# How Effective and Efficient Can the Kyoto Protocol Be in Controlling Global Carbon Emissions?

By

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**Abstract:** We derive the circumstances under which the Kyoto Protocol lead to effective and efficient control of emissions of carbon dioxide. We focus attention to abatement of carbon emissions produced as by-products of industrial production or deforestation. Since carbon emissions generate a positive private consumption benefit as well as a negative and global externality, we utilize the impure public good model to describe tastes. We find that both abatement trading and interregional transfers, implemented by an international authority, are necessary for the efficiency and effectiveness of the Kyoto Protocol. The equilibrium for the Kyoto Protocol game is Pareto efficient.

The Kyoto Protocol to the United Nations Framework Convention on Climate Change, completed December 10, 1997, will probably be remembered most for its innovative use of emissions trading to control global greenhouse gas emissions.[1] However, it will also be remembered for the promulgation of two other incentives – clean development mechanisms and international transfers. The idea behind clean development mechanisms is articulated in Article 11 of the protocol, whereby (1) "[less developed] countries will benefit from project activities resulting in certified emissions reductions," and (2) "[developed countries] may use the certified emissions reductions accruing from such project activities to contribute to compliance with part of their quantified emission limitation and reduction commitments."

In this paper, we derive the circumstances under which the Kyoto Protocol lead to effective and efficient control of global carbon emissions. We focus attention to abatement of carbon emissions produced as by-products of industrial production or deforestation. As such, carbon emissions generate a positive private consumption benefit as well as a negative and global externality. Thus, it seems natural to assume that the impure public good model provides an accurate description of tastes. In our framework, we assume that consumption preferences for each region -- for simplicity, there are only two -- can be represented by a single consumer and that both regions may participate in carbon abatement trading. There is an international agency, say the Global Environment

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[1] That emissions trading is a cost-effective means of controlling pollution is not much in debate. The theory behind its use is generally clear, simple, and favorable: compared to command-and-control policies, such as uniform quotas, emissions trading induces firms to obtain the same aggregate level of control at lower total cost (c.f. Tietenberg, 1992; Hanley, et al., 1997). Moreover, similar types of marketable permit programs in the U.S. used to control water, lead, and air pollution, have proven effective (Hahn, 1989; Stavins, 1998). All told, an impressive amount of research and experience underscores the benefits and costs associated with emissions trading programs (see Maloney and Yandle (1984), Coggins and Swinton (1996) and references therein).

Facility (GEF), whose objective is to implement interregional income transfers in order to satisfy a politically determined distribution of utility levels between the regions. The GEF lacks political and economical powers to design and enforce international mechanisms to control emissions of carbon dioxide.  This realistic assumption implies, for example, that the GEF is not capable of punishing regions that do not comply with international standards.  The interregional transfers implemented by the GEF are redistributive, namely, they are effected *after* the regions choose their own environmental actions, including abatement trading.

We start the analysis by characterizing a Pareto efficient allocation. Then, we examine a Stackelberg game, called ‘Kyoto Protocol’, whereby both regions provide and trade abatement units prior to the GEF deciding on the level of interregional transfer to be made. The regions are Stackelberg leaders and the GEF is a common Stackelberg follower. As we mentioned above, the GEF effects interregional transfers after it observes the decisions of the regions. The equilibrium concept used for the Kyoto Protocol game is subgame perfection.

For comparison purposes, we investigate two other noncooperative games. In the game called 'Autarky With Interregional Transfers,' we examine a situation similar to the Kyoto Protocol except that the regions do not trade abatement units. In the game 'Abatement Trading Without Interregional Transfers,' we assume that both regions can provide and trade abatement units, but there is no mechanism in place for the implementation of interregional transfers. Since each one of these games deviates from the Kyoto Protocol game in only one 'dimension,' the comparisons between the equilibrium for each game equilibrium and the equilibrium for the Kyoto Protocol game are immediate and informative: they reveal that both abatement trading and interregional transfers are necessary conditions for the efficiency of the Kyoto Protocol! While we find that the subgame perfect equilibrium for the Kyoto Protocol game is Pareto efficient, the equilibria for the other two noncooperative games are generally inefficient.

## **The Model**

Imagine an economy consisting of two politically autonomous regions, indexed by j, j = 1, 2, two regional governments and an international authority, the Global Environment Facility (GEF). The GEF is created by both regions to implement interregional transfers. The regions decide ex-ante the allocation of minimum utility levels that must be satisfied by any global agreement. Formally, let $\bar{u}^j$ denote region j's reservation level of utility. Any interregional transfer scheme implemented by the GEF must give region j a level of utility at least as high as $\bar{u}^j$.

There are three commodities, a numeraire good, a regional good and a 'global' good. The representative individual of region j derives the following utility from consumption of $x_j$ units of the numeraire good, $a_j$ units of regional pollution abatement and $A = a_1 + a_2$ units of global pollution abatement:

$$u^j \equiv u^j(x_j, a_j, A).$$

This utility function is assumed to be strictly concave, increasing in the first and third elements and decreasing in the second element. Provision of pollution abatement in region j reduces the availability of a commodity (e.g., electricity) that is positively related to positive emissions of carbon dioxide. The cost of pollution abatement, in terms of the numeraire good, in region j is $c^j \equiv c^j(a_j)$. This cost function is assumed to be strictly convex and increasing. Finally, the representative individual's income level in region j is denoted $m_j$.

## Pareto Efficiency

A Pareto efficient allocation can be obtained as a solution to the following problem:

$$\underset{\{x_1, x_2, a_1, a_2\}}{\text{Max}}\ u^1(x_1, a_1, a_1 + a_2)$$

$$\text{s.t.:} \quad u^2(x_2, a_2, a_1 + a_2) \geq \bar{u}^2 \qquad (\mu \geq 0)$$

$$x_1 + x_2 + c^1(a_1) + c^2(a_2) \leq m_1 + m_2 \qquad (\lambda \geq 0)$$

The Lagrangian is

$$L = u^1(x_1, a_1, a_1 + a_2) - \mu\left(\bar{u}^2 - u^2(x_2, a_2, a_1 + a_2)\right) - \lambda\left(x_1 + x_2 + c^1(a_1) + c^2(a_2) - m_1 - m_2\right).$$

Assuming an interior solution, the first order conditions are:

$$\frac{\partial L}{\partial x_1} = u^1_x - \lambda = 0 \Rightarrow u^1_x = \lambda > 0 \Rightarrow x_1 + x_2 + c^1(a_1) + c^2(a_2) = m_1 + m_2. \qquad (1)$$

$$\frac{\partial L}{\partial x_2} = \mu\, u^2_x - \lambda = 0 \Rightarrow \mu = \frac{\lambda}{u^2_x} > 0 \Rightarrow u^2(x_2, a_2, a_1 + a_2) = \bar{u}^2. \qquad (2)$$

$$\frac{\partial L}{\partial a_1} = u^1_a + u^1_A + \mu\, u^2_A - \lambda\, c^1_a = 0 \Rightarrow \frac{u^1_A}{u^1_x} + \frac{u^2_A}{u^2_x} = c^1_a - \frac{u^1_a}{u^1_x}. \qquad (3)$$

$$\frac{\partial L}{\partial a_2} = u^1_A + \mu\left(u^2_a + u^2_A\right) - \lambda\, c^2_a = 0 \Rightarrow \frac{u^1_A}{u^1_x} + \frac{u^2_A}{u^2_x} = c^2_a - \frac{u^2_a}{u^2_x}. \qquad (4)$$

Equation (1) tells us that it is efficient to fully employ all resources available. Equation (2) shows that maximization of region 1's utility requires keeping region 2's utility at its "reservation level." Equations (3) and (4) are the Samuelson conditions. The right hand side of each equation represents the marginal social benefit of abatement provision -- i.e., the sum of the marginal rates of substitution between the public good and the numeraire good. The left hand side of each equation represents the marginal regional cost of abatement provision -- i.e., the sum of marginal production and utility costs of abatement provision in terms of the numeraire good. For future reference, it is important to note that equations (3) and (4) imply the equalization of marginal regional costs of abatement provision:

$$c_a^1 - \frac{u_a^1}{u_x^1} = c_a^2 - \frac{u_a^2}{u_x^2}. \tag{5}$$

Equations (1) – (4) give us a solution to the Pareto efficiency problem. Since the utility functions are strictly concave and the cost functions are strictly convex, the first order conditions are necessary and sufficient, and the solution is a unique global maximum.

## The "Kyoto Protocol" Game

We shall now analyze the allocation of resources under the "Kyoto Protocol" game. As we mentioned in the introduction, this game consists of two stages. In the first stage, each regional government decide how many units of abatement it wishes to provide and trade taking each other's decisions as given. Having observed the regional governments decisions concerning abatement provision and trade, the Global Environment Facility (GEF) decides on the second stage of the game the level of the interregional income transfer. The equilibrium concept used for the game is subgame perfection.

We need to introduce some notation prior to solving the game. Let $a_1 \equiv z_1^d + z_1^e - z_1^i$ and $a_2 \equiv z_2^d + z_2^e - z_2^i$ denote the quantities of abatement units available in regions 1 and 2, respectively, after the regional governments decide how much abatement to provide and how much abatement to trade. The quantities $z_j^d$ represent the "domestic" units of pollution abatement available in region j prior to abatement trading. The quantities $z_j^e$ and $z_j^i$ denote the units of pollution abatement exported and imported by region j, respectively. Hence, $z_1^e = z_2^i$, $z_2^e = z_1^i$ and $A = a_1 + a_2 \equiv z_1^d + z_2^d$.

## The Second Stage of the Game

As it is usually done, we start at the last stage of the game. The GEF takes $\{z_1^d, z_2^d, z_1^i, z_2^i\}$as given and solves:

$$\underset{\{x_1, x_2\}}{\text{Max}}\ u^1\left(x_1, z_1^d + z_2^i - z_1^i, z_1^d + z_2^d\right)$$

$$\text{s.t.:}\qquad u^2\left(x_2, z_2^d + z_1^i - z_2^i, z_1^d + z_2^d\right) \geq \bar{u}^2,$$

$$x_1 + x_2 + c^1\left(z_1^d + z_2^i - z_1^i\right) + c^2\left(z_2^d + z_1^i - z_2^i\right) \leq m_1 + m_2.$$

Hence:

$$x_1 + x_2 + c^1\left(z_1^d + z_2^i - z_1^i\right) + c^2\left(z_2^d + z_1^i - z_2^i\right) = m_1 + m_2, \tag{6}$$

$$u^2\left(x_2, z_2^d + z_1^i - z_2^i, z_1^d + z_2^d\right) = \bar{u}^2. \tag{7}$$

Equations (6) and (7) implicitly define: $x_j\left(z_1^d, z_2^d, z_1^i, z_2^i\right)$, $j = 1, 2$.

## The First Stage of the Game

Region 1 solves the following problem, taking the choices of region 2 as given:

$$\underset{\{z_1^d, z_1^i\}}{\text{Max}}\ u^1\left(x_1\left(z_1^d, z_2^d, z_1^i, z_2^i\right), z_1^d + z_2^i - z_1^i, z_1^d + z_2^d\right)$$

Region 2 takes the choices of region 1 as given and solves:

$$\underset{\{z_2^d, z_2^i\}}{\text{Max}}\ u^2\left(x_2\left(z_1^d, z_2^d, z_1^i, z_2^i\right), z_2^d + z_1^i - z_2^i, z_1^d + z_2^d\right)$$

As the proof of the proposition below demonstrates, the conditions that characterize the Nash equilibrium in this stage of the game are conditions (3) and (4). Therefore,

**Proposition 1:** The subgame perfect equilibrium for the Kyoto Protocol Game is Pareto efficient.

**Proof.** Differentiation of equations (6) and (7) yields the following partial derivatives:

$$\frac{\partial x_1}{\partial z_1^d} = \frac{u_A^2}{u_x^2} - c_a^1, \tag{8a}$$

$$\frac{\partial x_2}{\partial z_1^d} = -\frac{u_A^2}{u_x^2}, \tag{8b}$$

$$\frac{\partial x_1}{\partial z_2^d} = \frac{u_A^2}{u_x^2} + \frac{u_a^2}{u_x^2} - c_a^2, \tag{8c}$$

$$\frac{\partial x_2}{\partial z_2^d} = -\frac{u_A^2}{u_x^2} - \frac{u_a^2}{u_x^2}, \tag{8d}$$

$$\frac{\partial x_1}{\partial z_1^i} = -\frac{\partial x_1}{\partial z_2^i} = \frac{u_a^2}{u_x^2} - c_a^2 + c_a^1, \tag{8e}$$

$$\frac{\partial x_2}{\partial z_2^i} = -\frac{\partial x_2}{\partial z_1^i} = \frac{u_a^2}{u_x^2}. \tag{8f}$$

To prove the proposition, it suffices to compute the first order conditions corresponding to region 1's maximization problem and substitute into these conditions the appropriate partial derivatives -- the first order conditions corresponding to region 2's maximization problem turn out to be redundant. The first order conditions for region 1's problem are as follows:

$$\frac{u_a^1}{u_x^1}+\frac{u_A^1}{u_x^1}+\frac{\partial x_1}{\partial z_1^d}=0 \Rightarrow \frac{u_A^1}{u_x^1}+\frac{u_A^2}{u_x^2}=c_a^1-\frac{u_a^1}{u_x^1}, \tag{9a}$$

$$\frac{\partial x_1}{\partial z_1^i}-\frac{u_a^1}{u_x^1}=0 \Rightarrow c_a^1-\frac{u_a^1}{u_x^1}=c_a^2-\frac{u_a^2}{u_x^2}. \tag{9b}$$

We obtain (9a) by substituting (8a) into one of the first order conditions and obtain (9b) by substituting (8e) into the other first order condition. Note that equation (9a) corresponds to equation (3) and equations (9a) and (9b) together imply equation (4). Since equations (6) and (7) correspond to equations (1) and (2), respectively, the subgame perfect equilibrium for the Kyoto Protocol game is Pareto efficient. ■

## Abatement Trading and Interregional Transfers are Necessary for Pareto Efficiency

We shall now demonstrate that each one the two key elements of the Kyoto Protocol -- abatement trading and interregional transfers -- is necessary for Pareto efficiency. We first analyze a game with interregional transfers but no abatement trading and show that its subgame perfect equilibrium is generally inefficient. Then, we consider a game with abatement trading but no interregional transfers. The Nash equilibrium for this game is also generally inefficient. Since each one of these games deviates from the Kyoto Protocol in only one 'dimension' and both dimensions, if put together, comprise the Kyoto Protocol game analyzed above, we will be able to conclude that both abatement trading and interregional transfers are necessary for Pareto efficiency.

### Autarky With Interregional Transfers

As in the Kyoto Protocol game, the second stage of this game is characterized by the GEF allocating the numeraire commodity in order to satisfy:

$$x_1(a_1,a_2)+x_2(a_1,a_2)+c^1(a_1)+c^2(a_2)=m_1+m_2, \tag{10a}$$

$$u^2(x_2(a_1,a_2),a_2,a_1+a_2)=\bar{u}^2. \tag{10b}$$

Differentiation of equations (10a) and (10b) enable the following partial derivatives:

$$\frac{\partial x_1}{\partial a_1} = \frac{u_A^2}{u_x^2} - c_a^1, \tag{11a}$$

$$\frac{\partial x_2}{\partial a_1} = -\frac{u_A^2}{u_x^2}, \tag{11b}$$

$$\frac{\partial x_1}{\partial a_2} = \frac{u_a^2}{u_x^2} + \frac{u_A^2}{u_x^2} - c_a^2, \tag{11c}$$

$$\frac{\partial x_2}{\partial a_2} = -\frac{u_a^2}{u_x^2} - \frac{u_A^2}{u_x^2}. \tag{11d}$$

The First Stage of the Game

Region 1 solves the following problem, taking the choice of region 2 as given:

$$\underset{\{a_1\}}{\text{Max}}\ u^1\left(x_1(a_1, a_2), a_1, a_1 + a_2\right)$$

The first order condition is

$$u_x^1 \frac{\partial x_1}{\partial a_1} + u_a^1 + u_A^1 = 0 \Rightarrow \frac{u_A^1}{u_x^1} + \frac{u_A^2}{u_x^2} = c_a^1 - \frac{u_a^1}{u_x^1}. \tag{12a}$$

Equation (12a) demonstrates that region 1 provides abatement at a level that satisfies the regional Samuelson condition.

Region 2 takes the choice of region 1 as given and solves:

$$\underset{\{a_2\}}{\text{Max}}\ u^2\left(x_2(a_1, a_2), a_2, a_1 + a_2\right)$$

The first order condition can be written as follows:

$$\frac{u_A^2}{u_x^2} = \frac{\partial x_1}{\partial a_2} + c_a^2 - \frac{u_a^2}{u_x^2}. \tag{12b}$$

Equation (12b) tells us that region 2 will not generally provide abatement at a level that satisfies the regional Samuelson condition. In the absence of trading, the marginal regional costs of abatement provision are not equalized. Therefore,

**Proposition 2:** The subgame perfect equilibrium without trade is generally inefficient.

## Trade Without Interregional Transfers

Suppose that there is no effective international authority and thus there is no mechanism to implement interregional transfers. In the absence of transfers, the game played by the regions simplifies to a simultaneous Nash noncooperative game, whereby each region decides how much abatement to provide and trade taking the other region's decisions as given.

Region 1 takes the choices of region 2 as given and solves:

$$\underset{\{z_1^d, z_1^i\}}{\text{Max}} \; u^1\left(m_1 - c^1\left(z_1^d + z_2^i - z_1^i\right) - p\left(z_1^i - z_2^i\right), z_1^d + z_2^i - z_1^i, z_1^d + z_2^d\right)$$

Note that we denote by p > 0 the per unit price of abatement. The first order conditions can be written as follows:

$$\frac{u_A^1}{u_x^1} = c_a^1 - \frac{u_a^1}{u_x^1}, \tag{13a}$$

$$c_a^1 - \frac{u_a^1}{u_x^1} = p. \tag{13b}$$

Equation (13a) informs us that region 1 ignores the positive effects that its provision of abatement confers on region 2 -- it provides abatement at a level that satisfies the equalization of the region's marginal benefit to the region's marginal cost. Equation (13b) shows that the volume of abatement units traded by region 1 satisfies the equalization of marginal regional cost of abatement provision and the marginal revenue originating with the sale of abatement.

Region 2 takes the choices of region 1 as given and solves:

$$\underset{\left\{z_2^d,\, z_2^i\right\}}{\text{Max}}\ u^2\left(m_2 - c^2\left(z_2^d + z_1^i - z_2^i\right) - p\left(z_2^i - z_1^i\right), z_2^d + z_1^i - z_2^i, z_1^d + z_2^d\right)$$

The first order conditions can be written as follows:

$$\frac{u_A^2}{u_x^2} = c_a^2 - \frac{u_a^2}{u_x^2}, \tag{14a}$$

$$c_a^2 - \frac{u_a^2}{u_x^2} = p. \tag{14b}$$

Similarly to the behavior displayed by region 1, region 2 chooses to provide abatement at a level that equates its marginal regional benefit from abatement provision to its marginal regional cost and to trade abatement units at a level where the marginal regional cost equates the marginal revenue from selling abatement.

Note that we observe the following conditions in the Nash equilibrium for this game:

$$c_a^1 - \frac{u_a^1}{u_x^1} = c_a^2 - \frac{u_a^2}{u_x^2} = p, \tag{15a}$$

$$\frac{u_A^1}{u_x^1} = \frac{u_A^2}{u_x^2} = p. \tag{15b}$$

Equations (15a) reveal that equations (13b) and (14b) imply equation (5); that is, due to abatement trading, marginal regional costs of abatement provision are equalized. But, equations (15b) tell us that the allocation is characterized by equalization of the marginal regional benefits from abatement provision to marginal regional costs of abatement provision rather than the equalization of the sum of the marginal regional benefits from abatement provision to marginal regional costs of abatement provision. Hence, we obtain the following result:

**Proposition 3:** The Nash equilibrium for the game without interregional transfers is generally inefficient.

## The Main Result

We are now ready to describe our main result:

**Theorem:** The two key elements of the Kyoto Protocol, namely, free trading of pollution abatement and interregional income transfers, are both necessary conditions for the Pareto efficiency of the agreement.

**Proof.** Compare the subgame perfect equilibrium for the Kyoto Protocol game with the equilibria for the other two games examined above. While the subgame perfect equilibrium for the Kyoto Protocol game is Pareto efficient, the other equilibria are generally inefficient. ■

## Conclusion

The Kyoto Protocol calls for the creation of a system of pollution abatement trading and for the implementation of interregional income transfers. Our analysis demonstrates that these two elements are necessary for the efficiency of the Protocol. It appears that an international agreement to control global warming can be effective provided that there is an international authority in charge of making appropriate transfers after the nations decide how much abatement to provide and trade. The transfer mechanism induces the nations to face their Lindahl prices when they decide on their contributions to the pure global good.

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