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WHO WOULD GET GAINS FROM EU'S QUANTITY RESTRAINT ON EMISSIONS TRADING IN THE KYOTO PROTOCOL?

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Who would Get Gains from EU's Quantity Restraint on Emissions Trading in the Kyoto Protocol?[1]

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ABSTRACT

The EU proposal on the quantity restraint of the emissions trading in the Kyoto Protocol aims at reducing so called *hot air* that would be generated by the purchase of emissions permits sold by a country whose actual emissions are much lower than the assigned amount. This proposal allows demanders to choose one out of ten possible quantity restraints, but suppliers have no choice on the restraint. In this paper, we show that no quantity restraint of all demanders is not a subgame perfect equilibrium, but quantity restraints with at least one country constitute the equilibria. Furthermore, the EU proposal certainly benefits demanders including EU with the sacrifice of suppliers.

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1. Introduction

The Kyoto Protocol to the Climate Convention in December 1997 requires that Annex B Parties under the Protocol (that is, advanced countries and countries that are undergoing the process of transition to a market economy) do not exceed their assigned amounts, calculated pursuant to their quantified emission limitation and reduction commitments. In order to implement this goal, it authorizes three major mechanisms called the Kyoto mechanism. These are emissions trading, joint implementation and the Clean Development Mechanism (CDM). However, we must design the details of these mechanisms as almost no details are given in the Protocol. The Fourth Conference of Parties at Buenos Aires in November 1998 following the Kyoto Conference adopted a "Plan of Action," but this plan is a timetable regarding what should be argued when, and hence no details of the protocol are given. Although the Fifth Conference of Parties at Bonn in November 1999 unofficially called for the ratification of the protocol by 2002, the details of the mechanisms will be determined at Hague on November, 2000.

One of the central issues in the Kyoto Protocol has been supplementarity of the Kyoto mechanism to domestic actions in reducing Greenhouse Gas (GHG) emissions. The European Community and several countries have been proposing quantitative constraints on the usage of three mechanisms. Specifically, the European Union Council of Ministers agreed on recommendations on definitions for supplementarity for the Kyoto Protocol on May 18, 1999, and EU proposed this new formula during the tenth sessions of the Subsidiary Bodies held at Bonn from May 31 to June 11, 1999 (see Council Conclusions on a Community Strategy on Climate Change (1999)): Net acquisitions by an Annex B Party for all three Kyoto mechanisms together must not exceed the higher of the two following alternatives:

(1) 5% of : $\dfrac{\text{its base year emissions multiplied by 5 plus its assigned amount}}{2}$; or

(2) 50% of: the difference between its annual actual emissions in any year of the period from 1994 to 2002, multiplied by 5, and its assigned amount.

Net transfers by an Annex B Party for all three Kyoto mechanisms together must not exceed (1).

Consider an example. Assume that a country emitted 100 units of GHGs in 1990, and assume further that the country's assigned amount is 94% per year of the emissions in 1990. By using formula (1), we have $\{(100 \times 5 + 94 \times 5) / 2\} \times 0.05 = 24.25$. That is, the country can rely on the Kyoto mechanism up to 24.25 units of acquisitions from the year of 2008 to 2012. Next, consider annual actual emissions from 1994 to 2002. There must be nine numbers. Suppose that annual actual emissions in 1999 are 124 units. Applying (2), we obtain $(124 \times 5 - 94 \times 5) \times 0.5 = 75$. That is, the country can acquire up to 75 units from 2008 to 2012. Thus, the country can choose one number out of ten numbers from formulas (1) and (2). The EU proposal says that the number is the upper limit of acquisitions of the country. On the other hand, if the country wants to become a supplier, then the maximum transfers must not exceed the quantity obtained by formula (1).

The EU proposal opens up two important strategic behaviors on the quantity restraints in Annex B countries. First, since a country that acquires emissions permits and credits can choose her own upper limit out of possible ten numbers, the choice itself is a strategy. Second, since a country can choose a number that has not yet realized, if the country wants to extend the upper limit, she would ban on the production of GHGs in 2001, and then cancel it at the beginning of 2002. By this way, the upper limit would be relaxed. On the other hand, because a country that supplies emissions permits and credits has just one upper limit, she cannot use the limit as a strategic variable.

Although the EU proposal put quantitative constraints to all three mechanisms, the applicability of supplementarity to all of them is doubtful. The Kyoto Protocol clearly states that both joint implementation and emissions trading are supplemental to domestic actions (Articles 6 and 17). However, there is no explicit statement on supplementarity for CDM (Article 12). Therefore, we do not impose any quantity restraint on the supply accruing from CDM in this paper.

Baron, Bosi, Lanza and Pershing (1999) are the initiators analyzing the proposal assuming that each country chooses the highest number among ten possibilities. Further, Kaino (1999) evaluates supplementarity in the Kyoto Protocol and then proposes some numerical simulation of the proposal. In this paper, we focus upon the *strategic* nature of the proposal. Specifically, we examine how the quantity restraints in the EU proposal affect on the total trading quantity of emissions permits, the price of emissions permits, and the payoffs of demanders and a supplier, by using a simple game-theoretic model. We find that each demander has a strong incentive to choose a quantity restraint in the following two-stage game. In the first stage, each demander simultaneously chooses whether or not she chooses a quantity restraint. In the second stage, the demanders that decided to choose quantity restraints simultaneously select their levels of quantity restraints, knowing the other demanders' quantity restraint decisions in the first stage. Then emissions trades occur: the quantities of all countries and the price are determined so that quantity demanded is equal to quantity supplied in a competitive emissions trading market.

We show that no quantity restraint of all demanders is not a subgame perfect equilibrium of the above two-stage game. Rather, at least one demander always puts a restraint as a subgame perfect strategy. On the other hand, the quantity restraints by demanders have a negative impact on the supplier. As the number of demanders choosing quantity restraints increases, the profit of supplier decreases, since the total trading quantity and the price decrease. Although achieving the goal of the EU proposal is uncertain, it certainly benefits demanders including EU with the sacrifice of suppliers such as countries in transition to a market economy and developing countries.

The paper is organized as follows. Section 2 investigates the basic model without CDM or supplier's quantity restraint. Section 3 introduces a more general model with CDM and supplier's quantity restraint. For both models, we examine the effects of quantity restraints of demanders on the total trading quantity, price, and the payoff of a supplier as well as the payoffs of demanders. Section 4 discusses the future agenda.

2. The basic model without CDM or supplier's quantity restraint.

Consider three countries, indexed by 0, 1, and 2.[1] We assume that the marginal abatement cost (MAC) curve of each country is linear, as illustrated in Figure 1 in which the horizontal axis denotes the quantity of emissions and the vertical axis represents the marginal abatement cost. The vertical dotted line indicates the goal amount assigned to each country by the Kyoto Protocol. We assume that countries 1 and 2 have the same MAC curve and the same assigned amount.

Figure 1 is around here.

In order to analyze the emissions trading market, it is convenient to superimpose Figures 1-1 and 1-2 of the MAC curves such that the assigned amount of every country is equal to the origin of the superimposed figure. See Figure 2.

Figure 2 is around here.

We denote the MAC curve of each country *i* in the superimposed figure by $MAC_i(x_i) = a_i - (a_i / b_i)x_i$, $i = 0,1,2$, where x_i is the difference between country *i*'s quantity of emissions and its assigned amount. Since countries 1 and 2 have the same MAC curve and the same assigned amount,

(A1) $a_1 = a_2$ and $b_1 = b_2$.

We also assume that

(A2) $a_1 > a_0 > 0$, $b_1 > 0$, and $b_0 > 0$.

[1] Throughout the paper, we focus on the case of three countries, one supplier and two demanders. However, it is easy to show that our main results hold in a more general case in which there are *n* demanders.

(A2) means that (i) $a_i / b_i > 0$, that is, the marginal cost to abate emissions increases as the quantity of emissions decreases; and (ii) the MAC curve of country 0 is below that of country 1 or 2 around $x_i = 0$, although the MAC curve of country 0 could intersect that of country 1 or 2, because of no assumption on the relation between their slopes, a_0 / b_0 and a_1 / b_1.

Since the MAC curve of country 0 is below that of country 1 or 2 around $x_i = 0$, country 0 is a supplier ($x_0 < 0$), while countries 1 and 2 are demanders ($x_1 > 0, x_2 > 0$) in the competitive emissions trading market, as Figure 2 shows. The competitive equilibrium price is $p(\varnothing)$ at which the total quantity demanded is equal to the quantity supplied.[2] The amount of emissions permits that each country $i \in \{1,2\}$ buys from country 0 at $p(\varnothing)$ is $x_i(\varnothing)$. Because countries 1 and 2 have the same MAC curve, $x_1(\varnothing) = x_2(\varnothing)$. The total amount of emissions permits that country 0 sells to countries 1 and 2 at $p(\varnothing)$ is $x_1(\varnothing) + x_2(\varnothing)$. The marginal abatement cost of each country is equal to the price $p(\varnothing)$.

The area of the triangle $a_1 p(\varnothing) e$ represents the surplus of each demander by emissions trading (abusing notation, we use a_i, b_i, and $p(\varnothing)$ to represent points on the two-dimensional space, although they themselves are real numbers.) For example, suppose that b_1 is the status quo of country $i \in \{1,2\}$. Then the area of the triangle $a_1 0 b_1$ denotes the abatement cost of country i to achieve the goal ($x_i = 0$) without emissions trading. On the other hand, with emissions trading, the cost to buy $x_i(\varnothing)$ of emissions permits from country 0 at the price $p(\varnothing)$ is equal to the area of the rectangular $p(\varnothing)0x_i(\varnothing)e$, and the domestic cost of country i to reduce ($b_1 - x_i(\varnothing)$) of emissions is equal to the area of the triangle $ex_i(\varnothing)b_1$. Therefore, the area of the trapezoid $p(\varnothing)0b_1e$ stands for the total abatement cost with emissions trading. The difference between the abatement cost without emissions trading and that with emissions trading is the surplus of each demander by emissions trading, which is equal to the area of the triangle $a_1p(\varnothing)e$.

Moreover, the area of the triangle $fa_0p(\varnothing)$ denotes the surplus of the supplier by emissions trading. For example, suppose that b_0 is the status quo of country 0. Then the area of the triangle $a_0 0 b_0$ stands for the abatement cost of country 0 to achieve the goal ($x_0 = 0$) without emissions trading. On the other hand, with emissions trading, if country 0 reduces $x_1(\varnothing) + x_2(\varnothing)$ of emissions in addition to the assigned amount, then she can sell $x_i(\varnothing)$ of emissions permits to each country $i \in \{1,2\}$. In comparison to the case in which country 0 reduces emissions to the assigned amount without emissions trading, the additional cost is equal to the area of the trapezoid $f(-[x_1(\varnothing) + x_2(\varnothing)])0a_0$. If country 0 sells $x_1(\varnothing) + x_2(\varnothing)$ of emissions permits at the price $p(\varnothing)$, then the surplus of country 0 by emissions trading is equal to the area of the triangle $fa_0p(\varnothing)$. Notice that the surplus of each country is independent of its status quo.

We ask whether a demander has an incentive to choose a restraint on the trading quantity of emissions permits. In an attempt to examine this question, we consider the following two-stage game (see Figure 3). In the first stage, each country

[2] In the following, we will analyze the situation in which each demander chooses a restraint on the trading quantity of emissions permits. The symbol ∅ represents the case in which no country selects a quantity restraint.

$i \in \{1,2\}$ simultaneously chooses whether or not she chooses a quantity restraint. In the second stage, the countries that decided to choose quantity restraints simultaneously select their levels of quantity restraints, knowing the other countries' quantity restraint decisions in the first stage. Then emissions trades occur: the quantities of all countries and the price are determined so that the quantity demanded is equal to the quantity supplied. In other words, we assume that the emissions trading market is competitive.[3]

Figure 3 is around here.

We will derive the unique subgame perfect equilibrium of this game. Let $R \subseteq \{1,2\}$ be the countries that decide to choose quantity restraints in the first stage. Also, let $x_i(R)$ be the equilibrium quantity of country $i \in \{1,2\}$, $p(R)$ be the equilibrium price, and $\pi_i(R)$ be the equilibrium payoff (surplus) of country $i \in \{1,2\}$ when the countries belonging in R choose quantity restraints. There are three cases to consider.

Case 1: $R = \varnothing$ (the case of no quantity restraint)

As we see in the above, Figure 2 illustrates the equilibrium quantities and the price for this case. We can compute them by solving the following simultaneous equations: $-x_0 = x_1 + x_2$ (the quantity demanded is equal to the quantity supplied), $p = a_0 - (a_0 / b_0)x_0$, $p = a_1 - (a_1 / b_1)x_1$, and $p = a_1 - (a_1 / b_1)x_2$ (the price is equal to the marginal abatement cost of each country). The equilibrium values are give by

(1) $x_1(\varnothing) = x_2(\varnothing) = \dfrac{b_0 b_1 (a_1 - a_0)}{a_1 b_0 + 2a_0 b_1}$,

[3] Our two-stage model seems to be artificial, but we can clearly compare the results for all possible cases of quantity restraint choices and can analyze the incentive problem on quantity restraints by using this

(2) $p(\varnothing)=\dfrac{a_0 a_1(b_0+2b_1)}{a_1 b_0+2a_0 b_1}$, and

(3) $\pi_1(\varnothing)=\pi_2(\varnothing)=\dfrac{1}{2}(a_1-p(\varnothing))x_1(\varnothing)=\dfrac{a_1}{2b_1}(x_1(\varnothing))^2=\dfrac{a_1 b_0^2 b_1(a_1-a_0)^2}{2(a_1 b_0+2a_0 b_1)^2}$.

It is straightforward to check that the equilibrium values are strictly positive under Assumption (A2).

Case 2: $R=\{1,2\}$ (the case in which both countries 1 and 2 choose quantity restraints)

Figure 2 illustrates the equilibrium values for Case 2. Suppose that each country $i\in\{1,2\}$ sets her quantity restraint level at $x_i(\{1,2\})$, and she buys that amount of emissions permits from country 0. Then at the price $p(\{1,2\})$, the total quantity demanded is equal to the quantity supplied. The total amount of emissions permits that country 0 sells at $p(\{1,2\})$ is $x_1(\{1,2\})+x_2(\{1,2\})$. The marginal abatement cost of country 0 is equal to $p(\{1,2\})$. The area of the trapezoid $a_1 p(\{1,2\})gh$ represents the payoff of each country $i\in\{1,2\}$, $\pi_i(\{1,2\})$.

We assume that each country $i\in\{1,2\}$ selects its quantity restraint level in order to maximize its own payoff, given the quantity restraint level of the other country. We can compute the unique Nash equilibrium as follows. The payoff of country $i\in\{1,2\}$ is given by

$$\pi_i=\frac{1}{2}(a_1-p+MAC_i(x_i)-p)x_i,$$

where $p=a_0-(a_0/b_0)x_0$ (the price is equal to the abatement cost of country 0), $-x_0=x_1+x_2$ (the quantity demanded is equal to the quantity supplied), and

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model.

$MAC_i(x_i) = a_1 - (a_1 / b_1)x_i$.

By using these equations, we obtain

$$\pi_i = \frac{1}{2}\left[2(a_1 - a_0) - \frac{a_1 b_0 + 2a_0 b_1}{b_0 b_1} x_i - \frac{2a_0}{b_0} x_j\right] x_i \ \ (i, j = 1,2; j \neq i).$$

Given x_j, each country $i \in \{1,2\}$ chooses x_i so as to maximize π_i. The first order condition is given by

$$\frac{\partial \pi_i}{\partial x_i} = (a_1 - a_0) - \frac{a_1 b_0 + 2a_0 b_1}{b_0 b_1} x_i - \frac{a_0}{b_0} x_j = 0 \ \ (i, j = 1,2; j \neq i).$$

From these simultaneous equations, we obtain

(4) $x_1(\{1,2\}) = x_2(\{1,2\}) = \dfrac{b_0 b_1 (a_1 - a_0)}{a_1 b_0 + 3a_0 b_1}$,

(5) $p(\{1,2\}) = \dfrac{a_0\{a_1(b_0 + 2b_1) + a_0 b_1\}}{a_1 b_0 + 3a_0 b_1}$,

(6) $\pi_1(\{1,2\}) = \pi_2(\{1,2\}) = \dfrac{a_1 b_0 + 2a_0 b_1}{2b_0 b_1}(x_1(\{1,2\}))^2 = \dfrac{b_0 b_1 (a_1 b_0 + 2a_0 b_1)(a_1 - a_0)^2}{2(a_1 b_0 + 3a_0 b_1)^2}$.

It is straightforward to check that the equilibrium values are strictly positive under Assumption (A2).

Case 3: $R = \{i\}$ (the case in which only one demander i chooses a quantity restraint)

Figure 2 illustrates the equilibrium values for Case 3. Suppose that country i sets her quantity restraint level at $x_i(\{i\})$, and she buys that amount of emissions permits from country 0. Then at the price $p(\{i\})$, the total quantity demanded is equal to the quantity supplied. The amount of emissions permits that country $j \neq i$ buys from country 0 at $p(\{i\})$ is $x_j(\{i\})$. The total amount of emissions permits that country 0 sells at $p(\{i\})$ is $x_i(\{i\}) + x_j(\{i\})$. Both the marginal abatement cost of country 0 and that of country j are equal to the price $p(\{i\})$. The area of the trapezoid $a_1 p(\{i\})\ell h$ represents the payoff of country i, $\pi_i(\{i\})$. The area of the triangle $a_1 p(\{i\}) m$ represents the equilibrium payoff of country j, $\pi_j(\{i\})$.

We assume that country i selects her quantity restraint level in order to maximize her own payoff. We can compute the unique optimal quantity restraint level of country i as follows. The payoff of i is given by

$$\pi_i = \frac{1}{2}(a_1 - p + MAC_i(x_i) - p)x_i,$$

where $p = a_0 - (a_0 / b_0)x_0$, $p = a_1 - (a_1 / b_1)x_j$, $j \neq i$ (the price is equal to both the abatement cost of country 0 and that of country $j \neq i$), $-x_0 = x_1 + x_2$ (the quantity demanded is equal to the quantity supplied), and $MAC_i(x_i) = a_1 - (a_1 / b_1)x_i$.

By using these equations, we obtain

$$x_j = \frac{b_0 b_1}{a_1 b_0 + a_0 b_1}\left[(a_1 - a_0) - \frac{a_0}{b_0}x_i\right],\ j \neq i, \text{ and}$$

$$\pi_i = \frac{a_1}{2[a_1 b_0 + a_0 b_1]}\left[2b_0(a_1 - a_0) - \frac{a_1 b_0 + 3a_0 b_1}{b_1}x_i\right]x_i.$$

Country i chooses x_i so as to maximize π_i. The first order condition is given by

$$\frac{\partial \pi_i}{\partial x_i} = \frac{a_1}{2[a_1 b_0 + a_0 b_1]}\left[2b_0(a_1 - a_0) - \frac{2[a_1 b_0 + 3a_0 b_1]}{b_1}x_i\right] = 0.$$

From this equation, we have

(7) $$x_i(\{i\}) = \frac{b_0 b_1 (a_1 - a_0)}{a_1 b_0 + 3a_0 b_1},$$

(8) $$x_j(\{i\}) = \frac{b_0 b_1 (a_1 - a_0)(a_1 b_0 + 2a_0 b_1)}{(a_1 b_0 + 3a_0 b_1)(a_1 b_0 + a_0 b_1)},\ j \neq i$$

(9) $p(\{i\}) = \dfrac{a_0 a_1[b_1(2a_1b_0 + 3a_0b_1) + b_0(a_1b_0 + 2a_0b_1)]}{(a_1b_0 + 3a_0b_1)(a_1b_0 + a_0b_1)}$,

(10) $\pi_i(\{i\}) = \dfrac{a_1(a_1b_0 + 3a_0b_1)}{2b_1(a_1b_0 + a_0b_1)}(x_i(\{i\}))^2 = \dfrac{a_1b_0^2b_1(a_1 - a_0)^2}{2(a_1b_0 + a_0b_1)(a_1b_0 + 3a_0b_1)}$, and

(11) $\pi_j(\{i\}) = \dfrac{1}{2}(a_1 - p(\{i\}))x_j(\{i\}) = \dfrac{a_1}{2b_1}(x_j(\{i\}))^2 = \dfrac{a_1b_0^2b_1(a_1 - a_0)^2(a_1b_0 + 2a_0b_1)^2}{2(a_1b_0 + a_0b_1)^2(a_1b_0 + 3a_0b_1)^2}$, $j \neq i$.

It is straightforward to check that the equilibrium values are strictly positive under Assumption (A2). [4]

Let $\pi_0(R) = -\dfrac{1}{2}(p(R) - a_0)x_0(R) = \dfrac{1}{2}(p(R) - a_0)[x_1(R) + x_2(R)]$ be the equilibrium payoff of country 0. We have the following result on the total equilibrium trading quantity, the equilibrium price, and the equilibrium payoff of country 0.

Theorem 1. *For* $i = 1,2$, $x_1(\varnothing) + x_2(\varnothing) > x_1(\{i\}) + x_2(\{i\}) > x_1(\{1,2\}) + x_2(\{1,2\}) > 0$, $p(\varnothing) > p(\{i\}) > p(\{1,2\}) > a_0$, and $\pi_0(\varnothing) > \pi_0(\{i\}) > \pi_0(\{1,2\}) > 0$.

Proof of Theorem 1: By (1), (4), (7), and (8),

$x_1(R) + x_2(R) = \dfrac{b_0b_1(a_1 - a_0)[2a_1b_0 + 3(2 - r)a_0b_1]}{[a_1b_0 + 3a_0b_1][a_1b_0 + (2 - r)a_0b_1]} > 0$ for all $R \subseteq \{1,2\}$, where $r = |R|$. By partially differentiating this with respect to *r*, we obtain

$$\frac{\partial[x_1(R) + x_2(R)]}{\partial r} = -\frac{a_0a_1b_0^2b_1^2(a_1 - a_0)}{[a_1b_0 + 3a_0b_1][a_1b_0 + (2 - r)a_0b_1]^2} < 0,$$

implying that $x_1(\varnothing) + x_2(\varnothing) > x_1(\{i\}) + x_2(\{i\}) > x_1(\{1,2\}) + x_2(\{1,2\})$. It follows from this relation that $p(\varnothing) > p(\{i\}) > p(\{1,2\}) > a_0$ and $\pi_0(\varnothing) > \pi_0(\{i\}) > \pi_0(\{1,2\})$. ■

[4] Note that $x_i(\{i\}) = x_i(\{1,2\})$, that is, the quantity restraint level when only one country choose a restraint is equal to that when two countries choose restraints in our simple linear model.

Figure 2 illustrates the results of Theorem 1. As the number of demanders choosing quantity restraints increases, the total trading quantity, the price, and the profit of the supplier decrease.

Concerning the equilibrium payoffs of two demanders, we have the following relations.

Theorem 2. *For* $i, j \in \{1,2\}$, $i \neq j$, $\pi_j(\{1,2\}) > \pi_j(\{i\}) > \pi_j(\{j\}) > \pi_j(\varnothing)$.

Proof of Theorem 2: First of all, by (6) and (11), we have

$$\pi_j(\{1,2\}) - \pi_j(\{i\}) = \frac{a_0^2 b_0 b_1^3 (a_1 b_0 + 2a_0 b_1)(a_1 - a_0)^2}{2(a_1 b_0 + a_0 b_1)^2 (a_1 b_0 + 3a_0 b_1)^2} > 0,\ i, j \in \{1,2\},\ i \neq j.$$

Second, by (10) and (11), we obtain

$$\pi_j(\{i\}) - \pi_j(\{j\}) = \frac{a_0^2 a_1 b_0^2 b_1^3 (a_1 - a_0)^2}{2(a_1 b_0 + a_0 b_1)^2 (a_1 b_0 + 3a_0 b_1)^2} > 0,\ i, j \in \{1,2\},\ i \neq j.$$

Third, by (3) and (10), we have

$$\pi_j(\{j\}) - \pi_j(\varnothing) = \frac{a_0^2 a_1 b_0^2 b_1^3 (a_1 - a_0)^2}{2(a_1 b_0 + a_0 b_1)(a_1 b_0 + 3a_0 b_1)(a_1 b_0 + 2a_0 b_1)^2} > 0,\ j \in \{1,2\}.\ \blacksquare$$

Figure 2 illustrates the results of Theorem 2. Since $\alpha + \beta < \delta$, the area of the trapezoid $a_1 p(\{1,2\}) g h$ is larger than the area of the triangle $a_1 p(\{i\}) m$, that is, $\pi_j(\{1,2\}) > \pi_j(\{i\})$. Also, it is clear that the area of the triangle $a_1 p(\{i\}) m$ is larger than the area of the trapezoid $a_1 p(\{i\}) \ell h$, that is, $\pi_j(\{i\}) > \pi_i(\{i\}) = \pi_j(\{j\})$. Further, since $\alpha < \gamma$, the area of the trapezoid $a_1 p(\{i\}) \ell h$ is larger than the area of the triangle

$a_1 p(\varnothing)e$, that is, $\pi_i(\{i\}) > \pi_i(\varnothing)$, $i \in \{1,2\}$.

Table 1 is the payoff matrix for the first stage decisions on quantity restraints. For each country, deciding to choose a quantity restraint in the first stage is a dominant strategy, since the payoff with choosing a quantity restraint is larger than that without it, regardless of whether the other country chooses a quantity restraint.

Table 1 is around here.

To sum up, at the unique subgame perfect equilibrium of the two-stage game, each country decides to choose a quantity restraint at the first stage, she sets her restraint level at that specified in (4) at the second stage, and then she buys that amount of emissions permits from country 0.

Finally, we compare the total equilibrium surpluses.

Theorem 3. $\sum_{\ell=0}^{2}\pi_\ell(\{1,2\}) < \sum_{\ell=0}^{2}\pi_\ell(\{i\}) < \sum_{\ell=0}^{2}\pi_\ell(\varnothing)$, $i = 1,2$.

Proof of Theorem 3: By using (1), (2), (4), (5), (7), (8), and (9), we have

$$\pi_0(\varnothing) = \frac{1}{2}(p(\varnothing) - a_0)[x_1(\varnothing) + x_2(\varnothing)] = \frac{2a_0 b_0 b_1^2 (a_1 - a_0)^2}{(a_1 b_0 + 2a_0 b_1)^2},$$

$$\pi_0(\{1,2\}) = \frac{1}{2}(p(\{1,2\}) - a_0)[x_1(\{1,2\}) + x_2(\{1,2\})] = \frac{2a_0 b_0 b_1^2 (a_1 - a_0)^2}{(a_1 b_0 + 3a_0 b_1)^2}, \text{ and}$$

$$\pi_0(\{i\}) = \frac{1}{2}(p(\{i\}) - a_0)[x_1(\{i\}) + x_2(\{i\})] = \frac{a_0 b_0 b_1^2 (a_1 - a_0)^2 (2a_1 b_0 + 3a_0 b_1)^2}{2(a_1 b_0 + a_0 b_1)^2 (a_1 b_0 + 3a_0 b_1)^2}.$$

It is easy to obtain from (3), (6), (10), (11), and the above equations that

$$\sum_{\ell=0}^{2}\pi_\ell(\varnothing)=\frac{b_0b_1(a_1-a_0)^2}{a_1b_0+2a_0b_1},$$

$$\sum_{\ell=0}^{2}\pi_\ell(\{1,2\})=\frac{b_0b_1(a_1b_0+4a_0b_1)(a_1-a_0)^2}{(a_1b_0+3a_0b_1)^2}, \text{ and}$$

$$\sum_{\ell=0}^{2}\pi_\ell(\{i\})=\frac{b_0b_1(a_1-a_0)^2\left\{a_0b_1(2a_1b_0+3a_0b_1)^2+a_1b_0[(a_1b_0+a_0b_1)(a_1b_0+3a_0b_1)+(a_1b_0+2a_0b_1)^2]\right\}}{2(a_1b_0+a_0b_1)^2(a_1b_0+3a_0b_1)^2}$$

By comparing these values, we have

$$\sum_{\ell=0}^{2}\pi_\ell(\{i\})-\sum_{\ell=0}^{2}\pi_\ell(\{1,2\})=\frac{a_0^2b_0b_1^3(a_1b_0+a_0b_1)(a_1-a_0)^2}{2(a_1b_0+a_0b_1)^2(a_1b_0+3a_0b_1)^2}>0 \text{ and}$$

$$\sum_{\ell=0}^{2}\pi_\ell(\varnothing)-\sum_{\ell=0}^{2}\pi_\ell(\{i\})=\frac{a_0^2a_1b_0^2b_1^3(a_1b_0+a_0b_1)(a_1-a_0)^2}{2(a_1b_0+2a_0b_1)(a_1b_0+a_0b_1)^2(a_1b_0+3a_0b_1)^2}>0. \blacksquare$$

Theorem 3 says that as the number of demanders choosing quantity restraints increases, the total surplus, defined as the sum of the payoffs of all three countries, decreases. Therefore, the equilibrium outcome in which two countries select quantity restraints is not efficient.

3. The model with CDM and supplier's quantity restraint.

In this section, we introduce the Clean Development Mechanism (CDM) and supplier's quantity restraint. There are three countries, indexed by 0, 1, and 2. As before, country 0 is a supplier and countries 1 and 2 are demanders in the emissions trading market. The MAC curves of countries 1 and 2 are the same and they are given by $MAC_i(x_i)=a_1-(a_1/b_1)x_i$, $i=1,2$. The MAC curve of country 0 is given by

(12) $MAC_0(x_0)=a_0-(a_0/b_0)x_0$.

We assume that country 0 puts a quantity restraint level on the emission trading, although the restraint level is given exogenously and county 0 has no choice, as stated in the EU proposal. Denote the quantity restraint level of country 0 by x_0^R. The MAC curve of CDM is given by

(13) $MAC_0^{CDM}(x_0) = a_0 - (a_0 / d_0)x_0$

for $x_0 \leq 0$. Since it is uncertain which is cheaper between the marginal abatement cost of the cheapest CDM project and the minimum marginal abatement cost in Annex B parties, we use the common intercept a_0 in (13) and in the supplier's MAC curve in (12). Figure 4 illustrates these MAC curves.

Figure 4 is around here.

We assume

(A3) $a_1 > a_0 > 0$, $b_1 > 0$, and $d_0 > b_0 > 0$.

(A3) means that the MAC curve of country 0 is below the MAC curves of countries 1 and 2 around $x_i = 0$, while it is always above the MAC curve of CDM. By (12) and (13), the constrained aggregate MAC curve of country 0 is given by

(14) $AMAC_0(x_0) = \begin{cases} a_0 - [a_0 / (b_0 + d_0)]x_0 & \text{if } -(b_0 + d_0)x_0^R / b_0 \leq x_0 \leq 0 \\ a_0(d_0 - x_0^R) / d_0 - (a_0 / d_0)x_0 & \text{if } x_0 < -(b_0 + d_0)x_0^R / b_0 \end{cases}$,

provided that $x_0 \leq 0$.

Consider the same two-stage game on quantity restraints as that examined in the previous section. The equilibrium quantities, price, and payoffs are given in Tables 2, 3, and 4. See the appendix for the derivations of the equilibrium values. It is easy to check that the equilibrium values are strictly positive under Assumption (A3).

Tables 2, 3, and 4 are around here.

The equilibrium quantities change, depending crucially on the quantity restraint level of country 0, x_0^R. Fix the values of the parameters a_0, a_1, b_0, b_1, and d_0. We will see that the point $(-x_1 - x_2, p)$, indicating the pair of the total equilibrium quantity and the equilibrium price, lies on the first segment of the constrained aggregate MAC curve for a sufficiently large value of x_0^R, while it lies on the second segment of the curve for a sufficiently small value of x_0^R. First, for the case in which neither country 1 nor 2 chooses a quantity restraint, the crucial value of x_0^R is $A(\varnothing)$ (see the second column in Table 2). If x_0^R is larger than $A(\varnothing)$, then the equilibrium quantities, $x_1(\varnothing)$ and $x_2(\varnothing)$, are constant and the total equilibrium quantity, $x_1(\varnothing) + x_2(\varnothing)$, is less than $(b_0 + d_0)x_0^R / b_0$ in which the constrained aggregate MAC curve is kinked. As Figure 5-1 illustrates, the point $(-x_1(\varnothing) - x_2(\varnothing), p(\varnothing))$ lies on the first segment of the curve. Also, if $x_0^R = A(\varnothing)$, then $x_1(\varnothing) + x_2(\varnothing) = (b_0 + d_0)x_0^R / b_0$ and the point $(-x_1(\varnothing) - x_2(\varnothing), p(\varnothing))$ coincides with the kink point of the curve. Moreover, if $x_0^R < A(\varnothing)$, then $x_1(\varnothing)$ and $x_2(\varnothing)$ decrease as the value of x_0^R decreases, and $x_1(\varnothing) + x_2(\varnothing) > (b_0 + d_0)x_0^R / b_0$. The point $(-x_1(\varnothing) - x_2(\varnothing), p(\varnothing))$ lies on the second segment of the curve, as Figures 5-2, 5-3, 5-4, 5-5, and 5-6 illustrate.

Figure 5-a and 5-b are around here.

Second, for the case in which only one country *i* chooses a quantity restraint, there are two crucial values of x_0^R, $A(\{i\})$ and $B(\{i\})$ (see the third and fourth columns in Table 2). If $x_0^R > A(\{i\})$, then the equilibrium quantities, $x_i(\{i\})$ and $x_j(\{i\})$, are constant and $x_i(\{i\}) + x_j(\{i\}) < (b_0 + d_0)x_0^R / b_0$. The point $(-x_i(\{i\}) - x_j(\{i\}), p(\{i\}))$ lies on the first segment of the constrained aggregate MAC curve, as Figures 5-1 and 5-2 illustrate. Also, if $B(\{i\}) \le x_0^R \le A(\{i\})$, then the equilibrium quantity of country *i*, $x_i(\{i\})$ (country *j*, $x_j(\{i\})$) decreases (increases) as the value of x_0^R decreases and $x_i(\{i\}) + x_j(\{i\}) = (b_0 + d_0)x_0^R / b_0$. The point $(-x_i(\{i\}) - x_j(\{i\}), p(\{i\}))$ coincides with the kink point of the curve, as Figure 5-3 illustrates. Notice that this corner solution case always happens for any value of $x_0^R \in [B(\{i\}), A(\{i\})]$. Moreover, if $B(\{i\}) > x_0^R$, then both $x_i(\{i\})$ and $x_j(\{i\})$ decrease as the value of x_0^R decreases, and $x_i(\{i\}) + x_j(\{i\}) > (b_0 + d_0)x_0^R / b_0$. The point $(-x_i(\{i\}) - x_j(\{i\}), p(\{i\}))$ lies on the second segment of the curve, as Figures 5-4, 5-5, and 5-6 illustrate.

Finally, for the case in which both countries 1 and 2 choose quantity restraints, there are two crucial values of x_0^R, $A(\{1,2\})$ and $B(\{1,2\})$ (see the fifth column in Table 2). If $x_0^R > A(\{1,2\})$, then the equilibrium quantities, $x_1(\{1,2\})$ and $x_2(\{1,2\})$, are constant and $(b_0 + d_0)x_0^R / b_0 > x_1(\{1,2\}) + x_2(\{1,2\})$. The point $(-x_1(\{1,2\}) - x_2(\{1,2\}), p(\{1,2\}))$ lies on the first segment of the constrained aggregate MAC curve, as Figures 5-1, 5-2, 5-3, and 5-4 illustrate. Also, if $B(\{1,2\}) \le x_0^R \le A(\{1,2\})$, then $x_1(\{1,2\})$ and $x_2(\{1,2\})$ decrease as the value of x_0^R decreases and $x_1(\{1,2\}) + x_2(\{1,2\}) = (b_0 + d_0)x_0^R / b_0$. The point $(-x_1(\{1,2\}) - x_2(\{1,2\}), p(\{1,2\}))$

coincides with the kink point of the curve, as Figure 5-5 illustrates. Notice again that this corner solution case always happens for any value of $x_0^R \in [B(\{1,2\}), A(\{1,2\})]$. Moreover, if $B(\{1,2\}) > x_0^R$, then $x_1(\{1,2\})$ and $x_2(\{1,2\})$ decrease as the value of x_0^R decreases and $x_1(\{1,2\}) + x_2(\{1,2\}) > (b_0 + d_0)x_0^R / b_0$. The point $(-x_1(\{1,2\}) - x_2(\{1,2\}), p(\{1,2\}))$ lies on the second segment of the curve, as Figure 5-6 illustrates.

The results of Theorem 1 concerning the total equilibrium quantity, the equilibrium price, and the profit of country 0 remain to be true, as the following theorem shows.

Theorem 4. *For* $i = 1,2$, $x_1(\varnothing) + x_2(\varnothing) > x_1(\{i\}) + x_2(\{i\}) > x_1(\{1,2\}) + x_2(\{1,2\}) > 0$, $p(\varnothing) > p(\{i\}) > p(\{1,2\}) > a_0$, and $\pi_0(\varnothing) > \pi_0(\{i\}) > \pi_0(\{1,2\}) > 0$.

The proof of Theorem 4 is given in the appendix. Theorem 4 says that as the number of demanders choosing quantity restraints increases, the total trading quantity, the price, and the profit of the supplier decrease. Figures 5-a and 5-b illustrate the results of Theorem 4. There are six cases to consider, depending on the quantity restraint level of country 0, x_0^R.

Case 1: $A(\varnothing) \le x_0^R$ (see Figure 5-1).

In this case, $(b_0 + d_0)x_0^R / b_0 \ge x_1(\varnothing) + x_2(\varnothing) > x_i(\{i\}) + x_j(\{i\}) > x_1(\{1,2\}) + x_2(\{1,2\})$. That is, if the quantity restraint level of country 0 (the supplier) is large enough, then for every configuration of the quantity restraint choices of two countries 1 and 2, the total equilibrium quantity is less than $(b_0 + d_0)x_0^R / b_0$ in which the constrained aggregate MAC curve is kinked. Each of the three points $(-x_1(\varnothing) - x_2(\varnothing), p(\varnothing))$, $(-x_i(\{i\}) - x_j(\{i\}), p(\{i\}))$, and $(-x_1(\{1,2\}) - x_2(\{1,2\}), p(\{1,2\}))$ lies on the first segment of the curve. The same analysis as that in the previous section applies to this case.

Case 2: $A(\{i\}) < x_0^R < A(\varnothing)$ (see Figure 5-2).

In this case, $x_1(\varnothing) + x_2(\varnothing) > (b_0 + d_0)x_0^R / b_0 > x_i(\{i\}) + x_j(\{i\}) > x_1(\{1,2\}) + x_2(\{1,2\})$, that is, only the total equilibrium quantity when neither country 1 nor 2 chooses a restraint is larger than $(b_0 + d_0)x_0^R / b_0$ in which the constrained aggregate MAC curve is kinked, while the other two total equilibrium quantities are less than it. The point $(-x_1(\varnothing) - x_2(\varnothing), p(\varnothing))$ lies on the second segment of the curve, while both the point $(-x_i(\{i\}) - x_j(\{i\}), p(\{i\}))$ and the point $(-x_1(\{1,2\}) - x_2(\{1,2\}), p(\{1,2\}))$ remain to lie on the first segment of the curve.

Case 3: $B(\{i\}) \le x_0^R \le A(\{i\})$ (see Figure 5-3).

In this case, $x_1(\varnothing) + x_2(\varnothing) > (b_0 + d_0)x_0^R / b_0 = x_i(\{i\}) + x_j(\{i\}) > x_1(\{1,2\}) + x_2(\{1,2\})$. The point $(-x_1(\varnothing) - x_2(\varnothing), p(\varnothing))$ lies on the second segment of the curve, the point $(-x_i(\{i\}) - x_j(\{i\}), p(\{i\}))$ is equal to the kink point, and the point $(-x_1(\{1,2\}) - x_2(\{1,2\}), p(\{1,2\}))$ lies on the first segment.

Case 4: $A(\{1,2\}) < x_0^R < B(\{i\})$ (see Figure 5-4).

In this case, $x_1(\varnothing)+x_2(\varnothing)>x_i(\{i\})+x_j(\{i\})>(b_0+d_0)x_0^R/b_0>x_1(\{1,2\})+x_2(\{1,2\})$. Both the point $(-x_1(\varnothing)-x_2(\varnothing),p(\varnothing))$ and the point $(-x_i(\{i\})-x_j(\{i\}),p(\{i\}))$ lie on the second segment of the curve, while the point $(-x_1(\{1,2\})-x_2(\{1,2\}),p(\{1,2\}))$ lies on the first segment.

Case 5: $B(\{1,2\})\le x_0^R\le A(\{1,2\})$ (see Figure 5-5).

In this case, $x_1(\varnothing)+x_2(\varnothing)>x_i(\{i\})+x_j(\{i\})>(b_0+d_0)x_0^R/b_0=x_1(\{1,2\})+x_2(\{1,2\})$. Both the point $(-x_1(\varnothing)-x_2(\varnothing),p(\varnothing))$ and the point $(-x_i(\{i\})-x_j(\{i\}),p(\{i\}))$ lie on the second segment of the curve, while the point $(-x_1(\{1,2\})-x_2(\{1,2\}),p(\{1,2\}))$ is equal to the kink point of the curve.

Case 6: $x_0^R<B(\{1,2\})$ (see Figure 5-6).

In this case, $x_1(\varnothing)+x_2(\varnothing)>x_i(\{i\})+x_j(\{i\})>x_1(\{1,2\})+x_2(\{1,2\})>(b_0+d_0)x_0^R/b_0$. In other word, if x_0^R is small enough, all three points $(-x_1(\varnothing)-x_2(\varnothing),p(\varnothing))$, $(-x_i(\{i\})-x_j(\{i\}),p(\{i\}))$, and $(-x_1(\{1,2\})-x_2(\{1,2\}),p(\{1,2\}))$ lie on the second segment of the curve.

Next we compare the equilibrium payoffs.

Theorem 5.

a) Case 1: $A(\{i\})<x_0^R$. In this case, $\pi_j(\{1,2\})>\pi_j(\{i\})$, $i,j\in\{1,2\}$, $i\neq j$.

Case 2: $B(\{1,2\}) \le x_0^R \le A(\{i\})$. *In this case,* $\pi_j(\{1,2\}) \gtreqless \pi_j(\{i\})$, $i, j \in \{1,2\}$, $i \ne j$, *if and only if*

(15) $$\left[p(\{i\}) - p(\{1,2\})\right] \cdot x_j(\{1,2\}) \gtreqless \left[MAC_j(x_j(\{1,2\})) - p(\{i\})\right] \cdot \left[x_j(\{i\})) - x_j(\{1,2\}))\right] / 2.$$

Case 3: $x_0^R < B(\{1,2\})$. *In this case,* $\pi_j(\{1,2\}) > \pi_j(\{i\})$, $i, j \in \{1,2\}$, $i \ne j$.

b) In all cases, $\pi_j(\{i\}) > \pi_j(\{j\}) > \pi_j(\varnothing)$, $i, j \in \{1,2\}$, $i \ne j$.

The proof of Theorem 5 is given in the appendix.

Remark: Condition (15) for Case 2 in Theorem 5 can be rewritten in terms of the parameters a_0, a_1, b_0, b_1, d_0 and x_0^R as follows:

Case 2-(i): $B(\{i\}) \le x_0^R \le A(\{i\})$. In this case, $\pi_j(\{1,2\}) \gtreqless \pi_j(\{i\})$, $i, j \in \{1,2\}$, $i \ne j$, if and only if $a_1 b_0^2 (b_0 + d_0)[a_1(b_0 + d_0) + 2a_0 b_1] \gtreqless [a_1(b_0 + d_0) + 3a_0 b_1]^2 \left[b_0 - a_0 x_0^R / (a_1 - a_0)\right]^2$.

Case 2-(ii): $A(\{1,2\}) < x_0^R < B(\{i\})$. In this case, $\pi_j(\{1,2\}) \gtreqless \pi_j(\{i\})$, $i, j \in \{1,2\}$, $i \ne j$, if and only if

$$(b_0 + d_0)(a_1 d_0 + a_0 b_1)^2 (a_1 d_0 + 3a_0 b_1)^2 [a_1(b_0 + d_0) + 2a_0 b_1]$$
$$\gtreqless a_1 (a_1 d_0 + 2a_0 b_1)^2 [a_1(b_0 + d_0) + 3a_0 b_1]^2 \left[d_0 + a_0 x_0^R / (a_1 - a_0)\right]^2.$$

Case 2-(iii): $B(\{1,2\}) \le x_0^R \le A(\{1,2\})$. In this case, $\pi_j(\{1,2\}) \gtreqless \pi_j(\{i\})$, $i, j \in \{1,2\}$, $i \ne j$, if and only if

$$(b_0 + d_0)(a_1 d_0 + a_0 b_1)^2 (a_1 d_0 + 3a_0 b_1)^2 x_0^R \left\{4b_0 b_1 (a_1 - a_0) - x_0^R [a_1(b_0 + d_0) + 4a_0 b_1]\right\}$$

$$\gtreqless 4a_1 b_0^2 b_1^2 (a_1 d_0 + 2a_0 b_1)^2 [d_0(a_1 - a_0) + a_0 x_0^R]^2 .$$

According to Theorem 5, $\pi_j(\{1,2\}) > \pi_j(\{i\})$ and $\pi_j(\{j\}) > \pi_j(\varnothing)$, $i, j \in \{1,2\}$, $i \neq j$ if either $A(\{i\}) < x_0^R$ or $x_0^R < B(\{1,2\})$. In other words, deciding to choose a quantity restraint in the first stage is a dominant strategy for each country if the point $(-x_1(\{1,2\}) - x_2(\{1,2\}), p(\{1,2\}))$ and the point $(-x_i(\{i\}) - x_j(\{i\}), p(\{i\}))$ lie on the same segment of the constrained MAC curve of country 0 (see Figures 5-1, 5-2, and 5-6). Figure 4 illustrates this result when $A(\{i\}) < x_0^R < A(\varnothing)$. Since $\alpha + \beta < \delta$, the area of the trapezoid $a_1 p(\{1,2\}) gh$ is larger than the area of the triangle $a_1 p(\{i\}) m$, that is, $\pi_j(\{1,2\}) > \pi_j(\{i\})$. Moreover, since $\alpha < \gamma$, the area of the trapezoid $a_1 p(\{i\}) \ell h$ is larger than the area of the triangle $a_1 p(\{i\}) e$, that is, $\pi_i(\{i\}) > \pi_i(\varnothing)$.

However, $\pi_j(\{1,2\})$ could be smaller than $\pi_j(\{i\})$ if $B(\{1,2\}) \leq x_0^R \leq A(\{i\})$. Figure 6 illustrates why this could happen, where $i = 2$ and $j = 1$. Let us consider two different values $\overline{a}_1$ and $\underline{a}_1$ with $\overline{a}_1 > \underline{a}_1$. Since the equilibrium quantities, prices, and payoffs, $x_1(\{1,2\})$, $p(\{1,2\})$, $\pi_1(\{1,2\})$, $x_1(\{2\})$, $p(\{2\})$, and $\pi_1(\{2\})$, change depending on a_1, we denote $x_1(\{1,2\})$ when $a_1 = \underline{a}_1$ by $\underline{x}_1(\{1,2\})$, $x_1(\{1,2\})$ when $a_1 = \overline{a}_1$ by $\overline{x}_1(\{1,2\})$, and so on. In Figure 6, we assume that in both the case of $a_1 = \underline{a}_1$ and the case of $a_1 = \overline{a}_1$, the inequalities $B(\{2\}) \leq x_0^R \leq A(\{2\})$ hold, that is, the point $(-x_1(\{1,2\}) - x_2(\{1,2\}), p(\{1,2\}))$ lies on the first segment of the constrained aggregate MAC curve of country 0, whereas the point $(-x_1(\{2\}) - x_2(\{2\}), p(\{2\}))$ is equal to the kink point of the curve. In particular, notice that $\underline{p}(\{2\}) = \overline{p}(\{2\})$. Namely, even when the value of a_1 rises from $\underline{a}_1$ to $\overline{a}_1$, the equilibrium price in which only country 2 chooses a quantity restraint does not change, since the total equilibrium quantity remains to be equal to $(b_0 + d_0)x_0^R / b_0$ at which the constrained aggregate MAC curve of country 0 is kinked.[5]

Figure 6 shows that as the value of a_1 increases, $\pi_1(\{2\})$ becomes larger than $\pi_1(\{1,2\})$ when the equilibrium price $p(\{2\})$ is constant. When $a_1 = \underline{a}_1$, the area of the trapezoid $\underline{a}_1\underline{p}(\{1,2\})\underline{gh}$ is larger than the area of the triangle $\underline{a}_1\underline{p}(\{2\})\underline{m}$ since $\delta + \theta > \alpha + \beta$, that is, $\underline{\pi}_1(\{1,2\}) > \underline{\pi}_1(\{2\})$ since the left-hand side of Inequality (15) in Theorem 5, $\left[\underline{p}(\{2\}) - \underline{p}(\{1,2\})\right] \cdot \underline{x}_1(\{1,2\})$, is larger than the right-hand side of (15), $\left[MAC_1(\underline{x}_1(\{1,2\})) - \underline{p}(\{2\})\right] \cdot \left[\underline{x}_1(\{2\}) - \underline{x}_1(\{1,2\})\right] / 2$. On the other hand, when $a_1 = \overline{a}_1$, the area of the trapezoid $\overline{a}_1\overline{p}(\{1,2\})\overline{gh}$ is smaller than the area of the triangle $\overline{a}_1\overline{p}(\{2\})\overline{m}$ since $\delta + \lambda < \alpha + \gamma$, that is, $\overline{\pi}_1(\{1,2\}) < \overline{\pi}_1(\{2\})$ since the left-hand side of (15) in Theorem 5, $\left[\overline{p}(\{2\}) - \overline{p}(\{1,2\})\right] \cdot \overline{x}_1(\{1,2\})$, is smaller than the right-hand side of (15), $\left[MAC_1(\overline{x}_1(\{1,2\})) - \overline{p}(\{2\})\right] \cdot \left[\overline{x}_1(\{2\}) - \overline{x}_1(\{1,2\})\right] / 2$. When the value of a_1 rises from $\underline{a}_1$ to $\overline{a}_1$, the difference $\left[p(\{2\}) - p(\{1,2\})\right]$ decreases, whereas the difference $\left[MAC_1(x_1(\{1,2\})) - p(\{2\})\right]$ increases. Moreover, the increase in $x_1(\{1,2\})$ is smaller than that in $\left[x_1(\{2\}) - x_1(\{1,2\})\right]$. Accordingly, the relation between the right-hand side and the left-hand side of (15) becomes reversed, and so does the relation between $\pi_1(\{1,2\})$ and $\pi_1(\{2\})$ when the value of a_1 changes from $\underline{a}_1$ to $\overline{a}_1$.

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[5] Also, note that $x_2(\{2\}) \neq x_1(\{1,2\})$, that is, the quantity restraint level when only one country choose a restraint is different from that when two countries choose restraints, in contrast to the case without CDM or supplier's quantity restraint. This is because the point $(-x_1(\{2\}) - x_2(\{2\}), p(\{2\}))$ is equal to the kink

Figure 6 is around here.

Next we give numerical examples to show that in the case of $B(\{1,2\}) \le x_0^R \le A(\{i\})$, $\pi_j(\{1,2\})$ may or may not be larger than $\pi_j(\{i\})$, depending on the values of a_0, a_1, b_0, b_1, d_0, and x_0^R.

Example 1: Let $a_0 = 40$, $a_1 = 100$, $b_0 = 40$, $b_1 = 60$, and $d_0 = 50$. In this case, for all $x_0^R \ge 0$, $\pi_j(\{1,2\}) > \pi_j(\{i\})$. Figure 7 illustrates this fact, where i = 2, j = 1, $A(\varnothing) \approx 20.87$, $A(\{1\}) \approx 19.65$, $B(\{2\}) \approx 19.13$, $A(\{1,2\}) \approx 17.78$, and $B(\{1,2\}) \approx 15.89$. Again, for each country, deciding to choose a quantity restraint in the first stage is a dominant strategy, since $\pi_j(\{1,2\}) > \pi_j(\{i\})$ and $\pi_j(\{j\}) > \pi_j(\varnothing)$, $i, j \in \{1,2\}$, $i \ne j$.

Figure 7 is around here.

Example 2: Let $a_1 = 10000$ and the values of the other parameters be the same as those in Example 1, i.e., $a_0 = 40$, $b_0 = 40$, $b_1 = 60$, and $d_0 = 50$. Then $\pi_j(\{1,2\})$ is smaller than $\pi_j(\{i\})$ for some values of x_0^R, although $\pi_j(\{1,2\})$ is larger than $\pi_j(\{i\})$ for most values of x_0^R. Figure 8 illustrates this fact, where i = 2, j = 1, $A(\varnothing) \approx 52.838$, $A(\{1\}) \approx 52.768$, $B(\{2\}) \approx 52.713$, $A(\{1,2\}) \approx 52.698$, and $B(\{1,2\}) \approx 52.587$. If 52.692 $< x_0^R < 52.733$, then $\pi_1(\{1,2\}) < \pi_1(\{2\})$; otherwise $\pi_1(\{1,2\}) \ge \pi_1(\{2\})$. Table 5 is the payoff matrix for the first stage decisions on quantity restraints in the former case. There are two Nash

point of the constrained aggregate MAC curve of country 0, whereas the point equilibria of this game: one country chooses a quantity restraint, while the other does not, since $\pi_j(\{1,2\}) < \pi_j(\{i\})$ and $\pi_j(\{j\}) > \pi_j(\emptyset)$, $i, j \in \{1,2\}$, $i \neq j$. In any case, at least one country chooses a quantity restraint at equilibrium, since $\pi_j(\{j\})$ is always larger than $\pi_j(\emptyset)$, $j \in \{1,2\}$.

Figure 8 and Table 5 are around here.

4. Concluding Remarks

It is obvious that the real aims of the EU proposal are to promote domestic reductions of GHG emissions, to stimulate technological investments, to control hot air and to commit ambitious goals in the following commitment periods. Nevertheless, the EU proposal has strategic economic consequences such that demanders gain and suppliers lose whether EU's policy makers intend them or not.

In the sulfur allowance program conducted by the Environmental Protection Agency (EPA) in the US, the permits have been traded by over the counter as well as in an auction market. Cason and Plott (1996) pointed out that the trading rule of the auction designed by EPA has serious flaws by an experimental method. We are sure that the designers of the auction did not have ill will. However, researchers and policy makers must bear in mind that a mistake without malice is really a mistake.

There have been various proposals on the design of institutions at the Conferences of Parties to the Climate Convention. We now know that only common sense and experience are not enough to design new institutions. Various approaches such as theory and experiment in economics would be of importance.

$(-x_1(\{1,2\}) - x_2(\{1,2\}), p(\{1,2\}))$ lies on the first segment of the curve.

Appendix

1. The derivations of equilibrium values with CDM and supplier's quantity restraint.

There are eight cases to consider.

Case 1: $R=\varnothing$ (the case in which neither country 1 nor 2 chooses a quantity restraint)

Case 1-1: $-(b_0+d_0)x_0^R/b_0 \le x_0$ or $x_0^R \ge A(\varnothing)$.

Suppose that $-(b_0+d_0)x_0^R/b_0 \le x_0$. Then $p=a_0-[a_0/(b_0+d_0)]x_0$, $p=a_1-(a_1/b_1)x_i$, $i\in\{1,2\}$, and $-x_0=x_1+x_2$. By solving these equations, or simply by replacing b_0 with b_0+d_0 in (1)-(3), we obtain the equilibrium values when $x_0^R \ge A(\varnothing)$ in Tables 2-4. Note that

$$x_0(\varnothing)+(b_0+d_0)x_0^R/b_0=-x_1(\varnothing)-x_2(\varnothing)+(b_0+d_0)x_0^R/b_0$$

$$=\frac{(b_0+d_0)\left\{[a_1(b_0+d_0)+2a_0b_1]x_0^R-2b_0b_1(a_1-a_0)]\right\}}{b_0[a_1(b_0+d_0)+2a_0b_1]},$$

which is non-negative if and only if $x_0^R \ge A(\varnothing)$.

Case 1-2: $-(b_0+d_0)x_0^R/b_0 > x_0$ or $x_0^R < A(\varnothing)$.

Suppose that $-(b_0+d_0)x_0^R/b_0 > x_0$. Then $p=\frac{a_0(d_0-x_0^R)}{d_0}-\frac{a_0}{d_0}x_0$, $p=a_1-(a_1/b_1)x_i$, $i\in\{1,2\}$, and $-x_0=x_1+x_2$. By solving these equations, or simply replacing a_0 with $\frac{a_0(d_0-x_0^R)}{d_0}$ and a_0/b_0 with $\frac{a_0}{d_0}$ in (1)-(3), we obtain the equilibrium values when $x_0^R < A(\varnothing)$ in Tables 2-4. Notice that

$$x_0(\varnothing)+(b_0+d_0)x_0^R / b_0 = -x_1(\varnothing)-x_2(\varnothing)+(b_0+d_0)x_0^R / b_0$$

$$= \frac{d_0\{[a_1(b_0+d_0)+2a_0b_1]x_0^R - 2b_0b_1(a_1-a_0)\}}{b_0[a_1d_0+2a_0b_1]},$$

which is negative if and only if $x_0^R < A(\varnothing)$.

Case 2: $R=\{1,2\}$ (the case in which every demander chooses a quantity restraint)

Case 2-1: $-(b_0+d_0)x_0^R / b_0 < x_0(\{1,2\})$ or $x_0^R > A(\{1,2\})$.

Suppose that $-(b_0+d_0)x_0^R / b_0 < x_0$. Then

$$\pi_i = \frac{1}{2}(a_1 - p + MAC_i(x_i) - p)x_i,\ i \in \{1,2\},$$

where $p = a_0 - [a_0 / (b_0+d_0)]x_0$, $-x_0 = x_1 + x_2$, and $MAC_i(x_i) = a_1 - (a_1 / b_1)x_i$.

That is,

$$\pi_i = \frac{1}{2}\left[2(a_1-a_0) - \frac{a_1(b_0+d_0)+2a_0b_1}{b_1(b_0+d_0)}x_i - \frac{2a_0}{b_0+d_0}x_j\right]x_i,\ j \neq i.$$

Given x_j, each country i is assumed to choose x_i so as to maximize its own payoff.

The first order condition is given by

$$\frac{\partial \pi_i}{\partial x_i} = (a_1-a_0) - \frac{a_1(b_0+d_0)+2a_0b_1}{b_1(b_0+d_0)}x_i - \frac{a_0}{b_0+d_0}x_j = 0,\ i,j \in \{1,2\}, i \neq j.$$

From these equations, or simply by replacing b_0 with b_0+d_0 in (4)-(6), we obtain the equilibrium values when $x_0^R > A(\{1,2\})$ in Tables 2-4. Notice that

$$x_0(\{1,2\})+(b_0+d_0)x_0^R / b_0 = -[x_1(\{1,2\})+x_2(\{1,2\})]+(b_0+d_0)x_0^R / b_0$$

$$= \frac{(b_0+d_0)\{[a_1(b_0+d_0)+3a_0b_1]x_0^R - 2b_0b_1(a_1-a_0)\}}{b_0[a_1(b_0+d_0)+3a_0b_1]},$$

which is positive if and only if $x_0^R > A(\{1,2\})$.

Case 2-2: $-(b_0+d_0)x_0^R/b_0 = x_0(\{1,2\})$ or $B(\{1,2\}) \le x_0^R \le A(\{1,2\})$.

Suppose that $-(b_0+d_0)x_0^R/b_0 = x_0$. We show that if $B(\{1,2\}) \le x_0^R \le A(\{1,2\})$, then the following strategy profile is a Nash equilibrium:

$$x_i^B(\{1,2\}) \equiv \frac{x_0^R(b_0+d_0)}{2b_0}, \; i \in \{1,2\}.$$

Pick any $i \in \{1,2\}$. Let $x_j = x_j^B(\{1,2\}) = \dfrac{x_0^R(b_0+d_0)}{2b_0}$, $j \ne i$. Then

$$\pi_i(x_i) = \frac{1}{2}\left[2(a_1-a_0) - \frac{a_1(b_0+d_0)+2a_0b_1}{b_1(b_0+d_0)}x_i - \frac{a_0}{b_0}x_0^R\right]x_i \qquad \text{if } x_i \le x_i^B(\{1,2\})$$

$$= \frac{1}{2}\left[2(a_1-a_0) + \frac{2a_0}{d_0}x_0^R - \frac{a_1d_0+2a_0b_1}{b_1d_0}x_i - \frac{a_0(b_0+d_0)}{b_0d_0}x_0^R\right]x_i \qquad \text{if } x_i > x_i^B(\{1,2\})$$

First of all, we prove that for any x_i such that $0 \le x_i < x_i^B(\{1,2\})$, $\dfrac{d\pi_i(x_i)}{dx_i} > 0$, implying that $\pi_i(x_i^B(\{1,2\})) > \pi_i(x_i)$. If $0 \le x_i \le x_i^B(\{1,2\})$, then

$$\frac{d\pi_i(x_i)}{dx_i} = \frac{2b_0b_1(b_0+d_0)(a_1-a_0) - a_0b_1(b_0+d_0)x_0^R - 2b_0[a_1(b_0+d_0)+2a_0b_1]x_i}{2b_0b_1(b_0+d_0)}.$$

Since $\dfrac{d^2\pi_i(x_i)}{dx_i^2} < 0$ for any $x_i \ge 0$, it is sufficient to prove that $\dfrac{d\pi_i(x_i^B(\{1,2\}))}{dx_i} \ge 0$. In fact, $\dfrac{d\pi_i(x_i^B(\{1,2\}))}{dx_i} = \dfrac{2b_0b_1(a_1-a_0) - x_0^R[a_1(b_0+d_0)+3a_0b_1]}{2b_0b_1}$,

which is non-negative since $x_0^R \le A(\{1,2\})$.

Next we prove that for any x_i such that $x_i > x_i^B(\{1,2\})$, $\dfrac{d\pi_i(x_i)}{dx_i} < 0$, implying that $\pi_i(x_i^B(\{1,2\})) > \pi_i(x_i)$. If $x_i \ge x_i^B(\{1,2\})$, then

$$\frac{d\pi_i(x_i)}{dx_i} = \frac{2b_0b_1d_0(a_1 - a_0) + 2a_0b_0b_1x_0^R - a_0b_1(b_0 + d_0)x_0^R - 2b_0[a_1d_0 + 2a_0b_1]x_i}{2b_0b_1d_0}.$$

Since $\frac{d^2\pi_i(x_i)}{dx_i^{\,2}} < 0$ for any $x_i \geq 0$, it is sufficient to prove that $\frac{d\pi_i(x_i^B(\{1,2\}))}{dx_i} \leq 0$. In fact, $\frac{d\pi_i(x_i^B(\{1,2\}))}{dx_i} = \frac{2b_0b_1d_0(a_1 - a_0) - x_0^R\{d_0[a_1(b_0 + d_0) + 3a_0b_1] + a_0b_0b_1\}}{2b_0b_1d_0}$,

which is non-positive since $x_0^R \geq B(\{1,2\})$.

Therefore, we conclude that $\pi_i(x_i^B(\{1,2\})) > \pi_i(x_i)$ for any $x_i \neq x_i^B(\{1,2\})$, and the strategy profile $(x_1^B(\{1,2\}), x_2^B(\{1,2\}))$ is a Nash equilibrium. By using this equilibrium quantities, it is easy to get the equilibrium price and payoffs when $B(\{1,2\}) \leq x_0^R \leq A(\{1,2\})$ in Tables 3 and 4.

Case 2-3: $-(b_0 + d_0)x_0^R / b_0 > x_0$ or $x_0^R < B(\{1,2\})$.

Suppose that $-(b_0 + d_0)x_0^R / b_0 > x_0$. Then

$$\pi_i = \frac{1}{2}(a_1 - p + MAC_i(x_i) - p)x_i,\ i \in \{1,2\},$$

where $p = a_0(d_0 - x_0^R) / d_0 - (a_0 / d_0)x_0$, $-x_0 = x_1 + x_2$, and $MAC_i(x_i) = a_1 - (a_1 / b_1)x_i$.

By simply replacing a_0 with $a_0(d_0 - x_0^R) / d_0$ and a_0 / b_0 with a_0 / d_0 in (4)-(6), we obtain the equilibrium values $x_0^R < B(\{1,2\})$ in Tables 2-4. Notice that

$$x_0(\{1,2\}) + (b_0 + d_0)x_0^R / b_0 = -x_1(\{1,2\}) - x_2(\{1,2\}) + (b_0 + d_0)x_0^R / b_0$$

$$= \frac{-2b_0b_1d_0(a_1 - a_0) + x_0^R\{d_0[a_1(b_0 + d_0) + 3a_0b_1] + a_0b_0b_1\}}{b_0[a_1d_0 + 3a_0b_1]},$$

which is negative if and only if $x_0^R < B(\{1,2\})$.

Case 3: $R=\{i\}$ (the case in which only one demander i chooses a quantity restraint)

Case 3-1: $-(b_0+d_0)x_0^R/b_0 < x_0$ or $x_0^R > A(\{i\})$.

Suppose that $-(b_0+d_0)x_0^R/b_0 < x_0$. Then

$$\pi_i = \frac{1}{2}(a_1 - p + MAC_i(x_i) - p)x_i,$$

where $p = a_1 - (a_1/b_1)x_j$, $j \neq i$, $p = a_0 - [a_0/(b_0+d_0)]x_0$, $-x_0 = x_1 + x_2$, and $MAC_i(x_i) = a_1 - (a_1/b_1)x_i$. By replacing b_0 with b_0+d_0 in (7)-(11), we obtain the equilibrium values when $x_0^R > A(\{i\})$ in Tables 2-4. Notice that

$$x_0(\{i\}) + (b_0+d_0)x_0^R/b_0 = -[x_i(\{i\}) + x_j(\{i\})] + (b_0+d_0)x_0^R/b_0$$

$$= \frac{(b_0+d_0)[a_1(b_0+d_0)+3a_0b_1][a_1(b_0+d_0)+a_0b_1][x_0^R - A(\{i\})]}{b_0[a_1(b_0+d_0)+3a_0b_1][a_1(b_0+d_0)+a_0b_1]},$$

which is positive if and only if $x_0^R > A(\{i\})$.

Case 3-2: $-(b_0+d_0)x_0^R/b_0 = x_0$ or $B(\{i\}) \le x_0^R \le A(\{i\})$.

Suppose that $-(b_0+d_0)x_0^R/b_0 = x_0$. We show that if $B(\{i\}) \le x_0^R \le A(\{i\})$, then the following strategy is the best choice for i:

$$x_i^B(\{i\}) \equiv \frac{x_0^R[a_1(b_0+d_0)+a_0b_1] - b_0b_1(a_1-a_0)}{a_1b_0}.$$

The payoff of i is provided by

$$\pi_i(x_i) = \frac{a_1}{2[a_1(b_0+d_0)+a_0b_1]}\left[2(b_0+d_0)(a_1-a_0) - \frac{a_1(b_0+d_0)+3a_0b_1}{b_1}x_i\right]x_i \quad \text{if } x_i \le x_i^B(\{i\})$$

$$= \frac{a_1}{2(a_1d_0+a_0b_1)}\left[2[d_0(a_1-a_0)+a_0x_0^R] - \frac{a_1d_0+3a_0b_1}{b_1}x_i\right]x_i \quad \text{if } x_i > x_i^B(\{i\}).$$

First of all, we prove that for any x_i such that $0 \le x_i < x_i^B(\{i\})$, $\frac{d\pi_i(x_i)}{dx_i} > 0$, implying that $\pi_i(x_i^B(\{i\})) > \pi_i(x_i)$. If $0 \le x_i \le x_i^B(\{i\})$, then

$$\frac{d\pi_i(x_i)}{dx_i} = \frac{a_1}{[a_1(b_0+d_0)+a_0b_1]}\left[(b_0+d_0)(a_1-a_0) - \frac{a_1(b_0+d_0)+3a_0b_1}{b_1}x_i\right].$$

Since $\frac{d^2\pi_i(x_i)}{dx_i^2} < 0$ for any $x_i \ge 0$, it is sufficient to prove that $\frac{d\pi_i(x_i^B(\{i\}))}{dx_i} \ge 0$. In fact,

$$\frac{d\pi_i(x_i^B(\{i\}))}{dx_i} = \frac{\left[b_0b_1(a_1-a_0)[2a_1(b_0+d_0)+3a_0b_1] - [a_1(b_0+d_0)+a_0b_1][a_1(b_0+d_0)+3a_0b_1]x_0^R\right]}{b_0b_1[a_1(b_0+d_0)+a_0b_1]},$$

which is non-negative since $x_0^R \le A(\{i\})$.

Next we prove that for any x_i such that $x_i > x_i^B(\{i\})$, $\frac{d\pi_i(x_i)}{dx_i} < 0$, implying that $\pi_i(x_i^B(\{i\})) > \pi_i(x_i)$. If $x_i \ge x_i^B(\{i\})$, then

$$\frac{d\pi_i(x_i)}{dx_i} = \frac{a_1}{a_1d_0+a_0b_1}\left[d_0(a_1-a_0) + a_0x_0^R - \frac{a_1d_0+3a_0b_1}{b_1}x_i\right].$$

Since $\frac{d^2\pi_i(x_i)}{dx_i^2} < 0$ for any $x_i \ge 0$, it is sufficient to prove that $\frac{d\pi_i(x_i^B(\{i\}))}{dx_i} \le 0$. In fact,

$$\frac{d\pi_i(x_i^B(\{i\}))}{dx_i} = \frac{b_0b_1(a_1-a_0)[2a_1d_0+3a_0b_1] - \{[a_1(b_0+d_0)+3a_0b_1](a_1d_0+a_0b_1)+a_0a_1b_0b_1\}x_0^R}{b_0b_1(a_1d_0+a_0b_1)},$$

which is non-positive since $x_0^R \ge B(\{i\})$.

Therefore, we conclude that $\pi_i(x_i^B(\{i\})) > \pi_i(x_i)$ for any $x_i \ne x_i^B(\{i\})$, and $x_i^B(\{i\})$ is the best choice for *i*. By using this equilibrium quantity, it is easy to obtain the equilibrium quantity of $j \ne i$, price, and payoffs when $B(\{i\}) \le x_0^R \le A(\{i\})$ in Tables 2-4.

Case 3-3: $-(b_0+d_0)x_0^R / b_0 > x_0$ or $x_0^R < B(\{i\})$.

Suppose that $-(b_0 + d_0)x_0^R / b_0 > x_0$. Then

$$\pi_i = \frac{1}{2}(a_1 - p + MAC_i(x_i) - p)x_i,$$

where $p = a_1 - (a_1 / b_1)x_j$, $j \neq i$, $p = a_0(d_0 - x_0^R) / d_0 - (a_0 / d_0)x_0$, $-x_0 = x_1 + x_2$, and $MAC_i(x_i) = a_1 - (a_1 / b_1)x_i$. By simply replacing a_0 with $a_0(d_0 - x_0^R) / d_0$ and a_0 / b_0 with a_0 / d_0 in (7)-(11), we obtain the equilibrium values when $x_0^R < B(\{i\})$ in Tables 2-4. Note that

$$x_0(\{i\}) + (b_0 + d_0)x_0^R / b_0 = -[x_i(\{i\}) + x_j(\{i\})] + (b_0 + d_0)x_0^R / b_0$$

$$= \frac{d_0\{[a_1(b_0 + d_0) + 3a_0b_1](a_1d_0 + a_0b_1) + a_0a_1b_0b_1\}[x_0^R - B(\{i\})]}{b_0(a_1d_0 + 3a_0b_1)(a_1d_0 + a_0b_1)},$$

which is negative if and only if $x_0^R < B(\{i\})$.

2. Proof of Theorem 4.

We will show that $x_1(\varnothing) + x_2(\varnothing) > x_1(\{i\}) + x_2(\{i\}) > x_1(\{1,2\}) + x_2(\{1,2\}) > 0$. It follows from this relation that $p(\varnothing) > p(\{i\}) > p(\{1,2\}) > a_0$, and $\pi_0(\varnothing) > \pi_0(\{i\}) > \pi_0(\{1,2\}) > 0$. There are six cases to consider.

Case 1: $A(\varnothing) \leq x_0^R$. By using the same idea as that of the proof of Theorem 1, it is easy to prove that $(b_0 + d_0)x_0^R / b_0 \geq x_1(\varnothing) + x_2(\varnothing) > x_i(\{i\}) + x_j(\{i\}) > x_1(\{1,2\}) + x_2(\{1,2\}) > 0$.

Case 2: $A(\{i\}) < x_0^R < A(\varnothing)$. By using the same idea as that of the proof of Theorem 1, it is easy to check that $(b_0 + d_0)x_0^R / b_0 > x_i(\{i\}) + x_j(\{i\}) > x_1(\{1,2\}) + x_2(\{1,2\}) > 0$.

Moreover, $x_1(\varnothing)+x_2(\varnothing)>(b_0+d_0)x_0^R/b_0$. Therefore, we have the desired result.

Case 3: $B(\{i\})\le x_0^R\le A(\{i\})$. In this case, $x_1(\varnothing)+x_2(\varnothing)>(b_0+d_0)x_0^R/b_0$, $(b_0+d_0)x_0^R/b_0=x_i(\{i\})+x_j(\{i\})$, and $(b_0+d_0)x_0^R/b_0>x_1(\{1,2\})+x_2(\{1,2\})>0$. From these inequalities, we have the desired result.

Case 4: $A(\{1,2\})<x_0^R<B(\{i\})$. By using the same idea as that of the proof of Theorem 1, it is easy to check that $x_1(\varnothing)+x_2(\varnothing)>x_i(\{i\})+x_j(\{i\})>(b_0+d_0)x_0^R/b_0$. Moreover, $(b_0+d_0)x_0^R/b_0>x_1(\{1,2\})+x_2(\{1,2\})>0$. Therefore, we have the desired result.

Case 5: $B(\{1,2\})\le x_0^R\le A(\{1,2\})$. By using the same idea as that of the proof of Theorem 1, it is easy to check that $x_1(\varnothing)+x_2(\varnothing)>x_i(\{i\})+x_j(\{i\})>(b_0+d_0)x_0^R/b_0$. Moreover, $(b_0+d_0)x_0^R/b_0=x_1(\{1,2\})+x_2(\{1,2\})>0$. Therefore, we have the desired result.

Case 6: $x_0^R<B(\{1,2\})$. By using the same idea as that of the proof of Theorem 1, it is easy to prove that $x_1(\varnothing)+x_2(\varnothing)>x_i(\{i\})+x_j(\{i\})>x_1(\{1,2\})+x_2(\{1,2\})>(b_0+d_0)x_0^R/b_0$.

■

3. Proof of Theorem 5.

First of all, we will prove the result for the relation between $\pi_j(\{1,2\})$ and $\pi_j(\{i\})$, $i,j\in\{1,2\}$, $i\neq j$. There are four cases to consider.

Case 1: $A(\{i\}) < x_0^R$. By using the same idea as that of the proof of Theorem 2, it is easy to prove that $\pi_j(\{1,2\}) > \pi_j(\{i\})$.

Case 2: $B(\{1,2\}) \le x_0^R \le A(\{i\})$. By using the relation that

$$\left[MAC_j(x_j(\{1,2\})) - p(\{i\})\right] \cdot x_j(\{1,2\}) = \left[a_1 - MAC_j(x_j(\{1,2\}))\right] \cdot \left[x_j(\{i\})) - x_j(\{1,2\}))\right],$$

it is easy to obtain that

$$\pi_j(\{1,2\}) - \pi_j(\{i\})$$

$$= \left[p(\{i\}) - p(\{1,2\})\right] \cdot x_j(\{1,2\}) - \left[MAC_j(x_j(\{1,2\})) - p(\{i\})\right] \cdot \left[x_j(\{i\})) - x_j(\{1,2\}))\right] / 2 .$$

The desired result immediately follows from the above equation.

Case 3: $x_0^R < B(\{1,2\})$. By using the same idea as that of the proof of Theorem 2, it is easy to prove that $\pi_j(\{1,2\}) > \pi_j(\{i\})$.

Next we will prove that $\pi_i(\{i\}) > \pi_i(\emptyset)$, $i \in \{1,2\}$. For the case in which neither 1 nor 2 chooses a quantity restraint, we denote the equilibrium payoff of *i* when $x_0^R \ge A(\emptyset)$ by $\underline{\pi_i}(\emptyset)$ and that when $x_0^R < A(\emptyset)$ by $\overline{\pi}_i(\emptyset)$. That is,

$$\underline{\pi_i}(\emptyset) \equiv \frac{a_1 b_1 (b_0 + d_0)^2 (a_1 - a_0)^2}{2[a_1(b_0 + d_0) + 2a_0 b_1]^2} \text{ and}$$

$$\overline{\pi}_i(\emptyset) \equiv \frac{a_1 b_1 [d_0(a_1 - a_0) + a_0 x_0^R]^2}{2[a_1 d_0 + 2a_0 b_1]^2} \text{ (see Table 4).}$$

Moreover, for the case in which only *i* chooses a quantity restraint, we denote the equilibrium payoff of i when $x_0^R > A(\{i\})$ by $\underline{\pi}_i(\{i\})$, that when $B(\{i\}) \le x_0^R \le A(\{i\})$ by $\pi_i^B(\{i\})$, and that when $x_0^R < B(\{i\})$ by $\overline{\pi}_i(\{i\})$. That is,

$$\underline{\pi}_i(\{i\}) \equiv \frac{a_1 b_1 (b_0 + d_0)^2 (a_1 - a_0)^2}{2[a_1(b_0 + d_0) + a_0 b_1][a_1(b_0 + d_0) + 3a_0 b_1]},$$

$$\pi_i^B(\{i\}) \equiv \frac{\{x_0^R[a_1(b_0 + d_0) + a_0 b_1] - b_0 b_1 (a_1 - a_0)\}\{3b_0 b_1 (a_1 - a_0) - x_0^R[a_1(b_0 + d_0) + 3a_0 b_1]\}}{2a_1 b_0^2 b_1},$$

$$\overline{\pi}_i(\{i\}) \equiv \frac{a_1 b_1 (a_1 d_0 + 3a_0 b_1)[d_0(a_1 - a_0) + a_0 x_0^R]^2}{2(a_1 d_0 + a_0 b_1)(a_1 d_0 + 3a_0 b_1)^2} \text{ (see Table 4).}$$

There are four cases to consider.

Case 1: $A(\varnothing) \le x_0^R$. In this case, $\pi_i(\varnothing) = \underline{\pi}_i(\varnothing)$ and $\pi_i(\{i\}) = \underline{\pi}_i(\{i\})$. By using the same idea as that of the proof of Theorem 2, it is easy to prove that $\underline{\pi}_i(\{i\}) > \underline{\pi}_i(\varnothing)$.

Case 2: $A(\{i\}) < x_0^R < A(\varnothing)$. In this case, $\pi_i(\varnothing) = \overline{\pi}_i(\varnothing)$ and $\pi_i(\{i\}) = \underline{\pi}_i(\{i\})$. Notice that $\frac{\partial \overline{\pi}_i(\varnothing)}{\partial x_0^R} > 0$ and $\frac{\partial \underline{\pi}_i(\{i\})}{\partial x_0^R} = 0$. Therefore, it is sufficient to show that $\underline{\pi}_i(\{i\}) > \overline{\pi}_i(\varnothing)$ if $x_0^R = A(\varnothing)$. Let $x_0^R = A(\varnothing)$. Then $\underline{\pi}_i(\varnothing) = \overline{\pi}_i(\varnothing)$. Moreover, by the above result for the Case 1, $\underline{\pi}_i(\{i\}) > \underline{\pi}_i(\varnothing)$. Thus we have the desired result.

Case 3: $x_0^R < B(\{i\})$. In this case, $\pi_i(\varnothing) = \overline{\pi}_i(\varnothing)$ and $\pi_i(\{i\}) = \overline{\pi}_i(\{i\})$. By using the same idea as that of the proof of Theorem 2, it is easy to prove that $\overline{\pi}_i(\{i\}) > \overline{\pi}_i(\varnothing)$.

Case 4: $B(\{i\}) \le x_0^R \le A(\{i\})$. In this case, $\pi_i(\varnothing) = \overline{\pi}_i(\varnothing)$ and $\pi_i(\{i\}) = \pi_i^B(\{i\})$. Notice that

$\frac{\partial \overline{\pi}_i(\varnothing)}{\partial x_0^R} > 0$ and $\frac{\partial \pi_i^B(\{i\})}{\partial x_0^R} \geq 0$ if $x_0^R \leq A(\varnothing)$. Moreover, $\pi_i^B(\{i\}) = \underline{\pi}_i(\{i\}) > \overline{\pi}_i(\varnothing)$ if $x_0^R = A(\{i\})$ and $\pi_i^B(\{i\}) = \overline{\pi}_i(\{i\}) > \overline{\pi}_i(\varnothing)$ if $x_0^R = B(\{i\})$. These imply that $\pi_i^B(\{i\}) > \overline{\pi}_i(\varnothing)$ if $B(\{i\}) \leq x_0^R \leq A(\{i\})$.

Finally, we will prove that $\pi_j(\{i\}) > \pi_j(\{j\})$, $i, j \in \{1,2\}$, $i \neq j$. Without loss of generality, let $i = 2$ and $j = 1$. For the case in which only 2 chooses a quantity restraint, but 1 not, we denote the equilibrium payoff of 1 when $x_0^R > A(\{2\})$ by $\underline{\pi}_1(\{2\})$, that when $B(\{2\}) \leq x_0^R \leq A(\{2\})$ by $\pi_1^B(\{2\})$, and that when $x_0^R < B(\{2\})$ by $\overline{\pi}_1(\{2\})$. That is,

$$\underline{\pi}_1(\{2\}) \equiv \frac{a_1 b_1 (b_0 + d_0)^2 (a_1 - a_0)^2 [a_1(b_0 + d_0) + 2a_0 b_1]^2}{2[a_1(b_0 + d_0) + 3a_0 b_1]^2 [a_1(b_0 + d_0) + a_0 b_1]^2},$$

$$\pi_1^B(\{2\}) \equiv \frac{b_1 [b_0(a_1 - a_0) - a_0 x_0^R]^2}{2a_1 b_0^2}, \text{ and}$$

$$\overline{\pi}_1(\{2\}) \equiv \frac{a_1 b_1 (a_1 d_0 + 2a_0 b_1)^2 [d_0(a_1 - a_0) + a_0 x_0^R]^2}{2(a_1 d_0 + a_0 b_1)^2 (a_1 d_0 + 3a_0 b_1)^2} \quad \text{(see Table 4).}$$

There are three cases to consider.

Case 1: $A(\{2\}) < x_0^R$. In this case, $\pi_1(\{2\}) = \underline{\pi}_1(\{2\})$ and $\pi_1(\{1\}) = \underline{\pi}_1(\{1\})$. By using the same idea as that of the proof of Theorem 2, it is easy to prove that $\underline{\pi}_1(\{2\}) > \underline{\pi}_1(\{1\})$.

Case 2: $B(\{2\}) \leq x_0^R \leq A(\{2\})$. In this case, $\pi_1(\{2\}) = \pi_1^B(\{2\})$ and $\pi_1(\{1\}) = \pi_1^B(\{1\})$. Notice that $\frac{\partial \pi_1^B(\{2\})}{\partial x_0^R} < 0$ and $\frac{\partial \pi_1^B(\{1\})}{\partial x_0^R} > 0$. Therefore, it is sufficient to show that

$\pi_1^B(\{2\}) > \pi_1^B(\{1\})$ if $x_0^R = A(\{1\})$. Let $x_0^R = A(\{1\})$. Then $\pi_1^B(\{2\}) = \overline{\pi}_1(\{2\})$ and $\pi_1^B(\{1\}) = \overline{\pi}_1(\{1\})$. By using the same idea as that of the proof of Theorem 2, it is easy to prove that $\overline{\pi}_1(\{2\}) > \overline{\pi}_1(\{1\})$.

Case 3: $x_0^R < B(\{2\})$. In this case, $\pi_1(\{2\}) = \overline{\pi}_1(\{2\})$ and $\pi_1(\{2\}) = \overline{\pi}_1(\{1\})$. By using the same idea as that of the proof of Theorem 2, it is easy to prove that $\overline{\pi}_1(\{2\}) > \overline{\pi}_1(\{1\})$. ■

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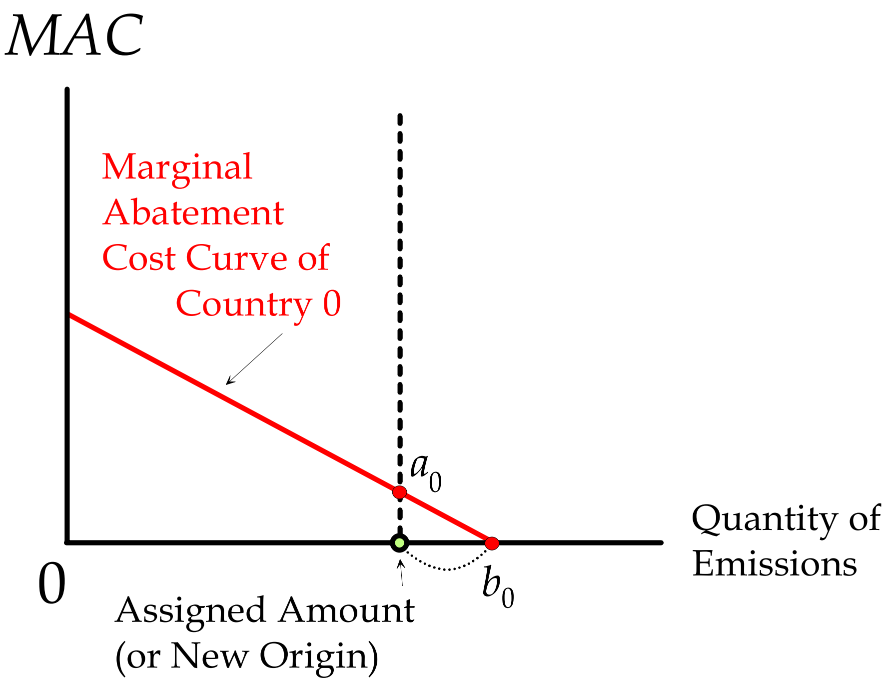

Figure 1-1: Country 0

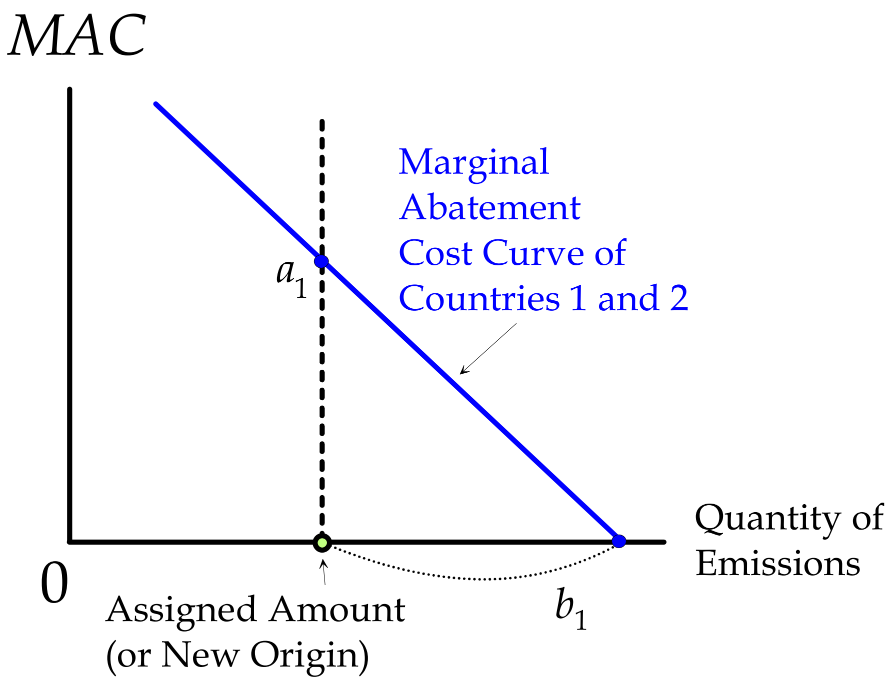

Figure 1-2: Countries 1 and 2

Figure 1. Marginal Abatement Cost Curves and Assigned Amounts

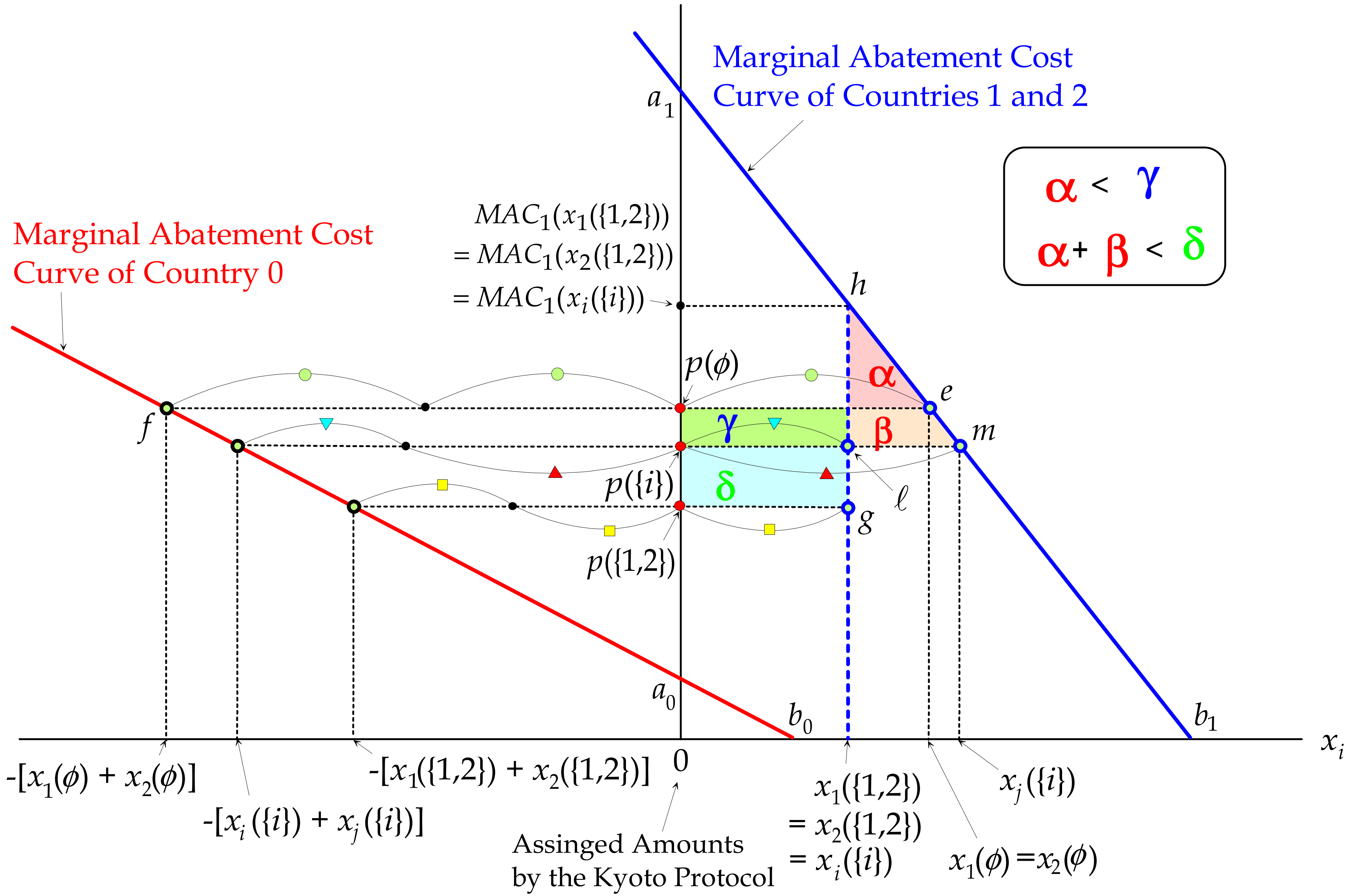

Figure 2. The Equilibrium Quantities, Price, and Payoffs without CDM or Supplier's Quantity Restraint.

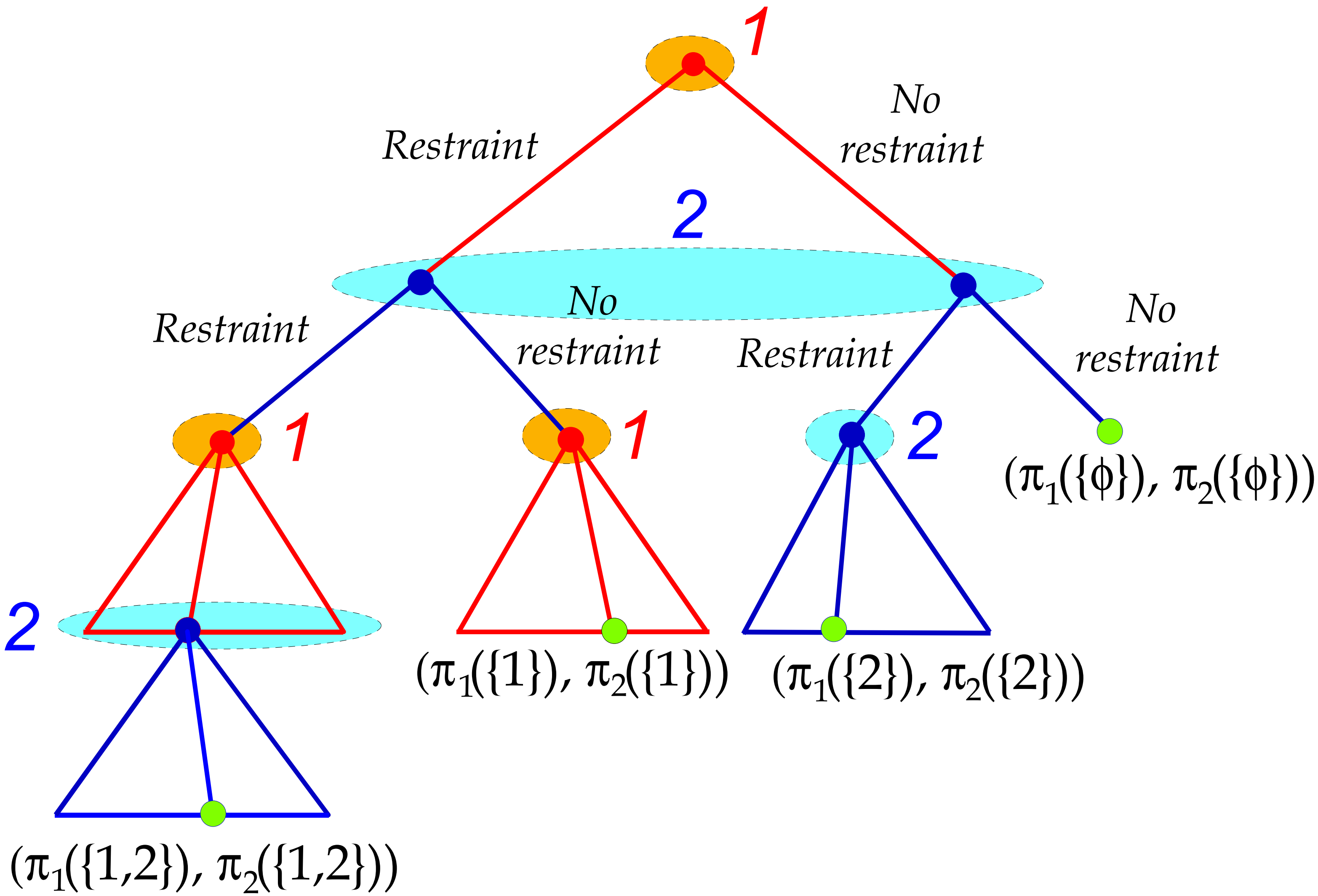

Figure 3. Two stage quantity restraint game tree.

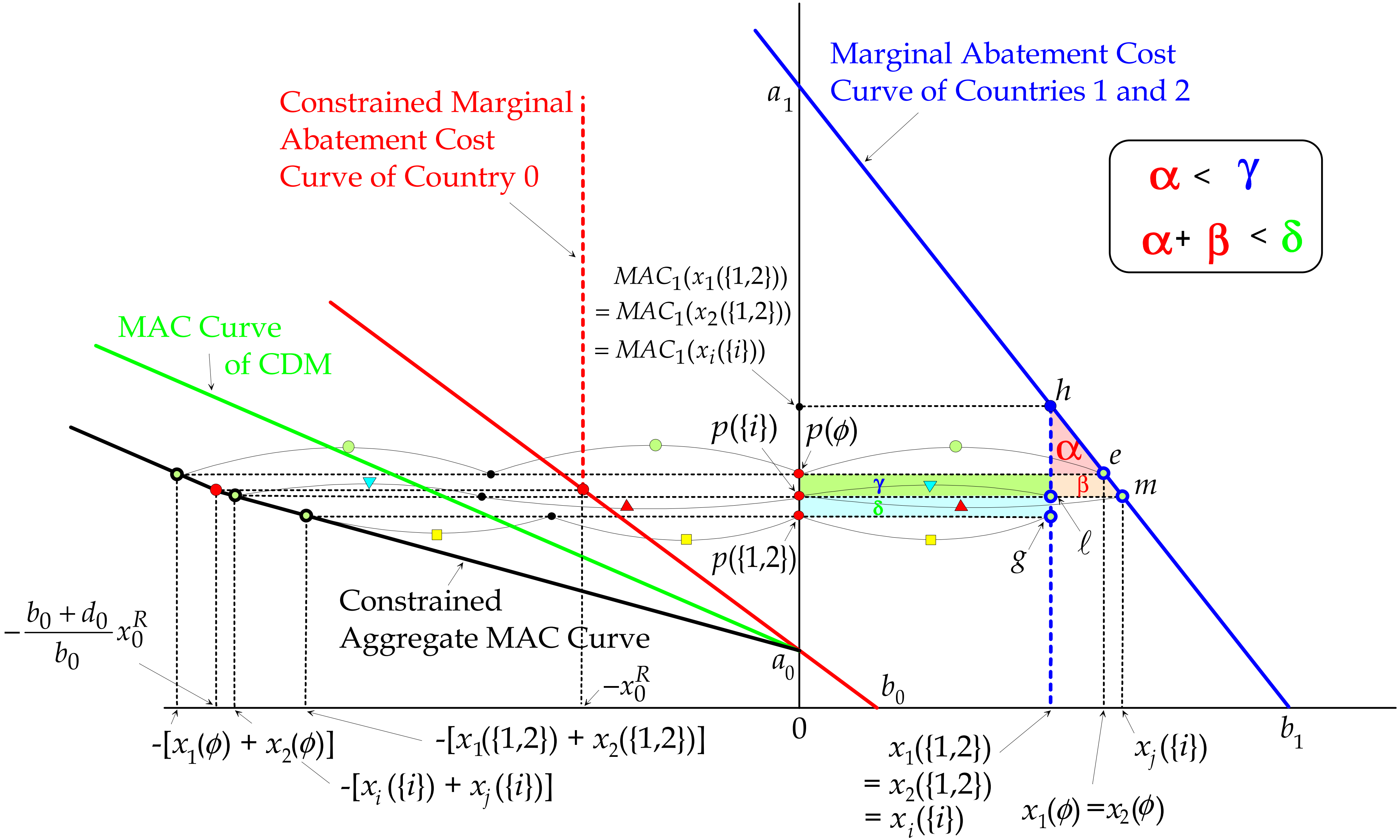

Figure 4. The Equilibrium Quantities, Price, and Payoffs with CDM and Supplier's Quantity Restraint in the case of $A(\{i\}) < x_0^R < A(\phi)$

Figure 5-1: $A(\phi) \leq x_0^R$

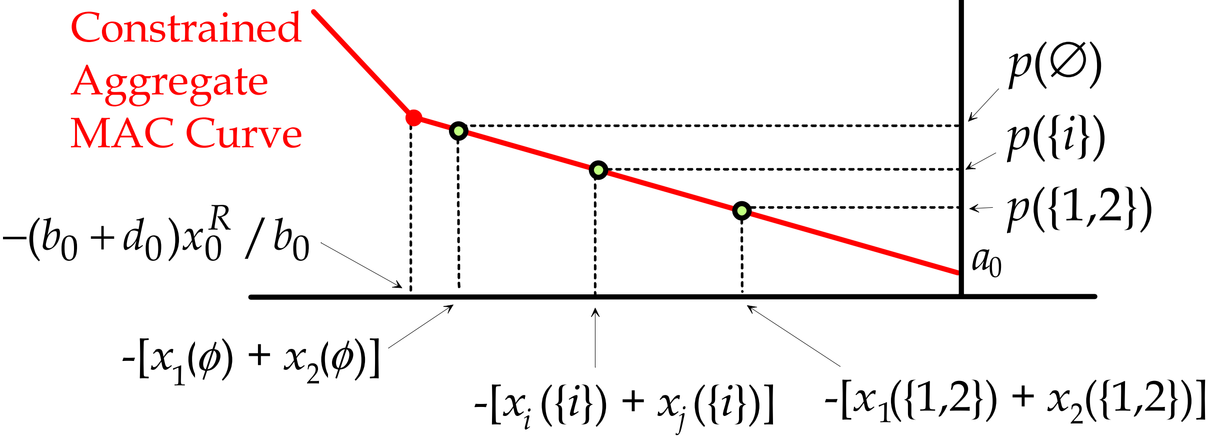

Figure 5-2: $A(\{i\}) < x_0^R < A(\phi)$

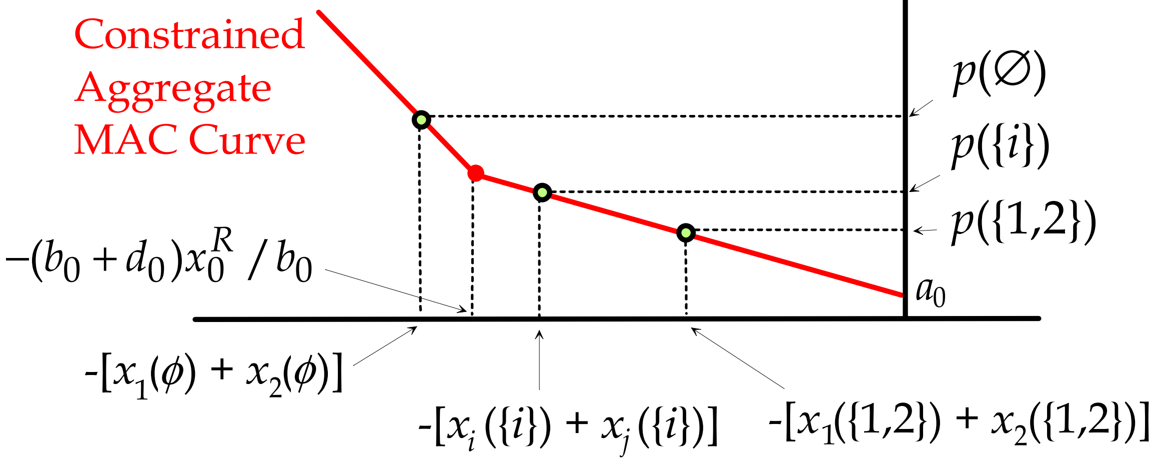

Figure 5-3: $B(\{i\}) \leq x_0^R \leq A(i)$

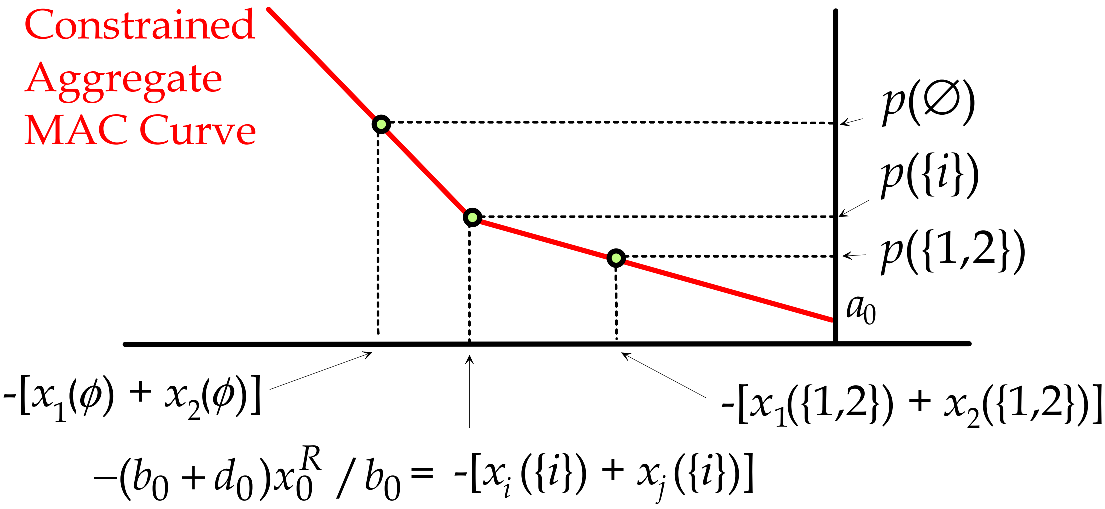

Figure 5-a. The Equilibrium Quantities with CDM and Supplier's Quantity Restraint.

Figure 5-4: $A(\{1,2\}) < x_0^R < B(i)$

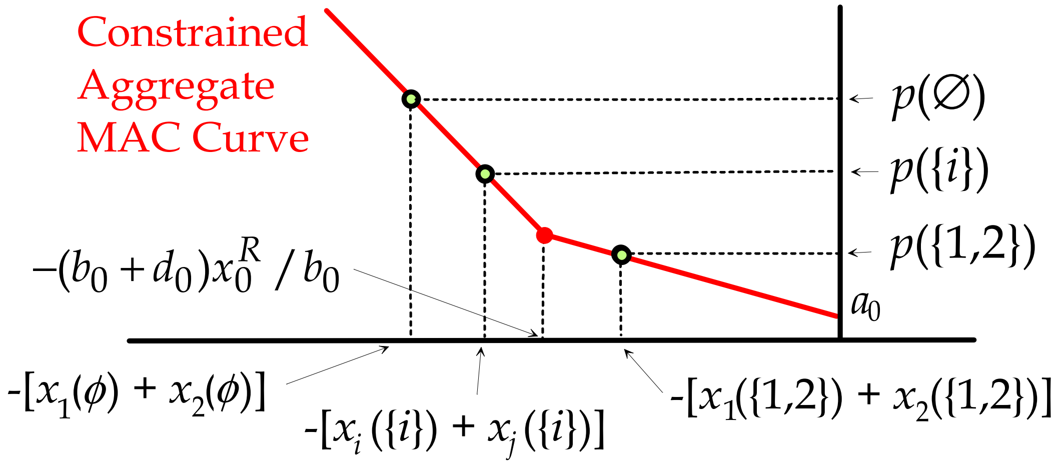

Figure 5-5: $B(\{1,2\}) \leq x_0^R \leq A(1,2)$

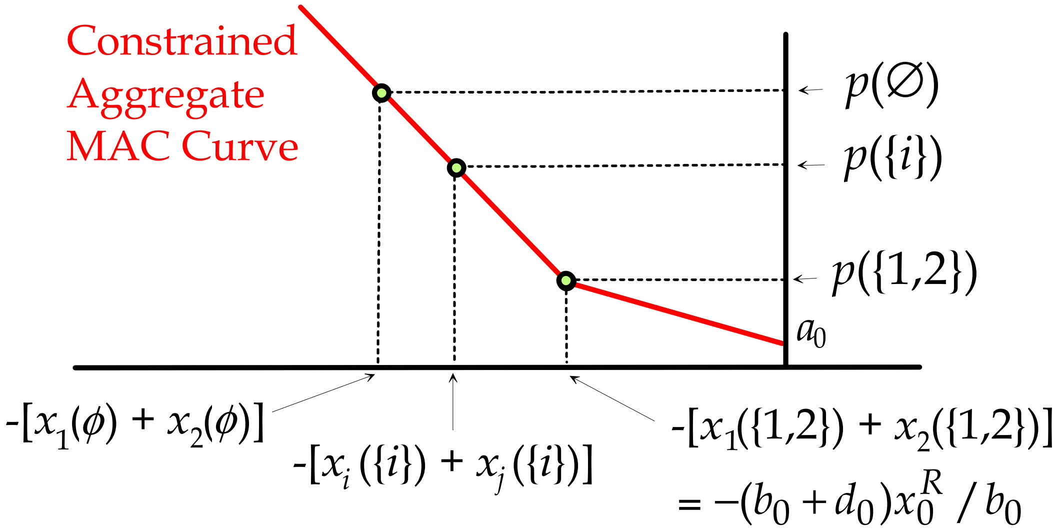

Figure 5-6: $x_0^R < B(\{1,2\})$

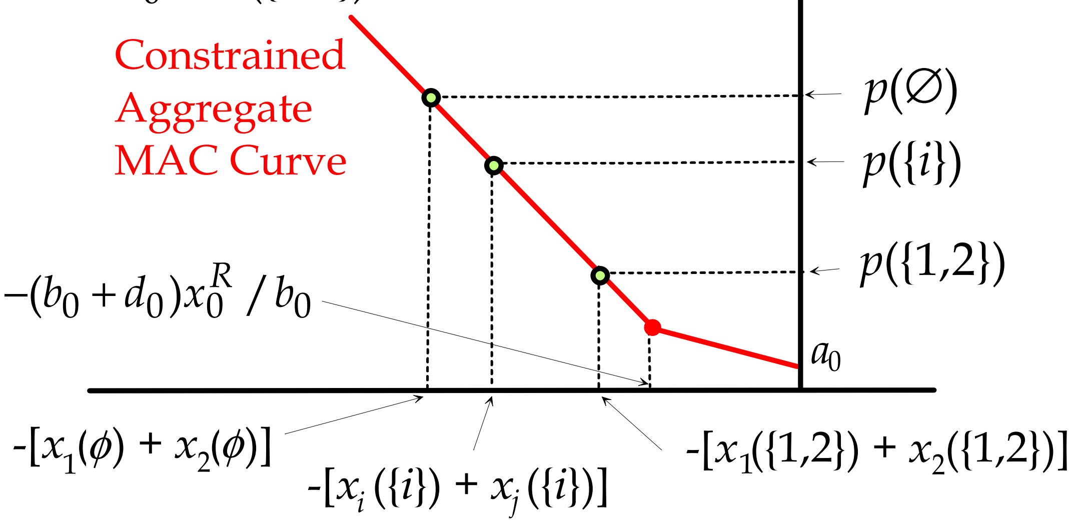

Figure 5-b. The Equilibrium Quantities with CDM and Supplier's Quantity Restraint.

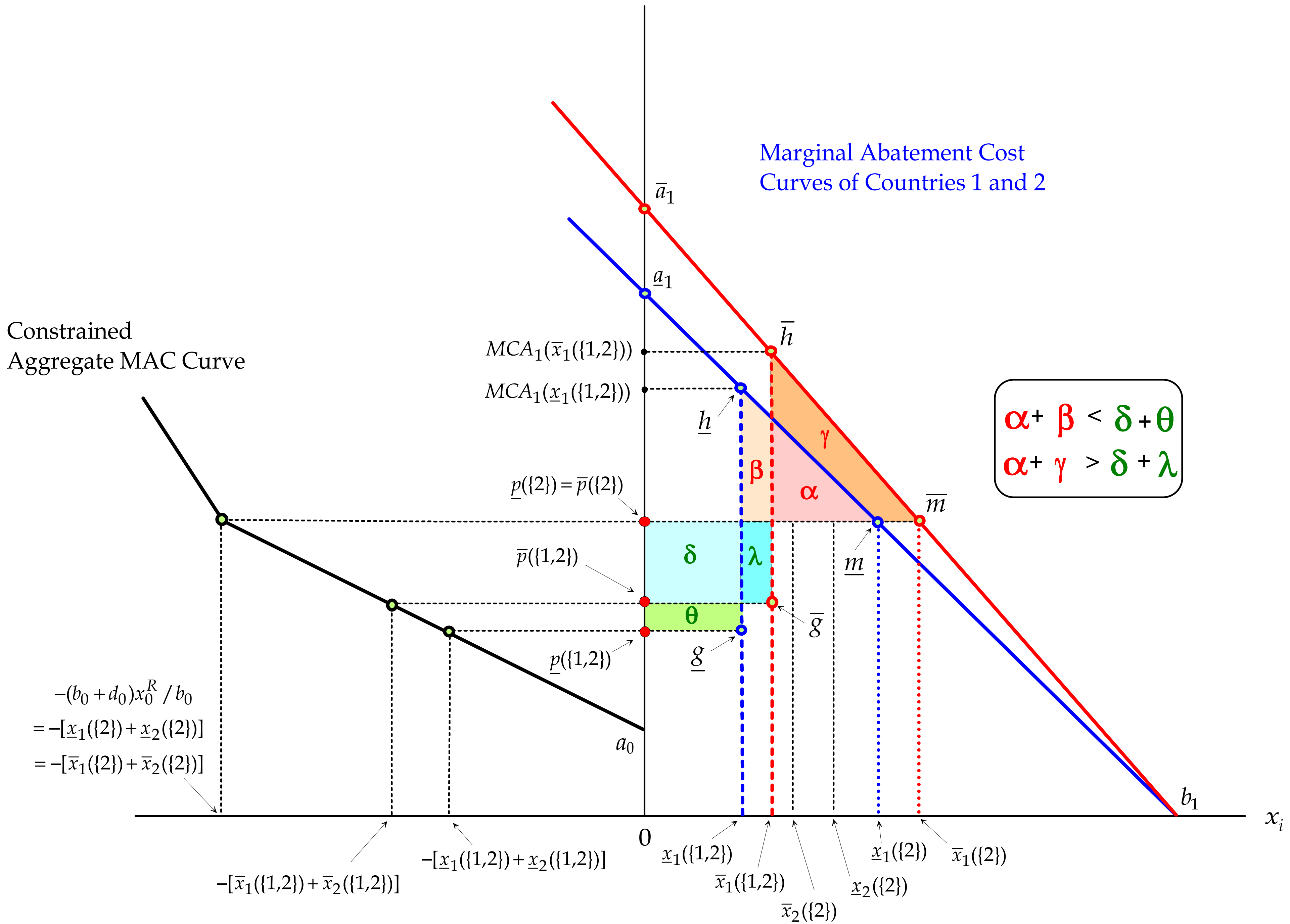

Figure 6. Comparison of Equilibrium Payoffs when the Vaule of a_1 Changes: the Case of $B(\{1\}) \le x_0^R \le A(\{1\})$

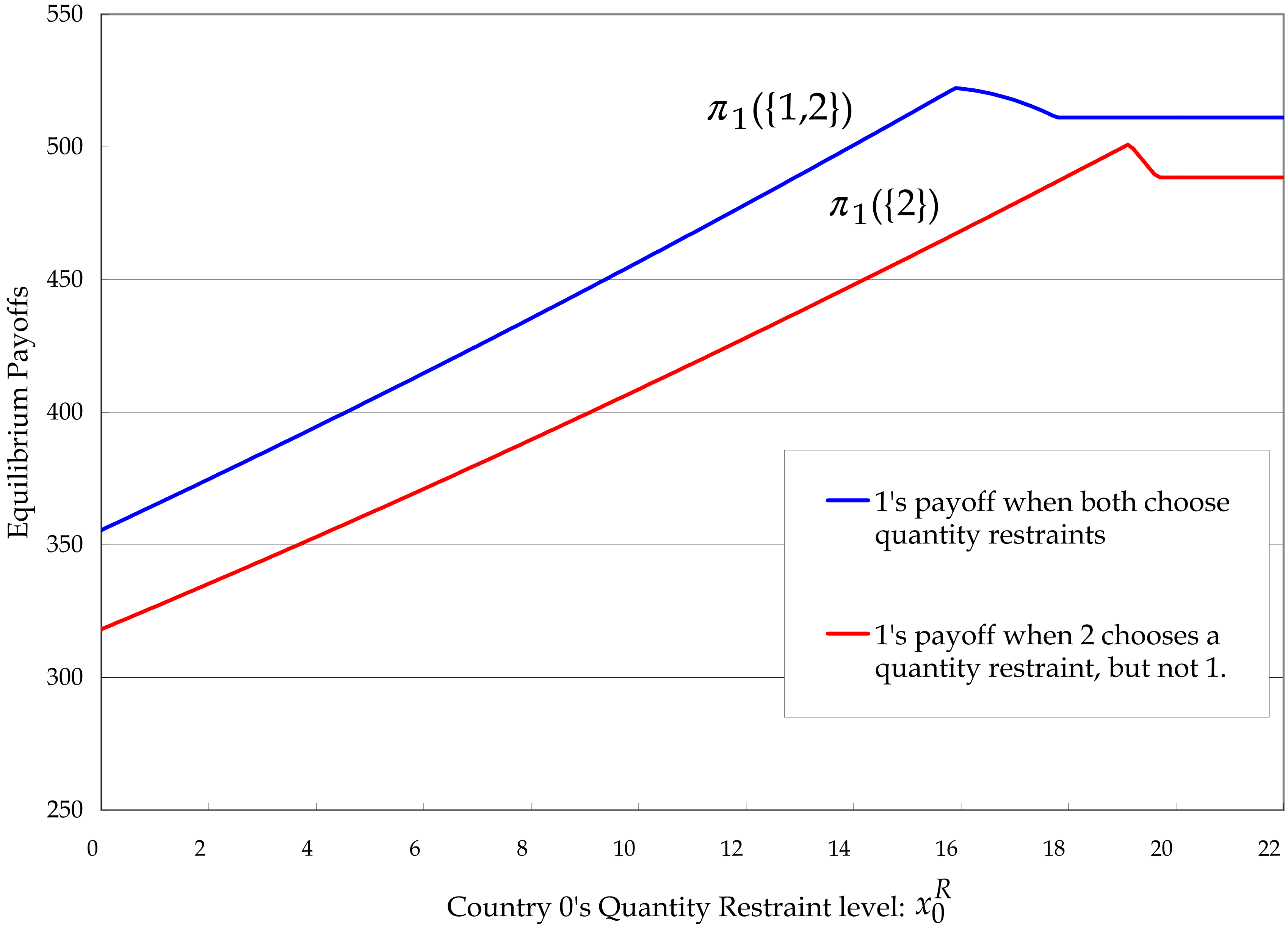

Figure 7. Comparison of Equilibrium Payoffs: Example 1

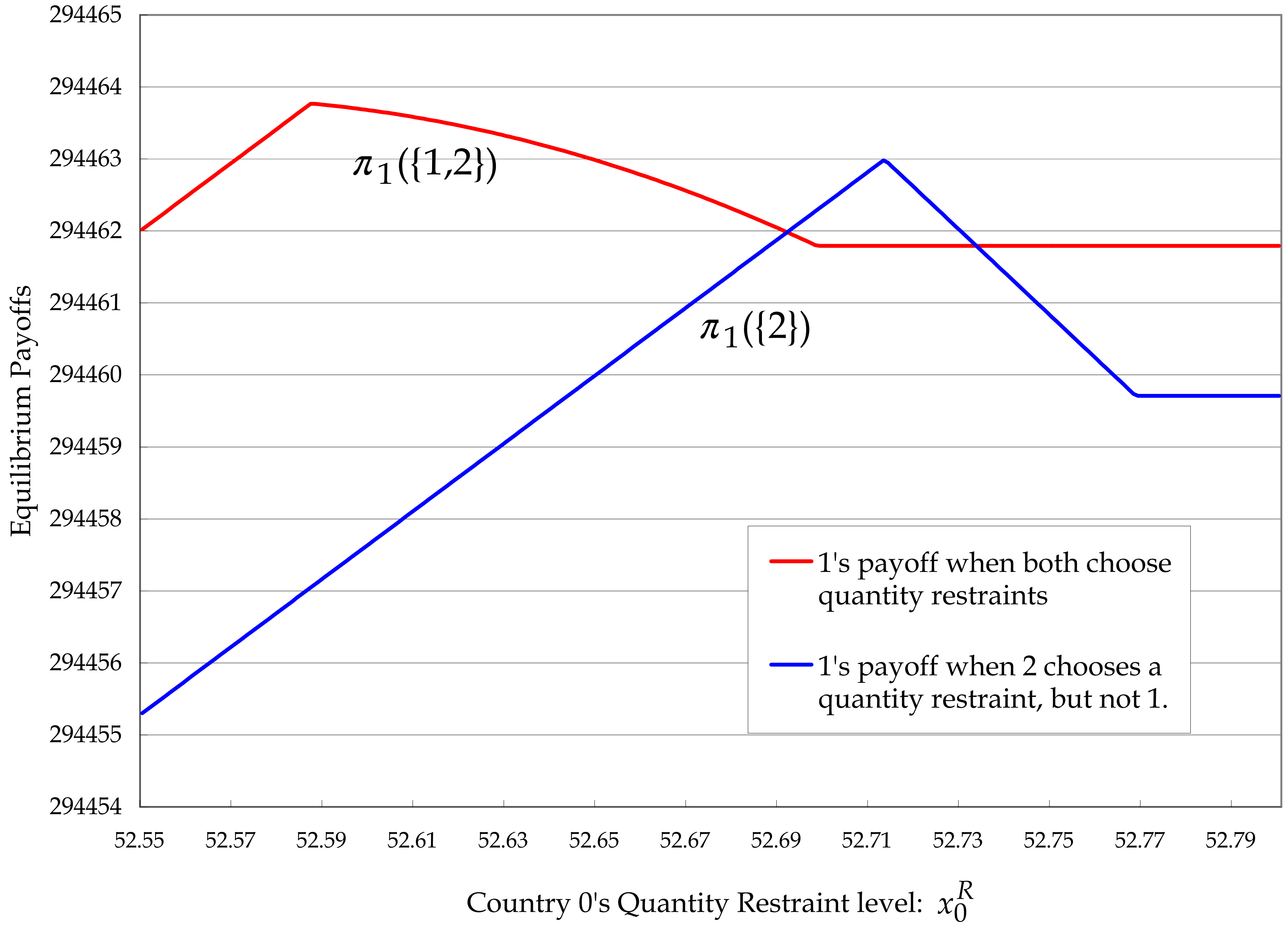

Figure 8. Comparison of Equilibrium Payoffs: Example 2

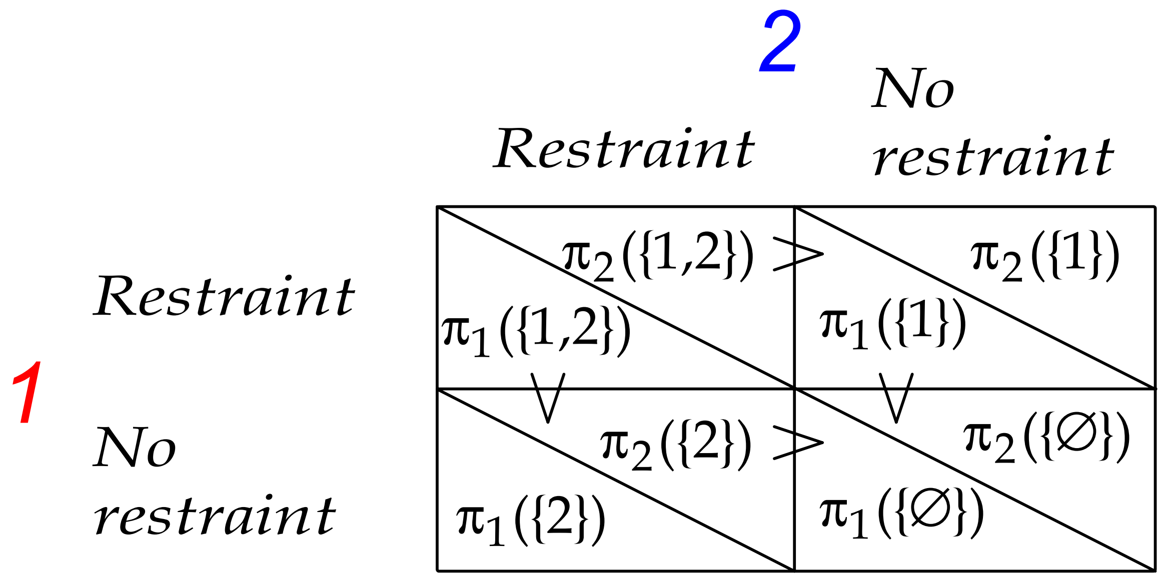

Table 1. The Payoff Matrix for the First Stage Decisions without CDM or Supplier's Quantity Restraint.

	Neither country 1 nor 2 chooses a quantity restraint.	Only one country i chooses a quantity restraint.		Both countries 1 and 2 choose quantity restraints.
	$x_i(\varnothing)\,,\ i=1,2$	$x_i(\{i\})$	$x_j(\{i\})\,,\ j\neq i$	$x_i(\{1,2\})\,,\ i=1,2$
$A(\varnothing)\le x_0^R$	$\dfrac{b_1(b_0+d_0)(a_1-a_0)}{a_1(b_0+d_0)+2a_0b_1}$	$\dfrac{b_1(b_0+d_0)(a_1-a_0)}{a_1(b_0+d_0)+3a_0b_1}$	$\dfrac{b_1(b_0+d_0)(a_1-a_0)[a_1(b_0+d_0)+2a_0b_1]}{[a_1(b_0+d_0)+3a_0b_1][a_1(b_0+d_0)+a_0b_1]}$	$\dfrac{b_1(b_0+d_0)(a_1-a_0)}{a_1(b_0+d_0)+3a_0b_1}$
$A(\{i\})<x_0^R<A(\varnothing)$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R]}{a_1d_0+2a_0b_1}$	$\dfrac{b_1(b_0+d_0)(a_1-a_0)}{a_1(b_0+d_0)+3a_0b_1}$	$\dfrac{b_1(b_0+d_0)(a_1-a_0)[a_1(b_0+d_0)+2a_0b_1]}{[a_1(b_0+d_0)+3a_0b_1][a_1(b_0+d_0)+a_0b_1]}$	$\dfrac{b_1(b_0+d_0)(a_1-a_0)}{a_1(b_0+d_0)+3a_0b_1}$
$B(\{i\})\le x_0^R\le A(\{i\})$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R]}{a_1d_0+2a_0b_1}$	$\dfrac{x_0^R[a_1(b_0+d_0)+a_0b_1]-b_0b_1(a_1-a_0)}{a_1b_0}$	$\dfrac{b_1[b_0(a_1-a_0)-a_0x_0^R]}{a_1b_0}$	$\dfrac{b_1(b_0+d_0)(a_1-a_0)}{a_1(b_0+d_0)+3a_0b_1}$
$A(\{1,2\})<x_0^R<B(\{i\})$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R]}{a_1d_0+2a_0b_1}$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R]}{a_1d_0+3a_0b_1}$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R][a_1d_0+2a_0b_1]}{(a_1d_0+a_0b_1)(a_1d_0+3a_0b_1)}$	$\dfrac{b_1(b_0+d_0)(a_1-a_0)}{a_1(b_0+d_0)+3a_0b_1}$
$B(\{1,2\})\le x_0^R\le A(\{1,2\})$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R]}{a_1d_0+2a_0b_1}$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R]}{a_1d_0+3a_0b_1}$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R][a_1d_0+2a_0b_1]}{(a_1d_0+a_0b_1)(a_1d_0+3a_0b_1)}$	$\dfrac{x_0^R(b_0+d_0)}{2b_0}$
$x_0^R<B(\{1,2\})$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R]}{a_1d_0+2a_0b_1}$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R]}{a_1d_0+3a_0b_1}$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R][a_1d_0+2a_0b_1]}{(a_1d_0+a_0b_1)(a_1d_0+3a_0b_1)}$	$\dfrac{b_1[d_0(a_1-a_0)+a_0x_0^R]}{a_1d_0+3a_0b_1}$

$$A(\varnothing)\equiv\frac{2b_0b_1(a_1-a_0)}{a_1(b_0+d_0)+2a_0b_1},\ A(\{i\})\equiv\frac{b_0b_1(a_1-a_0)[2a_1(b_0+d_0)+3a_0b_1]}{[a_1(b_0+d_0)+3a_0b_1][a_1(b_0+d_0)+a_0b_1]},\ B(\{i\})\equiv\frac{b_0b_1(a_1-a_0)[2a_1d_0+3a_0b_1]}{[a_1(b_0+d_0)+3a_0b_1](a_1d_0+a_0b_1)+a_0a_1b_0b_1},$$

$$A(\{1,2\})\equiv\frac{2b_1b_0(a_1-a_0)}{a_1(b_0+d_0)+3a_0b_1},\ \text{and}\ \ B(\{1,2\})\equiv\frac{2b_1b_0d_0(a_1-a_0)}{d_0[a_1(b_0+d_0)+3a_0b_1]+a_0b_0b_1}.$$

Table 2. The Equilibrium Quantities with CDM and Supplier's Quantity Restraint.

	Neither country 1 nor 2 chooses a quantity restraint.	Only one country i chooses a quantity restraint.	Both countries 1 and 2 choose quantity restraints.
	$p(\varnothing)$	$p(\{i\})$	$p(\{1,2\})$
$A(\varnothing) \le x_0^R$	$\frac{a_0 a_1 (b_0 + d_0 + 2b_1)}{a_1(b_0 + d_0) + 2a_0 b_1}$	$\frac{a_0 a_1 \{b_1[2a_1(b_0+d_0)+3a_0b_1]+(b_0+d_0)[a_1(b_0+d_0)+2a_0b_1]\}}{[a_1(b_0+d_0)+3a_0b_1][a_1(b_0+d_0)+a_0b_1]}$	$\frac{a_0\{a_1[(b_0+d_0)+2b_1]+a_0b_1\}}{a_1(b_0+d_0)+3a_0b_1}$
$A(\{i\}) < x_0^R < A(\varnothing)$	$\frac{a_0 a_1(2b_1 + d_0 - x_0^R)}{a_1 d_0 + 2a_0 b_1}$	$\frac{a_0 a_1 \{b_1[2a_1(b_0+d_0)+3a_0b_1]+(b_0+d_0)[a_1(b_0+d_0)+2a_0b_1]\}}{[a_1(b_0+d_0)+3a_0b_1][a_1(b_0+d_0)+a_0b_1]}$	$\frac{a_0\{a_1[(b_0+d_0)+2b_1]+a_0b_1\}}{a_1(b_0+d_0)+3a_0b_1}$
$B(\{i\}) \le x_0^R \le A(\{i\})$	$\frac{a_0 a_1(2b_1 + d_0 - x_0^R)}{a_1 d_0 + 2a_0 b_1}$	$\frac{a_0(b_0 + x_0^R)}{b_0}$	$\frac{a_0\{a_1[(b_0+d_0)+2b_1]+a_0b_1\}}{a_1(b_0+d_0)+3a_0b_1}$
$A(\{1,2\}) < x_0^R < B(\{i\})$	$\frac{a_0 a_1(2b_1 + d_0 - x_0^R)}{a_1 d_0 + 2a_0 b_1}$	$\frac{a_0 a_1\{b_1(2a_1d_0+3a_0b_1)+(a_1d_0+2a_0b_1)(d_0-x_0^R)\}}{(a_1d_0+a_0b_1)(a_1d_0+3a_0b_1)}$	$\frac{a_0\{a_1[(b_0+d_0)+2b_1]+a_0b_1\}}{a_1(b_0+d_0)+3a_0b_1}$
$B(\{1,2\}) \le x_0^R \le A(\{1,2\})$	$\frac{a_0 a_1(2b_1 + d_0 - x_0^R)}{a_1 d_0 + 2a_0 b_1}$	$\frac{a_0 a_1\{b_1(2a_1d_0+3a_0b_1)+(a_1d_0+2a_0b_1)(d_0-x_0^R)\}}{(a_1d_0+a_0b_1)(a_1d_0+3a_0b_1)}$	$\frac{a_0(b_0 + x_0^R)}{b_0}$
$x_0^R < B(\{1,2\})$	$\frac{a_0 a_1(2b_1 + d_0 - x_0^R)}{a_1 d_0 + 2a_0 b_1}$	$\frac{a_0 a_1\{b_1(2a_1d_0+3a_0b_1)+(a_1d_0+2a_0b_1)(d_0-x_0^R)\}}{(a_1d_0+a_0b_1)(a_1d_0+3a_0b_1)}$	$\frac{a_0\{d_0[a_1d_0+b_1(a_0+2a_1)]-x_0^R(a_1d_0+a_0b_1)\}}{d_0[a_1d_0+3a_0b_1]}$

$$A(\varnothing) \equiv \frac{2b_0b_1(a_1-a_0)}{a_1(b_0+d_0)+2a_0b_1},\ A(\{i\}) \equiv \frac{b_0b_1(a_1-a_0)[2a_1(b_0+d_0)+3a_0b_1]}{[a_1(b_0+d_0)+3a_0b_1][a_1(b_0+d_0)+a_0b_1]},\ B(\{i\}) \equiv \frac{b_0b_1(a_1-a_0)[2a_1d_0+3a_0b_1]}{[a_1(b_0+d_0)+3a_0b_1](a_1d_0+a_0b_1)+a_0a_1b_0b_1},$$

$$A(\{1,2\}) \equiv \frac{2b_1b_0(a_1-a_0)}{a_1(b_0+d_0)+3a_0b_1}, \text{ and } B(\{1,2\}) \equiv \frac{2b_1b_0d_0(a_1-a_0)}{d_0[a_1(b_0+d_0)+3a_0b_1]+a_0b_0b_1}.$$

Table 3. The Equilibrium Prices with CDM and Supplier's Quantity Restraint.

	Neither country 1 nor 2 chooses a quantity restraint.	Only one country i chooses a quantity restraint.		Both countries 1 and 2 choose quantity restraints.
	$\pi_i(\varnothing)$, $i=1,2$	$\pi_i(\{i\})$	$\pi_j(\{i\})$, $j \neq i$	$\pi_i(\{1,2\})$, $i=1,2$
$A(\varnothing) \leq x_0^R$	$\frac{a_1b_1(b_0+d_0)^2(a_1-a_0)^2}{2[a_1(b_0+d_0)+2a_0b_1]^2}$	$\frac{a_1b_1(b_0+d_0)^2(a_1-a_0)^2}{2[a_1(b_0+d_0)+a_0b_1][a_1(b_0+d_0)+3a_0b_1]}$	$\frac{a_1b_1(b_0+d_0)^2(a_1-a_0)^2[a_1(b_0+d_0)+2a_0b_1]^2}{2[a_1(b_0+d_0)+3a_0b_1]^2[a_1(b_0+d_0)+a_0b_1]^2}$	$\frac{b_1(b_0+d_0)[a_1(b_0+d_0)+2a_0b_1](a_1-a_0)^2}{2[a_1(b_0+d_0)+3a_0b_1]^2}$
$A(\{i\}) < x_0^R < A(\varnothing)$	$\frac{a_1b_1[d_0(a_1-a_0)+a_0x_0^R]^2}{2[a_1d_0+2a_0b_1]^2}$	$\frac{a_1b_1(b_0+d_0)^2(a_1-a_0)^2}{2[a_1(b_0+d_0)+a_0b_1][a_1(b_0+d_0)+3a_0b_1]}$	$\frac{a_1b_1(b_0+d_0)^2(a_1-a_0)^2[a_1(b_0+d_0)+2a_0b_1]^2}{2[a_1(b_0+d_0)+3a_0b_1]^2[a_1(b_0+d_0)+a_0b_1]^2}$	$\frac{b_1(b_0+d_0)[a_1(b_0+d_0)+2a_0b_1](a_1-a_0)^2}{2[a_1(b_0+d_0)+3a_0b_1]^2}$
$B(\{i\}) \leq x_0^R \leq A(\{i\})$	$\frac{a_1b_1[d_0(a_1-a_0)+a_0x_0^R]^2}{2[a_1d_0+2a_0b_1]^2}$	$\frac{CD}{2a_1b_0^2b_1}$, where $C \equiv x_0^R[a_1(b_0+d_0)+a_0b_1]-b_0b_1(a_1-a_0)$ $D \equiv 3b_0b_1(a_1-a_0)-x_0^R[a_1(b_0+d_0)+3a_0b_1]$	$\frac{b_1[b_0(a_1-a_0)-a_0x_0^R]^2}{2a_1b_0^2}$	$\frac{b_1(b_0+d_0)[a_1(b_0+d_0)+2a_0b_1](a_1-a_0)^2}{2[a_1(b_0+d_0)+3a_0b_1]^2}$
$A(\{1,2\}) < x_0^R < B(\{i\})$	$\frac{a_1b_1[d_0(a_1-a_0)+a_0x_0^R]^2}{2[a_1d_0+2a_0b_1]^2}$	$\frac{a_1b_1(a_1d_0+3a_0b_1)[d_0(a_1-a_0)+a_0x_0^R]^2}{2(a_1d_0+a_0b_1)(a_1d_0+3a_0b_1)^2}$	$\frac{a_1b_1(a_1d_0+2a_0b_1)^2[d_0(a_1-a_0)+a_0x_0^R]^2}{2(a_1d_0+a_0b_1)^2(a_1d_0+3a_0b_1)^2}$	$\frac{b_1(b_0+d_0)[a_1(b_0+d_0)+2a_0b_1](a_1-a_0)^2}{2[a_1(b_0+d_0)+3a_0b_1]^2}$
$B(\{1,2\}) \leq x_0^R \leq A(\{1,2\}$	$\frac{a_1b_1[d_0(a_1-a_0)+a_0x_0^R]^2}{2[a_1d_0+2a_0b_1]^2}$	$\frac{a_1b_1(a_1d_0+3a_0b_1)[d_0(a_1-a_0)+a_0x_0^R]^2}{2(a_1d_0+a_0b_1)(a_1d_0+3a_0b_1)^2}$	$\frac{a_1b_1(a_1d_0+2a_0b_1)^2[d_0(a_1-a_0)+a_0x_0^R]^2}{2(a_1d_0+a_0b_1)^2(a_1d_0+3a_0b_1)^2}$	$\frac{(b_0+d_0)x_0^RE}{8b_0^2b_1}$, where $E \equiv 4b_0b_1(a_1-a_0)-x_0^R[a_1(b_0+d_0)+4a_0b_1]$
$x_0^R < B(\{1,2\})$	$\frac{a_1b_1[d_0(a_1-a_0)+a_0x_0^R]^2}{2[a_1d_0+2a_0b_1]^2}$	$\frac{a_1b_1(a_1d_0+3a_0b_1)[d_0(a_1-a_0)+a_0x_0^R]^2}{2(a_1d_0+a_0b_1)(a_1d_0+3a_0b_1)^2}$	$\frac{a_1b_1(a_1d_0+2a_0b_1)^2[d_0(a_1-a_0)+a_0x_0^R]^2}{2(a_1d_0+a_0b_1)^2(a_1d_0+3a_0b_1)^2}$	$\frac{b_1(a_1d_0+2a_0b_1)[d_0(a_1-a_0)+a_0x_0^R]^2}{2d_0[a_1d_0+3a_0b_1]^2}$

$A(\varnothing) \equiv \frac{2b_0b_1(a_1-a_0)}{a_1(b_0+d_0)+2a_0b_1}$, $A(\{i\}) \equiv \frac{b_0b_1(a_1-a_0)[2a_1(b_0+d_0)+3a_0b_1]}{[a_1(b_0+d_0)+3a_0b_1][a_1(b_0+d_0)+a_0b_1]}$, $B(\{i\}) \equiv \frac{b_0b_1(a_1-a_0)[2a_1d_0+3a_0b_1]}{[a_1(b_0+d_0)+3a_0b_1](a_1d_0+a_0b_1)+a_0a_1b_0b_1}$, $A(\{1,2\}) \equiv \frac{2b_1b_0(a_1-a_0)}{a_1(b_0+d_0)+3a_0b_1}$, and

$B(\{1,2\}) \equiv \frac{2b_1b_0d_0(a_1-a_0)}{d_0[a_1(b_0+d_0)+3a_0b_1]+a_0b_0b_1}$.

Table 4. The Equilibrium Payoffs with CDM and Supplier's Quantity Restraint.

1 \ 2	Restraint		No restraint
Restraint	$\pi_1(\{1,2\})$, $\pi_2(\{1,2\})$	$<$	$\pi_1(\{1\})$, $\pi_2(\{1\})$
	$\wedge$		$\vee$
No restraint	$\pi_1(\{2\})$, $\pi_2(\{2\})$	$>$	$\pi_1(\{\emptyset\})$, $\pi_2(\{\emptyset\})$

Table 5. The case in which only one country chooses a quantity restraint.