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International Negotiations on Climate Change:
A Non-cooperative Game Analysis
of the Kyoto Protocol

by

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Abstract. We investigate international negotiations on CO_2 emissions reduction in the Kyoto Protocol by non-cooperative multilateral bargaining theory. The negotiation model has two phases, (i) allocating emission reductions to countries and (ii) international emissions trading. Anticipating the competitive equilibrium of emissions trading, each country evaluates an agreement of reduction commitments. We formulate the negotiation process as an n-person sequential bargaining game with random proposers. We show that there exists a unique stationary subgame perfect equilibrium of the bargaining game and that the equilibrium emissions reduction proposed by every country converges to the asymmetric Nash bargaining solution as the probability of negotiation failure by rejection goes to zero. The weights of countries in the asymmetric Nash solution are determined by their probabilities to be selected as proposers. Finally, we present numerical results based on actual emission data on the European Union (EU), the former Soviet Union (FSU), Japan and the United States (USA).

Key words: asymmetric Nash bargaining solution, CO_2 emissions trading, international negotiations, Kyoto Protocol, non-cooperative bargaining games.

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1 Introduction

The purpose of this paper is to consider international negotiations on climate change in a game theoretic framework. With the increase of environmental concerns in the late 1980s, the UN Framework Convention on Climate Change (UNFCC) was signed at the Rio Earth Summit in June 1992. The objective of the Convention was to stabilize greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Developed countries promised to return their emissions of CO_2 and other GHGs to 1990 levels by the year 2000. The Convention, however, lacked any legally binding commitments, and this voluntary approach was not successful. The third Conference of the Parties (COP3) to the Convention was held at Kyoto on 1-10 December 1997. The objective of the Kyoto conference was to adopt a "legally-binding protocol or other legal instrument"[3] committing developed countries to reducing their GHGs emissions.

More than 150 developed and developing countries attended the Kyoto conference. Intensive negotiations took place during the conference, and the Kyoto Protocol to the Convention was finally agreed.[4] The key contents of the Protocol are summarized as follows. First, Annex I countries (OECD countries and countries in the former Soviet Union (FSU) and Eastern Europe) as a whole reduce emissions by 5.2 per cent below 1990 levels between 2008 and 2012 (Article 3). Secondly, the quantified emission limitation or reduction commitment (QELRC) is assigned to each Annex I country (Article 4 and Annex B). The reduction rates of major emitting countries are as follows: Russia and Ukraine 0%; Japan 6%; the United States

[3]Ministerial Declaration at COP2, 8-19 July 1996. http://unfccc.int/sessions/cop2/l17.pdf

[4]The agreement was reached late in the morning of 11 December, 36 hours after the official deadline. For a detailed survey of the Kyoto Protocol, see Grubb et al.(1999). The full text of the protocol is available at http://unfccc.int/resource/docs/convkp/kpeng.pdf.

(USA) 7%; and the European Union (EU) 8%. Thirdly, the Protocol includes three "flexible" mechanisms for international emission transfer such as joint implementation (Article 6), the clean development mechanism (Article 12), and emissions trading (Article 17).

In this paper, we present a game theoretic model of international negotiations on the Kyoto Protocol. Our analysis is focused on reduction commitments of CO_2 emissions and emissions trading. The bargaining model has two consecutive stages, (i) allocating emission reductions to countries and (ii) international emissions trading. We assume that emissions trading takes place in a competitive market and that given a total target of emissions, the efficient reductions (minimizing the total reduction costs) can be attained across the countries in the emissions market. This enables us to solve the two-stage model by backward induction. Given the competitive equilibrium of emissions trading, the whole bargaining model of allocating emissions can be reduced to the n-person unanimous bargaining problem where an agreement requires the unanimous consent of countries. The countries evaluate the agreement of emissions allocation by their net costs after trading in the competitive emissions market.

We formulate a negotiation process on emission reductions by non-cooperative multilateral bargaining theory (see Selten 1981, Chatterjee et al. 1993, Moldovanu and Winter 1995, Okada 1996, among others).[5] Specifically, our model is based on the sequential bargaining game with random proposers introduced by Moulin (1984) and Okada (1996), which is a generalization of the Rubinstein's (1982) two-person alternating-offers model.

The negotiation process consists of a (possibly) infinite sequence of bargaining rounds.

[5]These works treat multilateral bargaining situations where coalitions of players are allowed to form. The model in this paper can be extended to such a general situation. See Okada (1996).

In the beginning of each round, every country is randomly selected as a proposer according to a predetermined probability distribution. If selected, a country proposes an allocation of emissions. All other countries either accept or reject the proposal sequentially. If all responders accept the proposal, then the proposal is agreed upon. If any country rejects the proposal, then negotiations can proceed to the next round with some positive probability and the same process is repeated. Negotiations, however, may stop with the remaining probability. The *disagreement point* of negotiations describes countries' costs in the failure of negotiations.

We show that there exists a unique stationary subgame perfect equilibrium (SSPE) of the negotiation process, and moreover that the equilibrium proposal by every country converges to the asymmetric Nash bargaining solution as the stopping probability of negotiations goes to zero. The weights of countries in the asymmetric Nash bargaining solution are determined by their probabilities to be selected as proposers.

In the second part of the paper, we present numerical results based on actual emission data on EU, FSU, Japan and USA. Employing the marginal costs of CO_2 emissions abatement estimated by Nordhaus (1991), we compute the competitive equilibrium price ($9.45 per carbon ton) in emissions trading among the four countries. Based on the numerical results, we discuss how the reduction commitments by the Kyoto Protocol can be supported by the asymmetric Nash bargaining solution under three different kinds of weight: equal weight, population weight and GDP weight.

The actual negotiations in the Kyoto conference involve many unknown factors which can be hardly analysed by any formal model. The Kyoto Protocol may be understood best as the outcome of an unseen political process, compromising various conflicting objectives.

Nevertheless, in our view, it is important to consider negotiations on the Kyoto Protocol by the formal methodology of game theory. A game theoretical model clarifies the strategic structure of international negotiations on the Protocol, and enables us to scrutinize on what kind of rational basis the Protocol is established. It helps us to understand a very complicated negotiation process on climate change from the strategic viewpoint of countries, and gives us quantative predictions on the emissions trading.

As far as we know, there are few game-theoretical works on the Kyoto Protocol. In our previous work (Okada 2002), we analyse negotiations on the Protocol by cooperative game theory. The negotiations on reduction commitments are formulated as a cooperative voting game. Several allocation rules (including the Kyoto Protocol) are evaluated from viewpoints of three major emitting countries, FSU, Japan and USA, based on the same empirical data as in this paper. The cooperative game approach has the difficulty that the stability is very restrictive: the set of stable outcomes (defined by the *core* solution) of the voting game is non-empty if and only if there exists at least one country possessing veto power. Unlike in the UN Security Council, however, all negotiating players are symmetric regarding the veto power in the international negotiations on climate change. By this reason, the unanimous voting rule where every country has a veto power is the most relevant for international negotiations on climate change. Then, the result of the cooperative game is vacant in that *all* allocations of emissions can be stable. The non-cooperative game approach in this paper overcomes this difficulty. It can select the (asymmetric) Nash bargaining solution as an unique SSPE of the barganing process. Non-cooperative behavior of countries is critical in international negotiations without any centralized power. Barrett (1992) analyses "acceptable"[6] allocation

[6] In the game theoretic terminology, the acceptability here means the individual rationality that each

schemes of emissions among China, FSU and USA, and demonstrates by empirical data that the uniform percentage abatement rule is preferred by these countries, without an analysis of bargaining procedure.

The paper is organized as follows. Section 2 presents a game-theoretic model of international negotiations on the Kyoto Protocol. The properties of a competitive equilibrium of emissions trading are reviewed. Section 3 presents a non-cooperative bargaining procedure on emissions reduction. The main theorem is proved. Section 4 presents numerical results on the competitive equilibrium of emissions trading among EU, FSU, Japn and USA. Section 5 concludes the paper.

2 The Model

Let $N = \{1, \cdots, n\}$ be the set of countries. For every $i \in N$, we denote by E_i country i's current level of CO_2 emissions. The total level of CO_2 emitted by n countries is given by $E = \sum_{i \in N} E_i$. Let x_i denote country i's reduction of CO_2 emissions where $0 \leq x_i \leq E_i$. The CO_2 abatement cost function of country i is denoted by $C_i(x_i)$. It is assumed that $C_i(x_i)$ is a differentiable, strictly convex and monotonically increasing function on R_+, the set of all non-negative real numbers. Let $MC_i(x_i)$ denote the marginal abatement cost function of country i. For a natural number $s = 1, 2, \cdots$, notation R^s_+ means the non-negative orthant of the s-dimensional Euclidean space R^s.

Our game theoretic model of international negotiations on climate change has the fol-

country's net benefit is at least as great under an allocation as it would be if negotiations failed.

lowing two consecutive phases, (i) negotiations on emission allocations, and (ii) emissions trading.

In the first phase of negotiations, n countries negotiate on an allocation of emissions. Let ω_i denote an amount of emission permits allocated to country i. Country i has to reduce $E_i - \omega_i$ amount of emissions if emissions trading is impossible. An *emission allocation* is formulated by a vector $\omega = (\omega_1, \cdots, \omega_n) \in R^n_+$. The total amount of CO_2 emission permits is given by $\overline{\omega} = \sum_{i=1}^n \omega_i$. In this paper, we assume that the total emissions target $\overline{\omega}$, $0 < \overline{\omega} < E$, is exogenously determined by scientific knowledge and that it is not an issue of negotiations. The agreement of an emission allocation $\omega = (\omega_1, \cdots, \omega_n)$ satisfying $\overline{\omega} = \sum_{i=1}^n \omega_i$ is reached by the unanimous consent among n countries. The negotiation process will be described in Section 3.

In the second phase of negotiations, n countries negotiate to sell and buy their emission permits, given the initial emission allocation $\omega = (\omega_1, \cdots, \omega_n)$ agreed in the first phase of negotiations. We assume that the emissions trading takes place in a competitive market. The competitive equilibrium of emissions trading is efficient in the sense that the total reduction costs across n countries attaining the emission target $\overline{\omega}$ is minimized.

Let p be a market price of emissions and let x_i be an actual level of emissions reduction by country i after the trading.

Definition 2.1. A *competitive equilibrium* of international CO_2 emissions trading with an initial emission allocation $\omega = (\omega_1, \cdots, \omega_n) \in R^n_+$ is defined to be a vector $(p^*, x_1^*, \cdots, x_n^*) \in$

R_+^{n+1} satisfying

$$x_i^* \in \text{argmin } \{C_i(x_i) + p^*(E_i - x_i - \omega_i) \ \mid \ 0 \leq x_i \leq E_i\} \quad \text{for any} \quad i \in N \tag{1}$$

$$\sum_{i \in N}(E_i - x_i^*) = \bar{\omega} \quad \text{where} \quad \bar{\omega} = \sum_{i \in N} \omega_i. \tag{2}$$

The minimum value of the optimization problem (1),

$$c_i^e \equiv C_i(x_i^*) + p^*(E_i - x_i^* - \omega_i) \tag{3}$$

is called the *competitive equilibrium reduction cost* for country i.

The definition can be explained as follows. If country i wants to reduce CO_2 emissions by x_i from E_i, it must possess $E_i - x_i$ amounts of emission permits. If the initial allocation ω_i of emissions is less than this level, country i has to purchase $E_i - x_i - \omega_i$ amounts of emission permits from other countries. Equation (1) means that every country i minimizes its CO_2 abatement net costs, given the equilibrium price p^* of emissions. Equation (2) is the balancedness condition of demand and supply for emission permits.

We review the standard properties of the competitive equilibrium. If x_i^* is an interior solution of country i's cost minimizing problem (1), then the well-known principle of *marginal cost pricing* must hold:

$$p^* = MC_i(x_i^*) \quad \text{for all } i \in N \tag{4}$$

where MC_i is the marginal reduction cost function of country i. It can be proved that the equilibrium emission reduction $x^* = (x_1^*, \cdots, x_n^*)$ minimizes the total reduction costs for n countries to attain the reduction target $\bar{\omega}$. That is, x^* is the optimal solution of

$$\min_{x \in R_+^n} \sum_{i \in N} C_i(x_i) \qquad s.t. \qquad \sum_{i \in N} x_i = \sum_{i \in N} (E_i - \omega_i). \tag{5}$$

We denote by $c(\bar{\omega})$ the minimum value of the total emissions reduction costs in (5) given the emission target $\bar{\omega}$.

Since a competitive equilibrium $(p^*, x_1^*, \cdots, x_n^*) \in R_+^{n+1}$ of the emissions trading can be characterized as a solution of the balancedness equation (2) of demand and supply and the marginal cost pricing equation (4), it is important to remark that the competitive equilibrium $(p^*, x_1^*, \cdots, x_n^*)$ is determined solely by the total reduction $r = E - \bar{\omega}$, given the marginal abatement cost functions of n countries. Since the total reduction level r is fixed throughout the analysis, we represent the competitive equilibrium reduction cost c_i^e for country i in (3) simply as a function $c_i^e(\omega_i)$ only of the initial emissions ω_i assigned to country i, independent of those assigned to other countries. The function c_i^e is called the *competitive equilibrium reduction cost function of country* i.

We summarize the properties of a competitive equilibrium of international CO_2 emissions trading in the following proposition.

Proposition 1. In the competitive equilibrium of the international CO_2 emissions trading with an initial emission allocation $\omega = (\omega_1, \cdots, \omega_n) \in R_+^n$, the emission price p^* and the emission reduction vector $x^* = (x_1^*, \cdots, x_n^*) \in R_+^n$ are solely determined by the total emission target $\bar{\omega} = \sum_{i \in N} \omega_i$. Given $\bar{\omega}$, the equilibrium reduction $x^* = (x_1^*, \cdots, x_n^*)$ is efficient so that it can minimize the total reduction costs for n countries to attain the emission target $\bar{\omega}$. The equilibrium reduction cost $c_i^e(\omega_i)$ of every country i is a decreasing function of the initial emission ω_i allocated to country i, and it satisfies

$$\sum_{i \in N} c_i^e(\omega_i) = c(\bar{\omega}) \tag{6}$$

where $c(\bar{\omega})$ is the total equilibrium reduction costs defined by the optimal value of (5).

When countries negotiate on emission allocations, they can anticipate the competitive equilibrium of international emissions trading. Thus, it is reasonable to assume that countries evaluate every emission allocation by their equilibrium reduction costs after emissions trading given the allocation. Equation (6) shows that the bargaining problem on emission allocations can be considered as a cost allocation problem where every country wants more emission permits to decrease its reduction costs. A dynamic model of the negotiation process on emission allocations will be described in the next section.

Remark. In this paper, we investigate the outcome of emissions trading by applying the competitive equilibrium in price theory. An alternative approach is to apply some solution concept (the Shapley value, for example) in cooperative game theory. To do this, an n-person game in coalitional form can be constructed as follows. Every subset S of N is called a *coalition* of countries. All member countries in coalition S jointly minimize their total costs of emission reduction by reallocating emission permits within the coalition. The total cost of reducing emissions for coalition S is given by:

$$\min_{x\in R_+^S}\sum_{i\in S}C_i(x_i)\qquad s.t.\qquad \sum_{i\in S}x_i\geq\sum_{i\in S}(E_i-\omega_i),\ \ 0\leq x_i\leq E_i,\ \text{ for any i}\in S,$$

assuming $\sum_{i\in S}(E_i-\omega_i)\geq 0$. The first constraint means that coalition S as a whole should not emit CO_2 more than the sum of emission permits assigned to all member countries. Let $C^\omega(S)$ denote the minimum cost above. It can be easily seen that the cost function C^ω of coalitions is sub-additive: $C^\omega(S\cup T)\leq C^\omega(S)+C^\omega(T)$ for any S and T with $S\cap T=\emptyset$. Formally, a *cooperative game of international CO_2 emissions trading* is defined by a pair (N,C^ω). For detailed discussions on cooperative games, see Shubik (1983).

3 A Non-cooperative Bargaining Process of Emissions Reduction

We describe a non-cooperative bargaining process of emissions reduction in the first negotiation phase briefly explained in the last section. The negotiation can be formulated as the *n-person unanimous bargaining problem* in the literature of the bargaining theory. Let $\omega=(\omega_1,\cdots,\omega_n)\in R_+^n$ be an emission allocation for n countries satisfying $\sum_{i\in N}\omega_i=\bar{\omega}$, and let Ω be the set of all emission allocations ω. Every country i evaluates an allocation $\omega=(\omega_1,\cdots,\omega_n)$ by its competitive equilibrium reduction cost $c_i^e(\omega_i)$ given in (3). The agreement of $\omega=(\omega_1,\cdots,\omega_n)$ is reached by the unanimous consent of all n countries.

To complete the description of the unanimous bargaining problem, we need to specify the *disagreement point* which shows what would happen in the case that negotiations fail. It is very difficult for us to estimate the diagreement point of the international negotiations on the Kyoto Protocol. There exist a lot of uncertain factors on climate change in environmental and economic aspects. Also, the failure of the Kyoto conference will cause further political uncertainty in international negotiations. Due to the difficulty to estimate future events in the case of negotiations failure, we simply assume in this paper that the breakdown of negotiations in the Kyoto conference delays the prevention of global warming and thus that each country i has to be burdened with some exogenous cost d_i. We assume

$$\sum_{i \in N} d_i > c(\bar{\omega}). \tag{7}$$

This condition means that the diagreement in the Kyoto conference causes higher reduction costs for countries as a whole than it would be under the Kyoto Protocol. The disagreement point of negotiations is given by $d = (d_1, \cdots, d_n) \in R^n_+$. By agreeing to an emission allocation $\omega = (\omega_1, \cdots, \omega_n)$, each country i can save its reduction costs by $d_i - c^e_i(\omega_i)$.

Definition 2. The *unanimous bargaining problem of CO_2 emissions reduction* is defined to be a triplet $B = (\Omega, d, (c^e_i)_{i \in N})$ where Ω is the set of all emission allocations $\omega = (\omega_1, \cdots, \omega_n) \in R^n_+$ for n countries satisfying $\sum_{i \in N} \omega_i = \bar{\omega}$, $d = (d_1, \cdots, d_n) \in R^n_+$ the disagreement point satisfying (7), and c^e_i the competitive equilibrium reduction cost function of country i defined in (3).

Before presenting a formal model of the negotiation process, we define a cooperative solution of the unanimous bargaining problem introduced by Nash (1950).

Definition 3. The *asymmetric Nash bargaining solution* of the unanimous bargaining problem $B = (\Omega, d, (c_i^e)_{i \in N})$ with a weight vector $\alpha = (\alpha_1, \cdots, \alpha_n) \in R_+^n$ is the optimal solution $\omega = (\omega_1, \cdots, \omega_n)$ of the maximization problem

$$\begin{aligned} \max \quad & (d_1 - c_1^e(\omega_1))^{\alpha_1} \cdot \ \cdots \ \cdot (d_n - c_n^e(\omega_n))^{\alpha_n} \\ \text{s.t.} \quad & \text{(i) } \omega = (\omega_1, \cdots, \omega_n) \in \Omega \\ & \text{(ii) } c_i^e(\omega_i) \leq d_i \quad \text{for all} \quad i = 1, \cdots, n \end{aligned}$$

where c_i^e is the competitive equilibrium reduction cost function of country i.[7]

The asymmetric Nash bargaining solution maximizes the weighted product of all countries' saving costs from emissions trading. The following proposition characterizes the asymmetric Nash bargaining solution.

Proposition 2. If the disagreement point $d = (d_1, \cdots, d_n)$ satisfies $c_i^e(0) \geq d_i$ for all $i \in N$, then the asymmetric Nash bargaining solution $\omega = (\omega_1, \cdots, \omega_n)$ of the unanimous bargaining problem $B = (\Omega, d, (c_i^e)_{i \in N})$ for n countries with a weight vector $\alpha = (\alpha_1, \cdots, \alpha_n) \in R_+^n$

[7] (7) guarantees that there exists an emission allocation $\omega = (\omega_1, \cdots, \omega_n)$ satisfying constraints (i) and (ii).

satisfies

$$\frac{d_1 - c_1^e(\omega_1)}{\alpha_1} = \cdots = \frac{d_n - c_n^e(\omega_n)}{\alpha_n}. \tag{8}$$

Proof. We first remark that the optimal solution of the maximization problem in Definition 3 is unchanged when we replace the objective function $(d_1 - c_1^e(\omega_1))^{\alpha_1} \cdot \cdots \cdot (d_n - c_n^e(\omega_n))^{\alpha_n}$ with the logarithmic value of it. That is, the Nash bargaining solution $\omega = (\omega_1, \cdots, \omega_n)$ with the weight vector $\alpha = (\alpha_1, \cdots, \alpha_n)$ is the optimal solution of the maximization problem

$$\begin{aligned} \max \quad & \alpha_1 \cdot \log(d_1 - c_1^e(\omega_1)) + \cdots + \alpha_n \cdot \log(d_n - c_n^e(\omega_n)) \\ \text{s.t.} \quad & \text{(i) } \omega_1 + \cdots + \omega_n = \bar{\omega}, \\ & \text{(ii) } \omega_i \geq 0 \quad \text{for all} \quad i = 1, \cdots, n, \\ & \text{(iii) } c_i^e(\omega_i) \leq d_i \quad \text{for all} \quad i = 1, \cdots, n \end{aligned}$$

The assumption that $c_i^e(0) \geq d_i$ for all $i \in N$ imply that constraint (ii) is not binding at the optimal solution. Constraint (iii) is not binding from (7), either. Therefore, it can be shown that the Nash bargaining solution $\omega = (\omega_1, \cdots, \omega_n)$ satisfies the first-order condition

$$-\frac{\alpha_i}{d_i - c_i^e(\omega_i)} \frac{dc_i^e(\omega_i)}{d\omega_i} + \lambda = 0, \quad \text{for all} \quad i = 1, \cdots, n \tag{9}$$

where λ is the Lagrange multiplier corresponding to constraint (i). Since we have $dc_i^e(\omega_i)/d\omega_i = -p^*$ for all $i = 1, \cdots, n$ from (3) where p^* is the competitive equilibrium price of emission, the theorem can be proved by (9). Q.E.D.

The condition $c_i^e(0) \geq d_i$ in the proposition presumes a natural situation that country i prefers the breakdown of negotiations to an agreement if it is assigned no permits of emission. The proposition shows that the ratio of saving costs to the weight should be equalized across n countries at the asymmetric Nash bargaining solution. Solving (3), (6) and (8), we can obtain an explicit formula of the asymmetric Nash bargaining solution $\omega^* = (\omega_1^*, \cdots, \omega_n^*)$ with the weight vector $\alpha = (\alpha_1, \cdots, \alpha_n)$,

$$\omega_i^* = \frac{1}{p^*}\{c_i^e(0) - d_i + \alpha_i(\sum_{i=1}^{n} d_i - c(\bar{\omega}))\} \tag{10}$$

where $c_i^e(0) = C_i(x_i^*) + p^*(E_i - x_i^*)$. The emission reduction cost $c_i^e(\omega_i^*)$ of country i at the Nash bargaining solution $\omega^* = (\omega_1^*, \cdots, \omega_n^*)$ is given by

$$c_i^e(\omega_i^*) = d_i + \alpha_i(c(\bar{\omega}) - \sum_{i=1}^{n} d_i). \tag{11}$$

We call (11) the *Nash bargaining reduction cost* of country i.

We now turn to our main problem to describe a bargaining process on emission reductions in the first phase of negotiations. We will prove that the asymmetric Nash bargaining solution can be attained as a non-cooperative equilibrium of the model, and moreover that the weight of each country for the Nash bargaining solution can be derived endogenously from the bargaining rule.

The bargaining process consists of a (possibly) infinite sequence of bargaining rounds.

The specific rule of the bargaining procedure is as follows..

(1) In the beginning of each round t $(= 1, 2, \cdots)$, every country $i \in N$ is randomly selected as a proposer with a predetermined probability θ_i.

(2) The selected country i proposes an emission allocation $\omega^i = (\omega^i_1, \cdots, \omega^i_n) \in \Omega$.

(3) All other countries in N either accept or reject the proposal ω^i sequentially according to a predetermined order over N. The order of responders does not affect the result in any critical way.

(4) If all responders accept the proposal ω^i, then it is agreed upon. In this case, every country $j \in N$ bears its competitive equilibrium reduction cost $c^e_j(\omega^i_j)$ in the emissions trading.

(5) If any country rejects the proposal ω^i, then the following events may happen. With probability $1 - \varepsilon$ $(0 < \varepsilon < 1)$, negotiations proceed to the next round $t + 1$ and the same process as in round t is repeated. The other possibility is that, with probability ε, negotiations stop and all countries $j \in N$ are burdened with their own costs d_j at the disagreement point $d = (d_1, \cdots, d_n)$.

(6) Every country can know perfectly past moves in the process whenever it makes a decision.

(7) All countries minimize their expected costs of emissions reduction after emissions trading.[8]

[8] In the event with probability zero that negotiations continue forever, we assume that the disagreement point $d = (d_1, \cdots, d_n)$ prevails.

The flowchart of the negotiation process is illustrated in Figure 1. The bargaining model above is denoted by Γ^ε where ε is the stopping probability of negotiations when a proposal is rejected. The game Γ^ε is formally represented as an infinite-length extensive game with perfect information where all players can make their choices with perfect knowledge of all past moves.

Insert Figure 1 about here

A (pure) strategy of every country $i \in N$ in the game Γ^ε is defined to be a sequence $\sigma_i = (\sigma_i^t)_{t=1}^\infty$ of t-th round strategies σ_i^t where σ_i^t prescribes (i) a proposal in round t, and (ii) a response policy assigning either "yes" or "no" to every possible proposal. Both a proposal and a response policy prescribed by the strategy σ_i may depend on the history of negotiations.

We investigate a stationary subgame perfect equilibrium of the bargaining game Γ^ε. Roughly, a subgame perfect equilibrium of Γ^ε is a strategy combination $\sigma = (\sigma_1, \cdots, \sigma_n)$ that prescribes the optimal action to every country at *every possible move* of the country in Γ^ε, given that all other countries follow σ. For a precise definition of a subgame perfect equilibrium of an extensive game, see Harsanyi and Selten (1988) or a standard textbook of game theory. A stationary subgame perfect equilibrium of Γ^ε is a subgame perfect equilibrium in which every country's equilibrium strategy is *stationary.* A stationary strategy in Γ^ε prescribes a proposal and a response policy, independent of negotiation history in past rounds. More precisely, a stationary subgame perfect equilibrium of Γ^ε is defined as follows.

Definition 4. A strategy combination $\sigma^* = (\sigma_1^*, \cdots, \sigma_n^*)$ of the bargaining game Γ^ε is called a *stationary subgame perfect equilibrium* (SSPE) of Γ^ε if it is a subgame perfect equilibrium with the property that for every $i \in N$ and every t $(= 1, 2, \cdots)$, the t-th round strategy σ_i^t of country i is independent of history before round t (the response policy may depend on history within round t).

The solution of a stationary subgame perfect equilibrium is employed in almost every literature of non-cooperative multilateral bargaining models (see Baron and Ferejohn 1989, Perry and Reny 1994, Chatterjee et al. 1993, Okada 1996 and 2000 among others).[9] It implies "forgiveness - let bygones be bygones" in the sense that countries do not treat others unfavorably even if they were treated so in past rounds of negotiations.

In the literature of the equilibrium selection theory developed by Harsanyi and Selten (1989), the SSPE of an extensive game satisfies the condition of *subgame consistency* which requires that every player should behave in the same way across *isomorphic subgames.* In our bargaining game Γ^ε, all subgames starting with the beginning of all rounds can be isomorphic since they have identical game trees. The SSPE imposes that every player should make the same proposal whenever he is selected as a proposer, and that his response to every possible proposal should be independent of the negotiation history in past rounds. It should be remarked that the response surely depends on a proposal itself and an in-round history, that is, who was a proposer and who have already accepted the proposal.

Two justifications for the SSPE may be possible. One is that negotiators representing countries have low-capacity of information processing and thus that they tend to behave

[9] It is well-known that the set of non-stationary subgame perfect equilibria is very large in sequential multilateral bargaining models like ours when the discount rate of future payoffs is close to zero, or when the stopping probability of negotiations is close to zero.

according to a simple strategy such as a stationary one. This kind of justification based on the strategic complexity is considered by Baron and Kalai (1993) and Chatterjee and Sabourian (2000). The other is based on the "focal point" arguments that it is easier for negotiators to coordinate their mutual expectations on stationary strategies. The focal point arguments have received much attention in game theory since the pioneering work of Schelling (1960).

We are now ready to state the main theorem that characterises an SSPE of Γ^ε.

Theorem. There exists a unique SSPE in the bargaining game Γ^ε of emissions reduction.[10] The expected equilibrium cost of every country in Γ^ε is equal to the asymmetric Nash bargaining reduction cost in $B = (\Omega, d, (c_i^e)_{i \in N})$ where the weight vector is given by the probability distribution $\theta = (\theta_1, \cdots, \theta_n)$ for selecting proposers. Moreover, as the stopping probability ε of negotiations becomes close to zero, the emission allocation proposed by every country converges to the asymmetric Nash bargaining solution of B.

Proof. We first prove the uniqueness of an SSPE in the bargaining game Γ^ε. Let $v^\varepsilon = (v_1^\varepsilon, \cdots, v_n^\varepsilon)$ be the expected equilibrium cost vector of n countries in an SSPE. Suppose that country i is selected as a proposer in the initial round. Each responder j bears the expected cost $(1-\varepsilon)v_j^\varepsilon + \varepsilon d_j$ if negotiations break down, since the equilibrium strategies are stationary. By backward induction, this fact implies that if country i proposes an emission allocation where all other countries j $(\neq i)$ bear no more than the expected costs

[10] More precisely, the equilibrium path of an SSPE is unique.

$(1-\varepsilon)v_j^\varepsilon + \varepsilon d_j$, the proposal is accepted by them.[11] Therefore, country i bears optimally the cost $c(\bar{\omega}) - \sum_{j \neq i} \{(1-\varepsilon)v_j^\varepsilon + \varepsilon d_j\}$ if it is selected as a proposer. By the definition of the expected cost v_i^ε, the following equation must hold,

$$v_i^\varepsilon = \theta_i[c(\bar{\omega}) - \sum_{j \neq i} \{(1-\varepsilon)v_j^\varepsilon + \varepsilon d_j)\}] + (1-\theta_i)\{(1-\varepsilon)v_i^\varepsilon + \varepsilon d_i\}, \quad \text{for all } i \in N. \tag{12}$$

Let $\bar{v} = \sum_{i=1}^n v_i^\varepsilon$ and $\bar{d} = \sum_{i=1}^n d_i$. Then, (12) can be arranged as

$$v_i^\varepsilon = \theta_i[c(\bar{\omega}) - (1-\varepsilon)\bar{v} - \varepsilon\bar{d}] + (1-\varepsilon)v_i^\varepsilon + \varepsilon d_i, \quad \text{for all } i \in N. \tag{13}$$

By summing both sides of (13) for all $i \in N$, we obtain $\bar{v} = c(\bar{\omega})$. By substituting this into (13) and solving it, we can obtain

$$v_i^\varepsilon = d_i + \theta_i[c(\bar{\omega}) - \bar{d}] \quad \text{for all } i \in N. \tag{14}$$

That is, the expected equilibrium cost of every country i is equal to the Nash bargaining reduction cost (11) in B with the weight vector $\theta = (\theta_1, \cdots, \theta_n)$. Note that v_i^ε is independent of ε. It follows from (14) that an SSPE in Γ^ε must be unique. In equilibrium, every country i proposes the emission allocation $\omega^i(\varepsilon) = (\omega_1^i(\varepsilon), \cdots, \omega_n^i(\varepsilon)) \in \Omega$ satisfying $c_i^e(\omega_i^i(\varepsilon)) = c(\bar{\omega}) - \sum_{j \neq i} c_j^e(\omega_j^i(\varepsilon))$ and $c_j^e(\omega_j^i(\varepsilon)) = (1-\varepsilon)v_j^\varepsilon + \varepsilon d_j$ for all $j \neq i$ where c_j^e is the country j's competitive equilibrium reduction cost given in (3).

Finally, the arguments above show that the reduction costs $(c_1^e(\omega_1^i(\varepsilon)), \cdots, c_n^e(\omega_n^i(\varepsilon))$ pro-

[11] When responders j bear exactly the expected costs $(1-\varepsilon)v_j^\varepsilon + \varepsilon d_j$, they are indifferent between accepting and rejecting the proposal. However, the proposer's cost minimization in the SSPE induces the acceptance by responders on equilibrium path even in this case.

posed by every country i converges to the Nash bargaining reduction costs $v^\varepsilon = (v_1^\varepsilon, \cdots, v_n^\varepsilon)$ as ε goes to zero. Since the correspondense in (3) between an emission allocation and a competitive equilibrium reduction cost vector is continuous and one-to-one, every country i's proposal $\omega^i(\varepsilon)$ converges to the asymmetric Nash bargaining solution of B as the stopping probability ε of negotiations goes to zero. Q.E.D.

The theorem shows that the asymmetric Nash bargaining solution can be supported as the SSPE of the bargaining model Γ^ϵ where the stopping probability ϵ of negotiations is sufficiently small. The weights of countries for the asymmetric Nash bargaining solution are determined by their probabilities to be selected as proposers. This result implies that the bargaining power of every country comes from the opportunity to make a proposal in the bargaining process.

4 Numerical Results

In this section, we compute the competitive equilibrium of international emissions trading among four major emitting countries EU, FSU, Japan and USA based on actual data. The Nash bargaining solution of the emission allocation is analysed empirically. We consider three different weights, equal weight, population weight, and GDP weight. By the numerical results, we consider how the formal model of the Nash bargaining solution can explain the actual agreement of reduction rates in the Kyoto protocol.

The most difficult task in our empirical analysis is to estimate marginal abatement costs of carbon emissions for countries. Based on a survey of nine different estimates in the USA and Western Europe, Nordhaus (1991) derives the following logarithmic functional form as the marginal abatement costs of the USA:

$$MC_{USA}(R) = -185.2 \cdot \ln(1 - R), \tag{15}$$

in units of 1989 US dollar per ton of carbon where R is the rate of emissions reductions (x/E)[12].

Based on the estimation by Nordhaus, Bohm and Larsen (1994) derive marginal reduction costs of carbon emissions for other countries. Their method is to obtain the marginal cost function of emission reductions for other countries by modifying that of the USA, taking into account the differences of countries' carbon intensities (E/GDP). Let e_{USA} be the carbon intensity of the USA (reference country). Bohm and Larsen assume that if any country l has carbon intensity e_l lower than the USA, it has already taken appropriate measures to reduce its carbon intensity. Thus, its marginal cost function starts at some higher level R_l^0 along the MC-curve of the USA. Figure 2 illustrates the USA's marginal cost function of emissions reduction and the starting point R_l^0 for country l's marginal cost.[13] The curve is steeper at R_l^0 than at the origin of the USA. The starting level R_l^0 is assumed to be

$$r_l = 1 - \frac{e_l}{e_{USA}}. \tag{16}$$

[12]In the above form, we assume zero intercept (Nordhaus estimates an intercept of -4.13).
[13]Figure 2 is also given in Okada (2002).

Then, the marginal cost function of country l is computed as

$$\begin{aligned} MC_l(R_l) &= 185.2 \cdot \ln(1 - r_l) - 185.2 \cdot \ln(1 - r_l - R_l) \\ &= -185.2 \cdot \ln(1 - \frac{R_l}{1 - r_l}). \end{aligned} \tag{17}$$

where R_l is the rate of emissions reduction by country l.

Insert Figure 2 about here

Similarly, if country h has carbon intensity e_h higher than the USA, its marginal cost of emissions reduction starts at some negative level R_h^0 along the MC-curve of the USA (see Figure 2). The starting point R_h^0 of country h is assumed to be

$$r_h = -1 + \frac{e_{USA}}{e_h}.$$

The marginal cost function of country h can be given by the same formula as (17), that is,

$$\begin{aligned} MC_h(R_h) &= -185.2 \cdot \ln(1 - r_h - R_h) + 185.2 \cdot \ln(1 - r_h) \\ &= -185.2 \cdot \ln(1 - \frac{R_h}{1 - r_h}). \end{aligned}$$

where R_h is the rate of emissions reduction by country h. The curve is flatter at r_h than at the origin of the USA.

Under the estimated marginal reduction costs of countries, we can obtain the explicit formula of the competitive equilibrium of CO_2 emissions trading (see Okada 2002).

Proposition 3. Under the marginal cost functions (17) of emissions abatement and an emission allocation $\omega = (\omega_1, \cdots, \omega_n)$, the equilibrium price p^* of emissions, the equilibrium reduction x_i^* of country i, and its equilibrium reduction cost $c_i^e(\omega_i)$ are given by

$$\begin{aligned} p^* &= -185.2 \cdot \ln[1 - \frac{E - \bar{\omega}}{\sum_{i=1}^n E_i(1-r_i)}] & (18) \\ x_i^* &= \frac{E_i(1-r_i)}{\sum_{j=1}^n E_j(1-r_j)}(E - \bar{\omega}) & (19) \\ c_i^e(\omega_i) &= 185.2x_i^* + p^*(E_i r_i - \omega_i) & (20) \end{aligned}$$

where $r_i = 1 - e_i/e_{USA}$ if country i's carbon intensity e_i is lower than e_{USA}, and $r_i = -1 + e_{USA}/e_i$, otherwise.

Proof. By solving (2), (4) and (17), we can prove (18) and (19). Since the country i's equilibrium reduction cost $C_i(x_i^*)$ is computed as

$$\begin{aligned} C_i(x_i^*) &= \int_0^{x_i^*} -185.2 \cdot \ln[1 - \frac{t}{E_i(1-r_i)}]dt \\ &= 185.2[E_i(1-r_i) - x_i^*] \cdot \ln[1 - \frac{x_i^*}{E_i(1-r_i)}] + 185.2x_i^* \\ &= p^*[x_i^* - E_i(1-r_i)] + 185.2x_i^*, \end{aligned}$$

we can prove (20) by (3). Q.E.D.

With help of Proposition 3, we can compute the competitive equilibrium of international emissions trading among EU, FSU, Japan and USA. Table 1 shows all relevant data for 1990 on these countries.[14] Data includes

- carbon emissions (E_i)
- population (n_i)
- gross domestic products (GDP_i)
- carbon intensity ($e_i \equiv E_i/GDP_i$)

It can be seen in Table 1 that carbon intensities are diverse among the major emitting countries. EU and Japan have the lowest carbon intensities, and the FSU does the highest one. The USA is in an intermediate position. This data implies that EU and Japan have already took much efforts to reduce carbon emissions in their domestic productions, and thus that these countries have to bear high costs to satisfy reductions commitment by the Kyoto Protocol if emissions trading is not allowed. Table 2 shows the reduction cost of each country without emissions trading. EU bears the highest reduction costs ($991 million) without emissions trading. The FSU does not bear any reduction costs.

Insert Tables 1 and 2 about here

Table 3 summarizes numerical results on the competitive equilibrium of international emissions trading under the Kyoto Protocol. The efficient reduction share among the four countries are roughly 12% by EU, 47% by FSU, 4% by Japan and 37% by USA. The small

[14] Data sourses. (1) carbon emissions: Marland et al. (2001), (2) population: United Nations Demographic Yearbook 1993 (population of FSU is compiled by Toyo Keizai Data Bank 1993). (3) GDP: United Nations Statistical Yearbook 1998 (1993 for FSU).

reduction share of EU and Japan reflects the fact that the marginal reduction costs of these two countries are less than those of FSU and USA. The reduction shares of EU, Japan and USA decrease compared to those without emissions trading. This fact means that these three countries will be buyers of emissions in the trading. FSU will sell about $83 million tons of emissions. It is remarkable that the total emissions reduction costs can be decreased significantly by emissions trading. The total saving costs amount to about $1030 million. Looking at the saving cost of each country, EU enjoys the highest saving costs (about $470 million). The FSU can earn the profit (about $400 million) by selling emissions. Japan also benefits from emissions trading, although its saving cost is not as large as EU. The saving costs of the USA is marginal ($52 million). From this result, it can be said that EU and FSU benefit the most from the emissions trading. The equilibrium price of emissions is $9.45 per carbon ton in the emissions trading among the four countries. In our previous study (Okada 2002), the equilibrium price of emissions is $6.27 among the three countries without EU. The present numerical result shows that the emission price increases if EU, a big buyer, enters the emissions market.

Insert Table 3 about here

We next consider how the asymmetric Nash bargaining solution can explain the actual agreement of reduction rates in the Kyoto Protocol. To compute the Nash bargaining solution, we need data on the disagreement point $d = (d_1, \cdots, d_n)$ of negotiations. Since we do not have any reliable estimation on such data, we consider a converse question: what disagreement points can support the reduction rates in the Kyoto Protocol as the asymmetric Nash bargaining solution. Mathematically, we consider a solution $d = (d_1, \cdots, d_n)$ of the following linear equations:

$$d_i = c_i^e(\omega_i) + \alpha_i(\sum_{i=1}^{n} d_i - c(\bar{\omega})), \quad \text{for all } i = \text{EU, FSU, Japan, USA}, \tag{21}$$

where ω_i is the emission assigned to country i by the Kyoto Protocol, and $c_i^e(\omega_i)$ is country i's equilibrium reduction costs given in Table 3. It should be noted that (21) includes three independent linear equations. This means that there exist a continuum of solutions $d = (d_1, \cdots, d_n)$ for (21). Given the total disagreement costs $\bar{d} = \sum_{i=1}^{4} d_i$, (21) has a unique solution of the disagreement point.

For the asymmetric Nash bargaining solution, we consider three kinds of weights, equal weight, population weight and GDP weight. The population (GDP, respectively) weight determines countries' weights to be proportional to their populations (GDPs, respectively). According to Table 1, EU has the largest weight under both rules of population and GDP. Japan has the smallest weight under the population rule, and FSU does under the GDP rule. Table 4 gives several disagreement points which can support the reduction rates in the Kyoto Protocol as the asymmetric Nash bargaining solution with different weights.

Insert Table 4 about here

The main findings of Table 4 are as follows. GDP gives a very low weight to the FSU. This means that the bargaining power of the FSU is very low in the negotiation process. Reflecting this fact, Table 4 shows that, in order for the Nash bargaining solution with the

GDP weights to support the reduction rates in the Kyoto protocol, the FSU should earn profits when negotiations fail. Since this is an unlikely event, we can conclude that the Nash bargaining solution with the GDP weights fails in explaining the agreement of the Kyoto Protocol. In both the equal weights and the population weights, the disagreement costs of EU and USA are larger than those of Japan and FSU. This means that if EU and USA estimate highly their damages in the failure of the Kyoto Protocol, the reduction rates agreed in the Kyoto Protocol can be supported as the asymmetric Nash bargaining solutions both with the equal weights and with the population weights.

5 Conclusion

We have considered international negotiations on CO_2 emissions reduction committed by the Kyoto Protocol in the framework of game theory. Specifically, we have presented a non-cooperative bargaining model of negotiations on emission reduction. The main theorem shows that there exists a unique stationary subgame perfect equilibrium (SSPE) of the bargaining model and that the equilibrium proposal by every country converges to the asymmetric Nash bargaining solution of emission reduction as the stopping probability of negotiations goes to zero. In the model, one country is selected randomly as a proposer in the beginning of every round. It is proved that the weight of every country for the asymmetric Nash bargaining solution is determined by the probability to be selected as a proposer. This result implies that the bargaining power of a country emerges from the opportunity to make a proposal in the bargaining process.

In the last part of the paper, we have considered by empirical data on the four major emitting countries how the formal model of the Nash bargaining solution can explain the actual agreement of reduction rates in the Kyoto protocol. We have computed the competitive equilibrium of emission trading among EU, FSU, Japan and USA based on the estimation of these countries' marginal costs of emissions reduction in the literature. The numerical results are summarized as follows. The emission price is $9.45 per carbon ton. EU, Japan and USA buy in total about 83 million tons of emissions from FSU. FSU earns about $400 million from trading. The emission trading reduces significantly the total reduction costs for the four countries. The total saving costs amount to $1030 million. Regarding the saving costs of individual countries, EU enjoys the highest saving costs ($470 million) and Japan the second highest ($110 million). USA has the least saving costs ($52 million). The numerical results show that if the equal weight or the population weight is employed, the asymmetric Nash bargaining solution can support the reduction rates in the Kyoto protocol when EU and USA evaluate their damages in the failure of negotiations greater than Japan and FSU. The Nash bargaining solution with the GDP weight fails in explaining the actual agreement of reduction rates. The main reason is that the bargaining power of FSU is very low under the GDP rule, while the Kyoto protocol gives FSU a favored outcome of the zero reduction for its participation in the protocol.

In addition to the numerical results, some political events before and after the Kyoto conference seem to support the result of the formal model in this paper. Before the Kyoto conference, EU, Japan and USA made three major proposals with the intention to affect the agreement in the conference in their favorable way.. EU made an early proposal to reduce

15% below 1990 levels by 2010. They also proposed a "bubble" approach that would group all the European nations together in reduction commitments. Japan proposed a 5% reduction claiming to differentiate individual countires based on emissions per GDP, emissions per capita and population. USA proposed that developped countries should reduce their greenhouse gases to 1990 levels by 2008-2012 and that developping countries should participate in emission reductions in a meaningful way. It is conceivable that these proposals increase the bargaining power of the three countries. After the Kyoto conference, the USA led by the new Republican president changed its policy to oppose the Kyoto protocol (March 2001). The deviation of the USA from the Kyoto protocol is indicated by our numerical result that its reduction cost by emissions trading is marginal ($52 million). There is no evidence that USA estimates highly its damage in the failure of negotiations. It is argued that an early commitment to reduce emissions would result in serious harm to the economy of the USA.

Finally, our analysis shows the usefulness of and the limitation of a game theoretic approach to international negotiations on climate change. Game theory enables us to understand strategic conflicts in the international negotiations on emission reduction. On the other hand, if one wants to derive some practical implications from the game theoretic analysis, reliable estimations of model parameters are necessary. In our model, we need to estimate countries' damages in the failure of negotiations on the Kyoto protocol. Although this is not an easy task at all, further empirical studies on international negotiations based on game theoretic models should be done in the future research.

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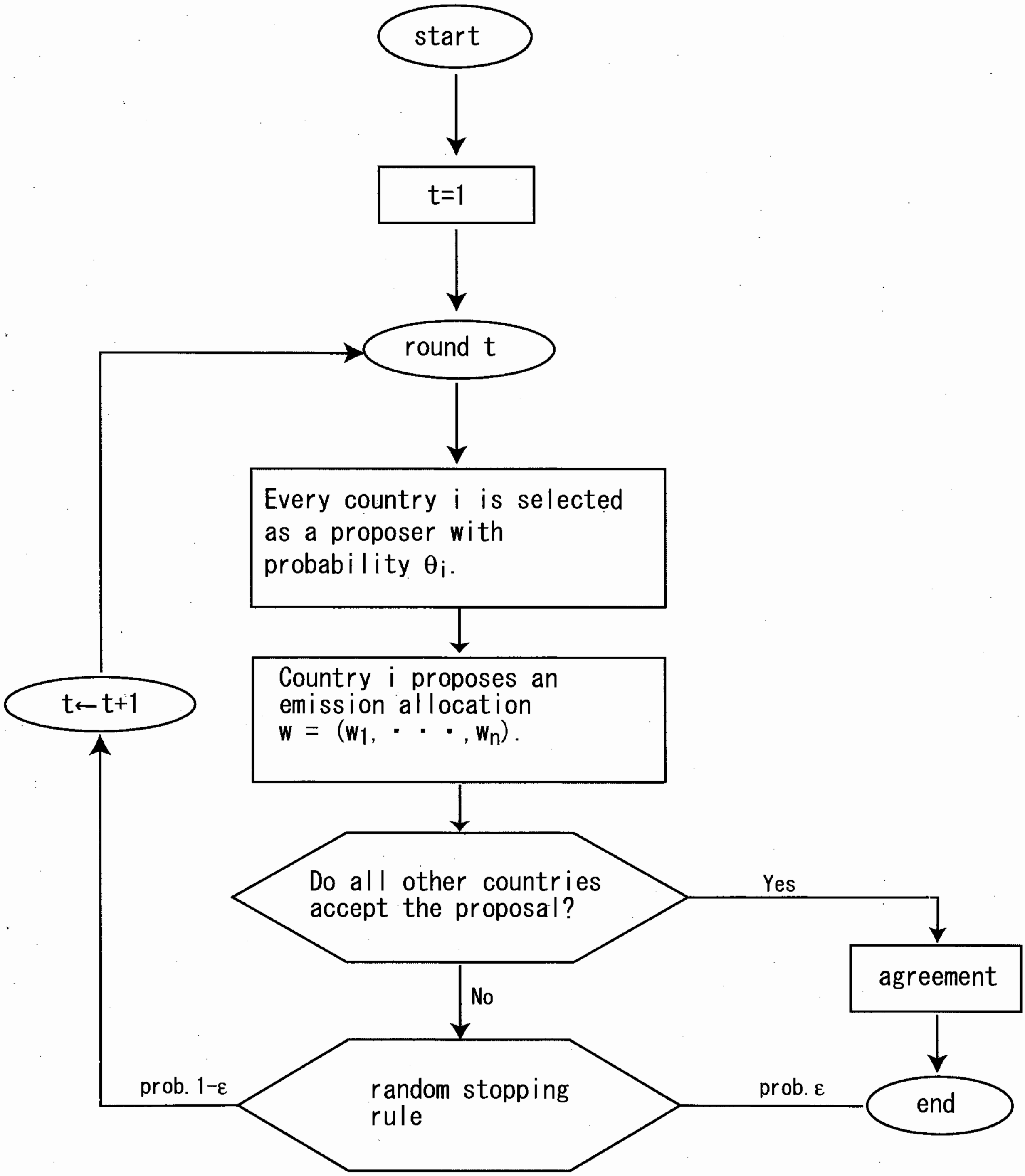

Figure 1. Flowchart of the negotiation process

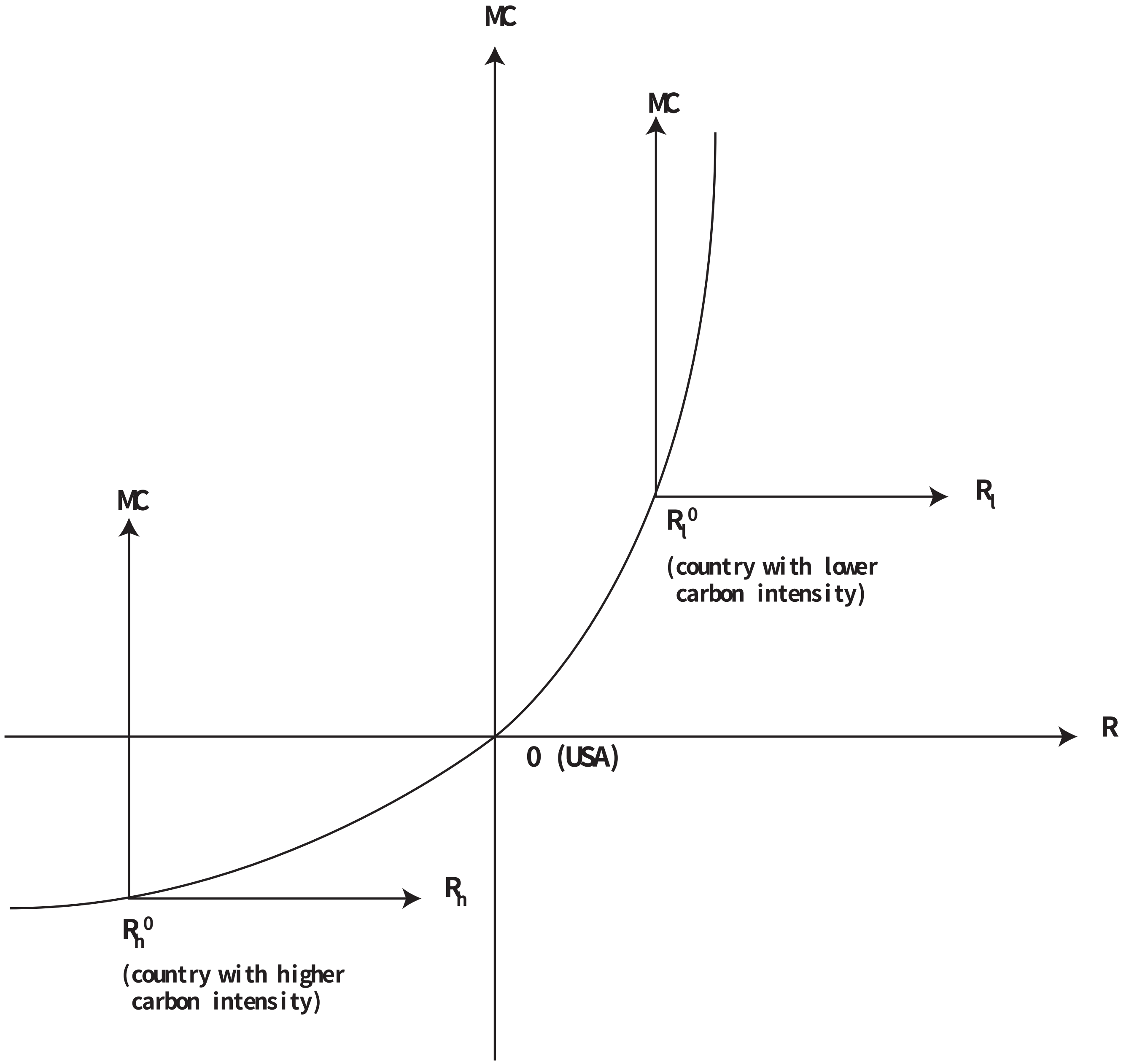

Figure 2. Marginal cost functions of different countries

Country	Carbon Emission	Population	GDP	Carbon intensity
Austria	16	7.72	162	0.1
Belgium	27	9.97	197	0.14
Denmark	14	5.14	133	0.11
Finland	14	4.99	137	0.1
France	99	56.74	1,216	0.08
Germany *)	243	79.37	1,770	0.14
Greece	20	10.09	84	0.24
Ireland	8	3.50	47	0.17
Italy	106	57.66	1,102	0.1
Luxembourg	3	0.38	11	0.27
Netherlands	38	14.95	295	0.13
Portugal	12	9.87	70	0.17
Spain	58	38.96	514	0.11
Sweden	13	8.56	238	0.05
United Kingdom	155	57.56	985	0.16
EU	826	365.46	6,961	0.12
FSU	1011	289.34	1,535	0.66
Japan	292	123.54	2,970	0.098
USA	1315	249.92	5,794	0.23
Total	3444	1028.26	17,260	

Table 1. Data on countries

Carbon Emission Ei: million tons
Population (1990) Ni: million
GDP: 1990 Billion US$

*) Population of Germany includes that of East Germany (GDR). GDP of Germany is for 1991.

country	initial permits (million tons)	reduction rate	reduction (million tons)	reduction costs (million $)
EU	760	0.08	66	991
FSU	1011	0	0	0
Japan	274	0.06	18	251
USA	1223	0.07	92	610
Total	3268		176	1852

Table 2. CO2 Reduction by Kyoto Protocol without Emissions Trading

country	initial permits (million tons)	initial reduction (million tons)	efficient reduction (million tons)	efficient reduction share	equilibrium costs (million $)	saving costs (million $)	permit price ($/ton)
EU	760	66	21.37	0.121	522	469	
FSU	1011	0	82.97	0.471	-398	398	
Japan	274	18	6.25	0.036	141	110	9.45
USA	1223	92	65.42	0.372	558	52	
Total	3268	176	176	1	823	1029	

Table 3. CO_2 Reduction by Kyoto Protocol with Emissions Trading

equal weight				
Total costs in disagreement (million $)	3000	4000	5000	weights
EU	1067	1317	1567	0.33
FSU	146	396	646	0.33
Japan	685	935	1185	0.33
USA	1102	1352	1602	0.33

population weight				
Total costs in disagreement (million $)	3000	4000	5000	weights
EU	1296	1652	2007	0.35
FSU	215	496	777	0.28
Japan	403	523	643	0.12
USA	1087	1331	1574	0.24

GDP weight				
Total costs in disagreement (million $)	3000	4000	5000	weights
EU	1400	1803	2207	0.4
FSU	-205	-116	-27	0.09
Japan	516	688	860	0.17
USA	1289	1625	1960	0.34

Table 4. Possible disagreement points yielding reduction commitments in the Kyoto protocol as the Nash bargaining solution