results in an increase in aggregate welfare with a self-enforcing IEA if and only if the following holds.

$$n(a_h^* - a^*) > \sum_{i \in \tilde{S}} a_i - \sum_{i \in \bar{S}} a$$

We show this by direct comparison of total welfare under symmetric situation and asymmetric situation. First, in general, the total welfare from implemented IEA $S$ can be written as follows:

$$\sum_{i \in S} u_i^m(s) + \sum_{i \in N \setminus S} u_i^{nm}(s) = ns - \sum_{i \in S} a_i$$

Let us denote the total welfare under symmetric countries as $\bar{U}$ and the total welfare from asymmetric countries as $\tilde{U}$. Then, we have:

$$\bar{U} = na^* - \sum_{i \in \bar{S}} a, \qquad \tilde{U} = na_h^* - \sum_{i \in \tilde{S}} a_i$$

Then the direct comparison of $\bar{U}$ and $\tilde{U}$, we have the result as follows:

$$\begin{aligned} \tilde{U} > \bar{U} &\Longleftrightarrow na_h^* - \sum_{i \in \tilde{S}} a_i > na^* - \sum_{i \in \bar{S}} a \\ &\Longleftrightarrow n(a_h^* - a^*) > \sum_{i \in \tilde{S}} a_i - \sum_{i \in \bar{S}} a \end{aligned}$$

□

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