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# Welfare maximizing emission permit allocations under constraints.

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# Welfare maximizing emission permit allocations under constraints*

Abstract:

This paper examines equity and efficiency properties of voluntary international environmental agreements. A classical welfare economics framework is used while focusing on one particular instrument, i.e. emissions trading. It is demonstrated that if emission permit allocations face no constraints, that is if the allocation of 'hot air' and negative permit endowments are allowed, the classical efficiency rule is preserved and we obtain a 'first best' solution. This result however breaks down when permit allocation constraints are imposed. If one of these constraints is binding, the global abatement target and the permit distribution are determined simultaneously. An empirical application confirms this result and reveals that binding allocation constraints shift the abatement target away from the first best solution. When more stringent stability concepts are imposed, the constraints on endowments become less binding. The welfare loss due to these constraints however gets larger as we become more inequality averse.

Promotor : Prof. Dr. S. PROOST

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# Contents

# 1. INTRODUCTION

Global warming is a typical common's problem: many regions contribute to pollution by emitting greenhouse gases and the greenhouse effect resulting from this pollution, will cause damage to all individuals from the current and future generations in all regions of the world. Effective control of such a problem requires an international agreement that should be characterised by three desirable properties: efficiency, equity and voluntary participation.

Efficiency refers on the one hand to an efficient allocation and on the other hand to cost efficiency. The efficient allocation rule determines how far we should go in reducing emissions, i.e. it determines our environmental target. If this environmental target is achieved at the lowest possible welfare cost, cost efficiency prevails. This is the case if marginal abatement costs across all participating regions are equalised. As developing regions face in general lower marginal abatement costs, it is desirable from an efficiency point of view to get them involved in the international environmental agreement (IEA). However, since lower marginal abatement costs require more abatement efforts from these nations, efficiency and equity principles come into conflict unless there are international transfers to compensate poorer nations.

Voluntary participation is necessary since no supranational authority exists to impose the international agreement. In this respect, some authors have investigated the concept of individual rationality. It states that countries will only be wiling to sign the IEA if they are not worse off under the agreement compared to the non-cooperative Nash outcome. The importance of these participation constraints for IEAs has already been emphasised by Barrett (1992). Eyckmans et al. (1994) used this stability concept when studying the equity and efficiency implications of three different international carbon agreements. Another stream of literature analyses the stability of IEAs and focuses on the concept of internal and external stability, introduced by d'Aspremont (1983) who used it to study cartel formation in an oligopoly (see for instance Barrett, 1994 and Carraro and Siniscalco, 1993). It states that, once the agreement is accomplished, no region should have an incentive to withdraw from the agreement in order to free ride on the efforts undertaken by the remaining signatories. Similarly, no signatory acting alone should want to accede to the IEA. A typical result emerging from this literature is that when the difference in net benefits between the non-cooperative and full cooperative outcome is large, i.e. when an IEA is needed most, the self-enforcing IEA can only sustain a small number of signatories and hence can only marginally improve upon the non-cooperative outcome (Barrett, 1994).

This paper focuses on one particular instrument to reduce greenhouse gases through an IEA: the imposition of tradable emission quotas. The advantage of such a system is that it provides a framework in which efficiency, stability and equity principles can be dealt with in the following sense. First, assuming a perfectly competitive permit market, regions will continue trading until their marginal cost of abatement equals the permit price. Hence marginal abatement costs are equalised and cost efficiency prevails. Secondly, the assignment of emission quotas can be used as a means to compensate potential losers from the IEA. Therefore participation constraints in this context of tradable emission quotas can be translated into an allocation of permits such that cooperation is rational. When specifying these participation constraints, we will consider both the individual rationality requirement as the internal stability concept. Thirdly, if the two previous conditions are satisfied, one can look whether there is some room left for equity issues. If this is the case, the initial allocation of tradable permits can be manipulated further in order to redistribute the benefits the different regions will get from trading.

In brief, the idea is to define a solution concept that trades off efficiency and equity such that the agreement is still self-enforcing. Dutta and Ray (1989) already combined stability and egalitarianism in transferable utility games. In a more recent paper, Germain and van Steenberghe (2001) explore the link between equity and the requirement of coalitional rationality while considering several allocation rules. As is common in the climate change literature dealing with equity, these allocation rules are derived from different equity principles such as the egalitarian principle, ability to pay, sovereignty, etc. (Rose et al., 1998). A drawback of this approach however, is that there exists no consensus on what constitutes an equitable agreement. Since one cannot choose for a particular equity criterion without relying on a value judgement, there exists little hope that, as long as the equity debate is carried on these criteria, an international consensus will be reached.

In this paper a classical welfare economics framework will be used in which equity considerations can be parameterized. Hence, the discussion on some "ad hoc" equity principles can be avoided. In particular, we look for a self-enforcing international tradable permit agreement that maximizes social welfare. Eyckmans et al. (1993) already used a social welfare maximizing framework to illustrate that in a world without side payments (i.e. in a second-best world) the traditional cost-efficient abatement prescription need not be optimal: instead of marginal costs to be equalised across regions, *weighted* marginal costs should be equalised across regions. The weights are necessary to satisfy either the participation constraints or to include equity concerns in the absence of international transfers.

Our welfare maximization problem however might result in an outcome in which some nations are allocated a negative emission endowment, implying that these nations have to pay for every ton of carbon they emit and in addition they face an additional fee on top of that. Another possibility is that certain regions receive an emission permit allocation that exceeds their business as usual emissions as is the case with Russia in the Kyoto protocol. The situation where assigned amounts of emissions are higher than the expected business as usual emissions in the commitment period is referred to with the term 'hot air' (UNFCCC, 1998). The former possibility is not likely to be considered as an acceptable option in an IEA and will therefore be ruled out. The debate on the desirability of allocating hot air however is still going on. In this paper we explore the impact of outlawing negative endowments and hot air on the permit price, on the global abatement target and on welfare.

Before continuing we should note that two important simplifying assumptions are made. First, in order to focus on the equity/efficiency trade off within a permit trading scheme in its pure form, we neglect spillovers to other markets. Hence the model considered is a partial equilibrium model. Secondly, the model in its current form is static and covers only one time period. To make it more interesting and realistic, it should be made dynamic so that banking of permits is possible.

The structure of this paper is as follows. Section 2 introduces the theoretical setup of the model. Section 3 deals with international carbon agreements in general. First, the optimization problem of a coalition of countries will be elaborated. Secondly, the concept of a Partial Agreement Nash Equilibrium (PANE) w.r.t. a coalition is defined. Subsequently, two extreme scenarios as to cooperation are considered as a benchmark, i.e. the Pareto efficient and the non-cooperative scenario. Finally we discuss two different stability concepts that can be used to specify the participation constraints in the optimization problem. In section 4 we focus on one particular instrument, i.e. an international tradable permit agreement. After characterizing the permit market equilibrium, we look for a welfare maximizing permit allocation. A distinction will be made between unconstrained permit endowments and permit endowments being constrained to be positive and/or by business as usual emissions. Because it is difficult to derive analytically in which direction the global abatement target will change due to binding allocation constraints, the empirical application in section 5 provides us with more insight in the different effects at play.

## 2. THEORETICAL MODEL

Consider a world economy with a set of regions $N = \{1, ..., n\}$. The preferences of each region are represented with a simple utility function that is increasing in the region's own income $X_i$ and in the global abatement effort $a_N$ undertaken:

$$U_i\left(X_i\left(a_i, T_i\right), a_N\right) \qquad (1)$$

The utility functions are twice continuously differentiable and bounded over $\mathbb{R}_+^2$. The second argument of the utility function, the total level of abatement, is equal to the sum of all regional abatement levels:

$$a_N \equiv \sum_{i=1}^{N} a_i$$

The first argument of the utility function, region i's income $X_i$, depends on the individual abatement level $a_i$ and is defined as:

$$X_i\left(a_i, T_i\right) \equiv \overline{Y}_i - C_i\left(a_i\right) + T_i$$

where $\overline{Y}_i$ denotes the baseline income level, $C_i\left(a_i\right)$ is region i's cost of abatement and $T_i$ denotes a transfer to region i. This transfer can be positive or negative. We assume that the baseline income level results from straight income maximization without environmental concern and that the abatement cost functions are increasing and convex in $a_i$. This abatement level $a_i$ of region i is equal to the difference between its fixed business as usual emission level $\overline{E}_i$ and its actual emission level $E_i$ where the business as usual level is the one that would occur in absence of any environmental concern:

$$a_i = \overline{E}_i - E_i .$$

Following Welsch (1993), we define the lower bound on abatement as $\underline{a}_i \equiv \overline{E}_i - \overline{z}_i$ where $\overline{z}_i$ denotes the maximal economically sustainable emission level for country i. This allows for negative abatement efforts if a country decides to increase its emissions relative to the reference period. Assuming in addition that a country will not abate more than its business as usual emissions, the individual abatement $a_i$ is defined over the interval $\left[\underline{a}_i, \overline{E}_i\right] \subset \mathbb{R}$.

This form (1) of the utility function captures the fact that each region bears the cost of its own abatement efforts but benefits from the abatement efforts undertaken by other nations.

# 3. INTERNATIONAL CARBON AGREEMENTS

## *3.1. Group welfare optimization*

In negotiations on International Environmental Agreements (IEAs) we often observe that cooperation is only partial. In the case of global warming, the 1997 Kyoto Protocol on greenhouse gases emission reduction may be seen as an example of such partial cooperation.

Assuming that the objective of a coalition is to maximize its welfare as a group, it has to decide on two matters:

(i) The environmental target or the amount of emission reduction to be undertaken. This is the issue of an efficient allocation.

(ii) The distribution of efforts over the different coalition members such that the environmental target can be achieved at the lowest possible cost. This is the problem of cost efficiency.

When determining the environmental target, a coalition needs to take into account how outsiders to the coalition determine their abatement strategies. In this respect, we will use the notion of a *Partial Agreement Nash Equilibrium (PANE)* introduced by Chander and Tulkens (1995 and 1997). It can be described as a Nash equilibrium where the players are coalitions instead of individual countries and will be elaborated further in section 3.2. This equilibrium concept should be clearly distinguished from a Stackelberg equilibrium in which a dominant group of countries chooses its abatement strategy first and the other regions are followers.

The distributional aspects of an international carbon agreement can be dealt with in different ways. Previous work in the climate change literature dealing with equity in the international burden sharing, mostly focuses on some ad hoc equity concepts (for an overview see especially Rose et al., 1998). In the context of tradable permits, a grandfathering rule for instance implies that permits are allocated in proportion to the regions' historical emissions. The egalitarian rule allocates to each nation an equal amount of quotas per capita. Since no consensus exists on what constitutes an equitable permit allocation, we opt for an approach in which inequality considerations are parameterized in a generalized group welfare function.

## 3.2. Partial Agreement Nash Equilibrium w.r.t. a coalition

Suppose that a coalition $S = \{1,...,s\} \subseteq N$ forms. The PANE w.r.t. coalition $S$ can be interpreted as a special type of Nash equilibrium in which a coalition $S$ coordinates its policies, taking as given the emission strategies of the outsiders who, in turn, are playing a non-cooperative Nash strategy against $S$. Formally, a Partial Agreement Nash Equilibrium w.r.t. coalition $S$ is defined as a combination of strategies that solves simultaneously the following maximization problems:

***(1) for all insiders*** $i \in S$:

$$\max_{a_1,\ldots,a_s,T_1,\ldots,T_s} \sum_{i \in S} \lambda_i U_i \left( X_i \left( a_i, T_i \right), a_S + \overline{a}_{-S} \right)$$

$$s.t.\ U_i \left( X_i \left( a_i, T_i \right), a_S + \overline{a}_{-S} \right) - U_i^{TP} \geq 0 \ \ \forall i \in S \qquad (2)$$

$$\sum_{i \in S} T_i = 0$$

where $a_S \equiv \sum_{i \in S} a_i$ , $\overline{a}_{-S} \equiv \sum_{i \notin S} a_i$ and $a_S + \overline{a}_{-S} = a_N$

***(2) for all outsiders*** $j \in N \setminus S$:

$$\max_{a_j} U_j \left( X_j \left( a_j, 0 \right), a_j + \overline{a}_{-j} \right) \qquad (3)$$

where $\overline{a}_{-j} \equiv \sum_{i \neq j} a_i$ and $a_j + \overline{a}_{-j} = a_N$

The insiders to a coalition $S$ choose an abatement strategy $a_S = \{a_1, \ldots, a_s\}$ in order to maximize a group welfare function, taking the strategies of the outsiders $\overline{a}_{-S}$ as given. In the welfare function each region i gets a weight $\lambda_i$ where $\sum_{i \in S} \lambda_i = 1$. These weights can be interpreted as ethical weights in a group welfare maximization framework or as bargaining weights in a bargaining context (Eyckmans et al., 1993).

Furthermore, since there is no supranational authority to impose the IEA, it is important that the agreement is self-enforcing. For this reason, participation constraints are imposed on the welfare maximization problem. We will label the utility a region can get by deviating with $U_i^{TP}$ where *TP* refers to *threat point*. At this stage no attention is devoted yet to the choice of a particular stability concept. This will be dealt with in section 3.3. In order to compensate potential losers from the IEA, we assume that lump sum side payments denoted by $T_i$ between coalition members are possible. These transfers must be budget balanced or sum up to zero.

The outsiders $j \in N \setminus S$ act as singletons when maximizing their welfare. They determine their abatement strategy $a_j$ so as to maximize their own welfare, taking the strategies $\overline{a}_{-j}$ of the other outsiders and of the coalition as given. Since these countries do not receive a transfer their income is equal to $X_i \left( a_i, 0 \right) = \overline{Y}_i - C_i \left( a_i \right)$.

## *3.2.2. Insider behaviour*

The Lagrangian of the coalition's maximization problem can be defined as follows:

$$\mathcal{L}\left(a_1,...,a_s,T_1,...T_s,\pi_1,...,\pi_s,\psi\right)=\sum_{i\in S}\left(\lambda_i+\pi_i\right)U_i\left(X_i\left(a_i,T_i\right),a_N\right)-\sum_{i\in S}\pi_i U_i^{TP}-\psi\left(\sum_{j\in S}T_j\right)$$

The first order conditions with respect to $a_i$ are given by

$$\tilde{\lambda}_i C_i'\left(a_i^{CS}\right)-\sum_{j\in S}\tilde{\lambda}_j B_j'\left(X_j\left(a_j^{CS},T_j^{CS}\right),a_N^{CS}\right)=0\ \ \forall i\in S \tag{4}$$

where $C_i'\left(a_i^{CS}\right)=\frac{\partial C_i\left(a_i^{CS}\right)}{\partial a_i}$ denotes the marginal abatement cost of region i and $B_j'\left(X_j\left(a_j^{CS},T_j^{CS}\right),a_N^{CS}\right)=\frac{\left(\partial U_j\left(X_j^{CS},a_N^{CS}\right)/\partial a_N\right)}{\left(\partial U_j\left(X_j^{CS},a_N^{CS}\right)/\partial X_j\right)}$ is the marginal benefit of abatement to region j expressed in terms of income, both evaluated in the PANE w.r.t. coalition $S$ which we denote by the superscript *CS*. $\tilde{\lambda}_i$ stands for the marginal social value to region i of an additional unit of income (Eyckmans et al., 1993) and is defined as follows:

$$\tilde{\lambda}_i\equiv\left(\lambda_i+\pi_i\right)\left(\frac{\partial U_i}{\partial X_i}\right) \tag{5}$$

$\tilde{\lambda}_i$ is a function of three parameters: the weight $\lambda_i$ of region i in the group welfare function, the shadow price $\pi_i$ of region i's participation constraint and the marginal utility of income to region i. From condition (4) it can be seen that the higher $\tilde{\lambda}_i$, the lower is the abatement requirement imposed on the region.

The shadow prices $\pi_i$ of the participation constraints are determined by the following Kuhn Tucker conditions:

$$U_i\left(X_i\left(a_i^{CS},T_i^{CS}\right),a_N\right)-U_i^{TP}\geq 0\ ;\ \pi_i^{FB}\geq 0\ ;\ \pi_i^{CS}\left[U_i\left(X_i\left(a_i^{CS},T_i^{CS}\right),a_N\right)-U_i^{TP}\right]=0\quad\forall i\in S$$

Thus, if the participation constraint for region i is binding, i.e. if $U_i\left(X_i\left(a_i^{CS},T_i^{CS}\right)\right)=U_i^{TP}$, the shadow price $\pi_i^{CS}$ is strictly positive and enhances the social welfare weight $\lambda_i$.

The first order conditions with respect to the transfers $T_i$ are given by

$$\tilde{\lambda}_i=\psi\ \ \forall i\in S \tag{6}$$

Hence, if lump transfers are possible, maximizing group welfare requires that the marginal social valuation of income $\tilde{\lambda}_i$ is equalised across all coalition members. As long as this is not the case, group welfare can be increased by redistributing income from nations with a lower $\tilde{\lambda}_i$ to nations with a higher $\tilde{\lambda}_i$. A higher marginal social valuation of income can be due to (i) a higher power or ethical weight of the region in the group welfare function, (ii) a higher marginal utility of income (which is the case for poorer regions since we assume that utility functions are concave), (iii) a positive shadow value of the region's participation constraint or a combination of these three factors.

Substituting condition (6) for $\tilde{\lambda}_i$ into (4), leads to the following expression, also known as the Samuelson rule for the optimal emission reductions by coalition $S$.

$$C_i'\left(a_i^{CS}\right)=\sum_{j\in S}B_j'\left(X_j^{CS},a_N^{CS}\right) \qquad \forall i\in S \tag{7}$$

This condition pins down the coalition's abatement target at its optimal level since the marginal cost of each region equals the sum of all marginal benefits. Indeed it illustrates that an optimal abatement policy by coalition $S\subset N$ internalizes all damages from all of its members but disregards damages to outsiders of the coalition. Furthermore, this expression implies that in order to achieve the coalition's abatement target at the lowest possible cost, marginal costs should be equalized across all coalition members.

### *3.2.3. Outsider behaviour*

The outsiders only take into account their own damages when determining their optimal environmental policy. This is reflected by the first order conditions of the outsiders' maximization problem (3) with respect to $a_j$:

$$\left(\frac{\partial U_j\left(X_j\left(a_j^{CS}\right),a_N^{CS}\right)}{\partial X_j}\right)C_j'\left(a_j^{CS}\right)=\left(\frac{\partial U_j\left(X_j\left(a_j^{CS}\right),a_N^{CS}\right)}{\partial a_N}\right) \qquad \forall j\in N\setminus S$$

Or simplified:

$$C_j'\left(a_j^{CS}\right)=B_j'\left(X_j\left(a_j^{CS}\right),a_N^{CS}\right) \quad \forall j\in N\setminus S \tag{8}$$

where $B_j'\left(X_j\left(a_j^{CS}\right),a_N^{CS}\right)$ again stands for the marginal benefit of emission abatement to region j expressed in terms of income, evaluated in the PANE w.r.t. coalition $S$. According to condition (8), outsiders from a coalition abate emissions up to the point where their marginal cost equals their marginal utility of abatement in terms of marginal appreciation of an extra unit of income and they disregard the marginal abatement benefits of the other regions.

### *3.2.4. Two extreme PANE scenarios*

In this section we explore two extreme cooperation scenarios that are encompassed by the definition of a PANE, i.e. the Pareto efficient scenario ($S = N$) and the non-cooperative Nash equilibrium ($S = \{i\}$ for any $i \in N$).

#### a) Pareto efficiency

It is useful to consider the full cooperative Pareto efficient scenario as a benchmark. In this scenario, also referred to as the *first best* problem, all n regions are assumed to participate in the IEA. In this sense the Pareto efficient scenario can be considered as a special case of a PANE in which all regions belong to the coalition.

In order to characterize the optimum, we assume that there exists a global planner that disposes of the vector of individual abatement levels $(a_1,...,a_n)$ and of lump sum side payments $(T_1,...,T_n)$ as instruments to maximize social welfare. Formally, the problem is very similar to the one of the insiders in a PANE (see (2)). The only difference is that now all regions are insiders hence $a_S = a_N$ or there are no reaction functions of outsiders to be taken into account.

Hence, the Pareto efficient solution can be found by maximizing the following social welfare function

$$\max_{a_1,...,a_n,T_1,...,T_n} \sum_{i\in N} \lambda_i U_i \left( X_i\left(a_i,T_i\right),a_N\right) \text{ with } \sum_{i\in N}\lambda_i = 1$$
$$s.t.\ U_i\left( X_i\left(a_i,T_i\right),a_N\right) - U_i^{TP} \geq 0 \quad \forall i \in N$$
$$\sum_{i\in N} T_i = 0$$

The Lagrangian function associated to this maximization problem is given by:

$$\mathcal{L}\left(a_1,...,a_n,T_1,...T_n,\pi_1,...,\pi_n,\psi\right) = \sum_{i\in N}\left(\lambda_i+\pi_i\right)U_i\left(X_i\left(a_i,T_i\right),a_N\right) - \sum_{i\in N}\pi_i U_i^{TP} - \psi\left(\sum_{j\in N}T_j\right)$$

Deriving the first order conditions w.r.t. $a_i$ and $T_i$ analogously to section 3.2.2, we obtain:

$$\tilde{\lambda}_i = \psi \quad \forall i \in N \tag{9}$$

$$C_i'\left(a_i^{FB}\right) = \sum_{j\in N} B_j'\left(X_j^{FB},a_N^{FB}\right) \quad \forall i \in N \tag{10}$$

where *FB* refers to *First Best*.

Hence, according to condition (9) the optimal transfers in a first best world should be such that the marginal social valuation of income $\tilde{\lambda}_i$ is equalized across all nations. Condition (10) is also known as the Samuelson rule for Pareto efficient provision of emission reduction. It pins down the global abatement target at its optimal level and states that in order to achieve the global abatement target at the lowest possible cost, marginal costs should be equalized across all nations.

### b) The Nash equilibrium

If regions do not sign an international IEA, such a situation can be characterized by means of the Nash equilibrium concept. In the Nash equilibrium, each player chooses its strategy in order to maximize its own welfare, taking the strategies of the other players as given. A Nash equilibrium is often called *strategically stable* or *self-enforcing* since no single player wants to deviate from his or her strategy.

Assuming that all n regions behave non-cooperatively, they choose their abatement level $a_i$ in order to maximize their utility, taking the abatement efforts of the other regions as given. Hence the problem we have to solve is exactly the same as the one of the outsiders of a coalition given by (3):

$$\max_{a_i} U_i\left(X_i\left(a_i\right), a_i + \overline{a}_{-i}\right) \quad \forall i \in N \tag{11}$$

The first order conditions of this maximization problem w.r.t. $a_i$ are

$$C_i'\left(a_i^{NC}\right) = B_i'\left(X_i\left(a_i^{NC}\right), a_N^{NC}\right) \;\; \forall i \in N \tag{12}$$

where $C_i'\left(a_i^{NC}\right)$ and $B_i'\left(X_i\left(a_i^{NC}\right), a_N^{NC}\right)$ denote respectively the marginal abatement costs and the marginal abatement benefit of region i, both evaluated in the non-cooperative (*NC*) outcome. Condition (12) shows that in the non-cooperative equilibrium regions indeed only take into account their own benefits from emission reduction when determining an emission reduction strategy.

The Nash equilibrium is found by solving simultaneously the system of n first order conditions in (12). Under the assumptions of (i) compact and convex strategy spaces $\mathcal{S}_i = \left[\underline{a}_i, \overline{E}_i\right] \in \mathbb{R} \;\; \forall i \in N$, (ii) utility functions $U_i\left(X_i\left(a_i\right), a_N\right)$ twice continuously differentiable and bounded over $\mathbb{R}_+^2 \;\; \forall i \in N$ and (iii) concave utility functions $U_i\left(X_i\left(a_i\right), a_N\right)$ in $a_i \;\; \forall i \in N$, there exists at least one Nash non-cooperative equilibrium (see Friedman, 1986). For further reference we call the Nash utility level of region i $U_i^{NC}$.

The difference with the PANE outcome for the outsiders as described in section 3.2.3 is that in the Nash equilibrium the utility level of region i will be lower than the utility level of region i if it were an outsider in a PANE. The reason is that in the Nash equilibrium, countries do not benefit from the higher emission reduction efforts undertaken by the coalition in a PANE.

## 3.3. Stability concepts

Thus far we defined the participation constraint of region i by means of a not specified threat point $U_i^{TP}$. In order to make this more concrete, we have to stipulate what constitutes a self-enforcing IEA. There exists however no consensus among economists on this matter. Therefore we will explore in this section two stability concepts which are commonly used in the literature on IEAs, i.e. individual rationality (see for instance Chander and Tulkens, 1995, 1997)[1]) and internal & external stability (see for instance Carraro and Siniscalco, 1991, 1993, Barrett, 1994).

### 3.3.1. Individual rationality

If under a certain agreement a region is worse off compared to the non-cooperative outcome, it will not accept this agreement. In this case we will say that the proposed agreement does not satisfy *individual rationality*. Formally, the individual rationality requirement implies that the agreement should satisfy the participation constraint of each region i, given by:

$$U_i\left(X_i\left(a_i,T_i\right),a_N\right)-U_i^{NC}\geq 0\ \ \forall i\in N \tag{13}$$

where $U_i^{NC}$ denotes the earlier specified utility of region i in the Nash equilibrium.

The underlying assumption of this stability concept is that if a country i deviates from the coalition $S$, this will lead to a complete disintegration of the remaining coalition $S\setminus\{i\}$. This constitutes a strong threat to possible deviators since the other players will react on a deviation by choosing their Nash strategy, resulting in small emission reductions. This assumption can be justified by arguing that players are pessimistic or cautious when they consider deviating (Eyckmans, 2001).

[1] They consider also the concept of coalitional rationality, a concept that we did not study here for practical reasons: it would imply that $2^{16}$ coalitions have to be checked in our empirical application since the model contains 16 regions.

### *3.3.2. Internal and external stability*

Another stream of literature in environmental economics uses the stability concept developed by d'Aspremont et al. (1983) in the context of cartel formation. An agreement is said to be stable if (i) no signatory wants to withdraw unilaterally from the agreement and if (ii) no nonsignatory wants to join the agreement.

Formally, coalition $S \subseteq N$ is said to be stable if it is

(i) **Internally stable:** $U_i^S \geq U_i^{S \setminus \{i\}}$ for all $i \in S$ and (14)

(ii) **Externally stable:** $U_j^S \geq U_j^{S \cup \{j\}}$ for all $j \in N \setminus S$. (15)

The internal stability concept is built on the assumption that deviators compare their payoff being a member of a coalition to their free riding payoff. They assume that if they have left the coalition, the remaining coalition $S \setminus \{i\}$ remains together so that they can still enjoy the benefits of the coalition's environmental policy without contributing any effort their selves. This assumption can be justified by arguing that players are optimistic when they consider deviating (Eyckmans, 2001).

# 4. AN INTERNATIONAL TRADABLE PERMIT AGREEMENT

In the previous section we discussed the PANE w.r.t a coalition, assuming that lump sum transfers are possible to stabilize the IEA and to compensate poorer regions to the extent that there is still some scope left. In this section we make the more realistic assumption that there is no unlimited effective international side payment scheme available but that transfers between regions occur in the form of emissions trading. More specifically emissions trading implies transfers of the following form:

$$T_i = p\left(\omega_i - E_i\right)$$

where $p$ denotes the permit price, $\omega_i$ is the permit endowment to region i and $E_i$ denotes the actual emissions of region i. Depending on whether region i is a net importer $\left(\omega_i < E_i\right)$ or net exporter $\left(\omega_i > E_i\right)$, the transfer will be negative or positive.

In this setup the only policy variable is the initial allocation of emission rights $\omega_i$ over the participating regions. In section 4.1 we will study the permit market equilibrium and derive individual abatement supply functions. In section 4.2 we will consider whether the previously derived Samuelson conditions still hold, even if we put restrictions on the allocation of permits.

## 4.1. Permit market equilibrium

In order to characterize the permit market equilibrium, we make the following assumptions. Permit trading takes place between firms and there is only one representative firm per region. Furthermore, we assume that there are enough permit sellers and buyers so that the firms are price takers. Firms choose their optimal abatement level $a_i$ in order to maximize profits. We make the simplifying assumption that the level of abatement chosen has no influence on the firm's production output. Hence, when determining their optimal abatement level, firms only consider the revenue they get from permit trading. Formally, firms choose their abatement level in order to maximize the following profit function:

$$\max_{a_i} p\left(a_i + \omega_i - \bar{E}_i\right) - C\left(a_i\right) \qquad \forall i \in S \tag{16}$$

The first term denotes the revenues the firm gets from selling permits. Since the abatement level is equal to the difference between business as usual emissions $\bar{E}_i$ and the actual emissions $E_i$, this can also be rewritten as $p\left(\omega_i - E_i\right)$. The second term is the cost of abatement. The first order conditions of this problem are given by:

$$p = C_i'\left(a_i\right) \quad \forall i \in S \tag{17}$$

I.e. firms are willing to abate emissions up to the point where their marginal cost of abatement equals the permit price which they take as given. This is an attractive feature of permit trading as a policy instrument since it ensures cost efficiency.

From condition (17) we can derive firm i's supply function of emission abatement in function of the permit price:

$$C_i'^{-1}\left(p\right) = a_i \equiv \alpha_i\left(p\right) \quad \forall i \in S \tag{18}$$

The properties of the individual abatement supply functions can be derived as follows:

$$\alpha_i'\left(p\right) = \frac{da_i}{dp} = \frac{1}{C_i''\left(p\right)} > 0 \quad \forall i \in S \tag{19}$$

I.e. from the convexity of the abatement cost functions, we obtain that the individual abatement supply is increasing in the permit price. The aggregate abatement supply $a_S$ by coalition $S$ is found by summing over all individual abatement supply functions:

$$a_S \equiv \sum_{i \in S} a_i = \sum_{i \in S} \alpha_i\left(p\right) = \sum_{i \in S} C_i'^{-1}\left(p\right) \tag{20}$$

Its properties can be derived as follows:

$$\frac{da_S}{dp} = \sum_{i \in S} \alpha_i'(p) = \sum_{i \in S} \frac{1}{C_i''(p)} > 0 \tag{21}$$

This derivative describes the effect of a change in the permit price on the overall emission abatement effort: the higher the permit price, the more abatement will be undertaken. It can be rewritten as:

$$\frac{dp}{da_S} = \frac{1}{\sum_{i \in S} \alpha_i'(p)} = \frac{1}{\sum_{i \in S} \frac{1}{C_i''(p)}} > 0 \tag{22}$$

The intuition behind this result is that the larger the global abatement level is, the more costly it gets to reduce emissions further due to convexity of the abatement cost functions, what implies a higher permit price.

The permit market equilibrium for the set of regions $\{1,...,s\} = S$ is given by the price $p$ with $p \geq 0$, for which the total abatement level $a_S$ equals total business as usual emissions minus the aggregate permit level $\omega_S$, or:

$$a_S = \overline{E}_S - \omega_S \tag{23}$$

Where $\overline{E}_S = \sum_{i \in S} \overline{E}_i$ and $\omega_S = \sum_{i \in S} \omega_i$. Thus, by fixing the aggregate permit level $\omega_S$, the total level of abatement $a_S$ is also implicitly determined. Combining condition (23) and condition (20) we get:

$$\overline{E}_S - \omega_S = \sum_{i \in S} \alpha_i(p) \tag{24}$$

Hence through pinning down the total amount of permits to be distributed in coalition $S$, the total amount of emission reduction that will be undertaken within coalition $S$ and thus also the level of the permit price is implicitly determined. Therefore, the permit price can be written as a function of total permit endowment $\omega_S$:

$$p = \rho(\omega_S)$$

The effect of a change in endowment on the permit price can be seen as follows:

$$\rho'(\omega_S) = \frac{d\rho(\omega_S)}{d\omega_S} = \frac{dp}{da_S}\frac{da_S}{d\omega_S} = \frac{-1}{\sum_{j \in S} \alpha_j'(p)} < 0 \quad \forall i \in S \tag{25}$$

where we have used condition (22) and (23) for the last step. Hence, an increase in total endowments causes a reduction in the permit price what strokes with our intuition since emission permits become less scarce.

## 4.2. Welfare maximizing permit allocation

### 4.2.1. Unconstrained emission permit allocation

First we solve the PANE w.r.t. coalition $S$ with the allocation of permits not being constrained. That is, we allow for an endowment that exceeds a country's business as usual emissions (so called 'hot air') and for the allocation of a negative amount of permits.

As stated earlier (see paragraph 3.2), in the PANE w.r.t. $S$, a coalition $S$ coordinates its policies, taking as given the emission strategies of the outsiders who, in turn, are playing a non-cooperative Nash strategy against $S$. Hence the outsiders $i \in N \setminus S$ choose an emission abatement strategy as to maximize their own welfare, taking the abatement strategies of all other countries as given. Their maximization problem is exactly the one specified by condition (3). The first order conditions derived from this also carry through:

$$C_i'\left(a_i^{CS}\right) = B_i'\left(X_i^{CS}, a_N^{CS}\right) \qquad \forall i \in N \setminus S$$

where the superscript *CS* denoted that we are in the PANE w.r.t. coalition $S$.

The problem for the coalition members $j \in S$ can be formulated as follows:

$$\begin{aligned} &\max_{\omega_1,\ldots,\omega_s} \sum_{j \in S} \lambda_j U_j\left(X_j\left(\omega_S\right), a_S + \bar{a}_{-S}\right) \\ &\quad s.t.\, U_j\left(X_j\left(\omega_S\right), a\right) - U_j^{TP} \geq 0 \quad \forall j \in S \end{aligned} \tag{26}$$

where the income of region j is redefined as follows:

$$X_j\left(\omega_S\right) \equiv \bar{Y}_j - C_j\left[\alpha_j\left(\rho\left(\omega_S\right)\right)\right] - \rho\left(\omega_S\right)\left[\bar{E}_j - \alpha_j\left(\rho\left(\omega_S\right)\right) - \omega_j\right] \tag{27}$$

$\bar{Y}_j$ is the baseline income level, $\bar{E}_j$ denotes the business as usual emissions of region j, $\omega_j$ stands for the emission endowment allocated to region j, $\rho\left(\omega_S\right)$ denotes the permit price in function of the total emission permit endowment $\omega_S$, $\alpha_j\left(\rho\left(\omega_S\right)\right)$ is the supply of abatement of region j in function of $\omega_S$ and $C_j\left[\alpha_j\left(\rho\left(\omega_S\right)\right)\right]$ is region j's abatement cost function.

Expression (27) states that the income of region j now includes, besides the baseline income level minus the cost of abatement, the cost or revenue from emissions trading. If the region is a net permit buyer, the last term between square brackets in (27) (business as usual emissions minus sum of abatement effort and permit endowment) is positive and the region faces an extra cost. If the region is a net permit seller, this term will be negative and the region will see its income increase.

The corresponding Lagrangian function for the coalition welfare maximization problem is defined as:

$$\begin{aligned}&\mathcal{L}(\omega_1,...,\omega_s,\pi_1,...,\pi_s)\\&=\sum_{j\in S}(\lambda_j+\pi_j)U_j\left[\overline{Y}_j-C_j\left[\alpha_j(\rho(\omega_S))\right]-\rho(\omega_S)\left(\overline{E}_j-\alpha_j(\rho(\omega_S))-\omega_j\right),\sum_{k\in S}\alpha_k(\rho(\omega_S))\right]\\&\quad-\sum_{j\in S}\pi_j U_j^{TP}\end{aligned}$$

(28)

In Appendix A : it is shown that the first order conditions w.r.t. $\omega_i$ of this maximization problem can be reduced to:

$$\tilde{\lambda}_i=\frac{\left[\rho'(\omega_S)\sum_{j\in S}\tilde{\lambda}_j NIM_j+\sum_{j\in S}\tilde{\lambda}_j B_j'(X_j,a_N)\right]}{\rho(\omega_S)}\quad\forall i\in S \tag{29}$$

where $NIM_j=\overline{E}_j-\alpha_j(\rho(\omega_S))-\omega_j$ denotes net permit imports of region j. This condition reveals that the right hand side is equal for all regions that belong to the coalition or:

$$\tilde{\lambda}_i=\tilde{\lambda}^{UC}\quad\forall i\in S \tag{30}$$

where *UC* refers to the emission endowments being *un*constrained. Condition (30) states that in a world with unconstrained allocations, optimization requires that emission rights are distributed in such a way that the marginal social value of income is equalized across all regions. Using (30) and replacing $\rho(\omega_S)$ by $C_i'(a_i)$ (see condition (17)), we can rewrite (29) as follows:

$$C_i'(a_i)=\rho'(\omega_S)\sum_{j\in S}NIM_j+\sum_{j\in S}B_j'(X_j,a_N)\quad\forall i\in S \tag{31}$$

Since the unweighted sum of net imports over all regions equals zero, and using condition (17), expression (31) can be reduced to the well known Samuelson rule for the optimal emission reductions by coalition $S$ :

$$C_i'(a_i^{CS})=\sum_{j\in S}B_j'(X_j^{CS},a_N^{CS})\qquad\forall i\in S \tag{32}$$

Hence we have obtained the same equilibrium conditions as we obtained for the PANE scenario with lump sum transfers (see condition (8) and (7) from paragraph 3.2).

### *4.2.2. Constrained emission permit allocation*

#### a) Case 1: Positivity restriction on $\omega_i$

Imposing positivity restrictions on the allocation of permits does not alter the equilibrium conditions for the outsiders to the coalition. Therefore we focus on the maximization problem of coalition $S$. The problem of coalition $S$ is identical to problem (26), except for one additional constraint, i.e. the permit allocations are not allowed to be negative, or:

$$\omega_i \geq 0 \qquad \forall i \in S \tag{33}$$

In this case, the following Kuhn-Tucker conditions can be derived:

$$\omega_i \geq 0 \quad ; \quad \frac{\partial \mathcal{L}}{\partial \omega_i} \leq 0 \quad ; \quad \left(\frac{\partial \mathcal{L}}{\partial \omega_i}\right)\omega_i = 0 \qquad \forall i \in S \tag{34}$$

If the positivity constraint on permit endowments is not binding for region i, $\omega_i > 0$ and thus $\frac{\partial \mathcal{L}}{\partial \omega_i} = 0$. In Appendix A : we derived from this that among unconstrained regions, the marginal social values of an extra unit of income are equalized:

$$\tilde{\lambda}_i = \frac{\rho'(\omega_S)\sum_{j\in S}\tilde{\lambda}_j NIM_j + \sum_{j\in S}\tilde{\lambda}_j B'_j}{\rho(\omega_S)} = \tilde{\lambda}_+^{UC}$$

where the *plus*-sign refers to the fact that we are dealing with a positivity restriction and the superscript *UC* here denotes that the positivity constraint is not binding.

If on the other hand, the lower constraint is binding for region i, $\omega_i = 0$ and $\frac{\partial \mathcal{L}}{\partial \omega_i} < 0$ yielding:

$$\tilde{\lambda}_i\,\rho(\omega_S) - \rho'(\omega_S)\sum_{j\in S}\tilde{\lambda}_j NIM_j - \sum_{j\in S}\tilde{\lambda}_j B'_j < 0 \text{ or:}$$

$$\tilde{\lambda}_i < \frac{\rho'(\omega_S)\sum_{j\in S}\tilde{\lambda}_j NIM_j + \sum_{j\in S}\tilde{\lambda}_j B'_j}{\rho(\omega_S)} = \tilde{\lambda}_+^{UC}$$

This implies that $\tilde{\lambda}_i < \tilde{\lambda}_+^{UC}$. This condition reveals that in contrast with the unconstrained emission abatement problem, the marginal social value to region i of an additional unit of income is region specific and thus is not equalized across all counties in the optimum. This result can be interpreted in the following way: since group welfare maximization requires the marginal social values of income $\tilde{\lambda}_i$ to be equalized across countries, the marginal social value of income for region i is 'too low'. Bearing in mind the definition of $\tilde{\lambda}_i$ (see (5) ), the only way to raise $\tilde{\lambda}_i$, is to increase the marginal utility of income $\frac{\partial U_i}{\partial X_i}$ of country i (if we leave the weight $\lambda_i$ of each region in the group welfare function unchanged). Hence region i's income $X_i$ should go down. In other words, reducing the income of region i by giving it a negative emission permit endowment would increase overall welfare but this is not possible because of the constraint imposed on $\omega_i$.[2]

### b) Case 2: 'No hot air' restriction on $\omega_i$

Problem (26) is now extended with the following constraint:

$$\omega_i \leq \overline{E}_i \qquad \forall i \in S \tag{35}$$

This expression states that the emission permits a region receives are not allowed to exceed the region's business as usual emissions or, in other words it denotes that allocating hot air is not allowed. The Lagrangian can then be formulated as follows:

$$\begin{aligned}\mathcal{L}&\left(\omega_1,...,\omega_S,\pi_1,...,\pi_S,\phi_1,...,\phi_S\right)\\ &=\sum_{j\in S}\left(\lambda_j+\pi_j\right)U_j\left(\bar{Y}_j-C_j\left[\alpha_j\left(\rho(\omega_S)\right)\right]-\rho(\omega_S)\left(\overline{E}_j-\alpha_j\left(\rho(\omega_S)\right)-\omega_j\right),\sum_{k\in S}\alpha_k\left(\rho(\omega_S)\right)\right)\\ &\quad-\sum_{j\in S}\pi_j U_j^N-\sum_{j\in S}\phi_j\left(\omega_j-\overline{E}_j\right)\end{aligned}$$

From the first order conditions with respect to $\omega_i$ we can now derive that the marginal social value of income of region i must be equal to:

$$\tilde{\lambda}_i = \frac{\rho'(\omega_S)\sum_{j\in S}\tilde{\lambda}_j NIM_j + \sum_{j\in S}\tilde{\lambda}_j B'_j + \phi_i}{\rho(\omega_S)} \qquad \forall i \in S \tag{36}$$

The Kuhn-Tucker conditions for the additional constraint are the following:

$$\overline{E}_i - \omega_i \geq 0 \quad ; \quad \phi_i \geq 0 \quad ; \quad \left(\overline{E}_i - \omega_i\right)\phi_i = 0 \qquad \forall i \in S$$

We know that if the allocation constraint is not binding for region i, i.e. if $\omega_i \leq \overline{E}_i$, the Lagrange multiplier of the no hot air constraint $\phi_i$ equals zero and we can again write that

[2] Another way to see this is to consider how the Samuelson rule (32) is affected. This is done in Appendix B :.

$\tilde{\lambda}_i = \tilde{\lambda}_{BAU}^{UC}$ where *BAU* refers to the emission endowments being constrained by their business as usual emissions and the superscript *UC* again denotes that the constraint on emission endowments is not binding.

If however the allocation constraint is binding for region i, the Lagrange multiplier $\phi_i$ is strictly positive which implies that $\tilde{\lambda}_i = \tilde{\lambda}_{BAU}^{UC} + \dfrac{\phi_i}{\rho(\omega_S)} > \tilde{\lambda}_{BAU}^{UC}$. This means that the marginal social values of an additional unit of income are not equalized in the optimum for regions facing a binding 'no hot air' restriction on their emission endowment. The interpretation of this is that overall welfare would increase if region i was allocated a larger amount of permits but this is impossible because of the upper constraint (35) imposed on the permit endowments[3].

### c) Case 3: Positivity and 'no hot air' constraint on $\omega_i$

We now add constraint (33) and (35) simultaneously to problem (26). Formally this implies that $0 \leq \omega_i \leq \overline{E}_i$. We can distinguish three different possibilities:

- Among the regions for which none of the two constraints is binding we find that $\tilde{\lambda}_i = \tilde{\lambda}_{+,BAU}^{UC}$. The *plus*-sign and *BAU* refer to the fact that we impose both the positivity constraint as well as the 'no hot air' restriction on the maximization problem.
- If for a region i the lower constraint is binding we have that $\tilde{\lambda}_i < \tilde{\lambda}_{+,BAU}^{UC}$.
- If the 'no hot air' constraint becomes binding for a region i the result is that $\tilde{\lambda}_i > \tilde{\lambda}_{+,BAU}^{UC}$.

### d) Assessment

From the previous sections we can conclude that when constraints are imposed upon the allocation of permits which is the only redistribution instrument in our model, the Samuelson rule for the optimal provision of emission abatement by coalition $S$ breaks down. Hence, equity and efficiency considerations cannot be separated any more but have to be considered simultaneously. It is however difficult to derive definite analytical results on the consequence of positivity and no hot air constraints on the global abatement target and the permit price. Therefore we provide a description of the different effects at play.

Let us first focus on condition (29) which can be rewritten as follows:

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[3] See Appendix C : for a consideration of how the Samuelson rule breaks down.

$$\rho(\omega_S)=\frac{\left[\rho'(\omega_S)\sum_{j\in S}\tilde{\lambda}_j NIM_j+\sum_{j\in S}\tilde{\lambda}_j B_j'\left(X_j,a_N\right)\right]}{\tilde{\lambda}_i}\quad \forall i\in S \tag{37}$$

We know that the optimality condition requires that $\tilde{\lambda}_i=\tilde{\lambda}_{+,BAU}^{UC}$ . Using this, condition (37) reduces to:

$$\rho(\omega_S)=\sum_{j\in S}B_j'\left(X_j,a_N\right)$$

This states that the permit price should equal the sum of marginal benefits of the coalition members.

In the case where marginal social values of income are not equalized across regions, condition (37) can be interpreted in the following way. If we use $\tilde{\lambda}$ to refer to the vector of marginal social values of income of regions $\{1,...,s\}$ and we denote the vector of net imports by $NIM$ , the covariance between these two vectors can be written as follows (see Appendix D :):

$$\operatorname{cov}\left(\tilde{\lambda},NIM\right)=\frac{\sum_{j\in S}\tilde{\lambda}_j NIM_j}{s}$$

Hence by plugging this in to condition (37), we obtain

$$\rho(\omega_S)=\frac{\left[\rho'(\omega_S)\,s\operatorname{cov}\left(\tilde{\lambda},NIM\right)+\sum_{j\in S}\tilde{\lambda}_j B_j'\left(X_j,a_N\right)\right]}{\tilde{\lambda}_i}\quad \forall i\in S \tag{38}$$

This states that if the covariance between $\tilde{\lambda}$ and $NIM$ is positive, i.e. if the marginal social value of income and the net imports of countries are positively correlated, the permit price $\rho(\omega_S)$ will be lower (remember that $\rho'(\omega_S)<0$). If on the other hand this covariance is negative, i.e. if countries with a *low* marginal social value of income are net permit importers, the permit price will be higher.

In the context of climate change we can expect that poor countries with a high marginal utility and hence a high $\tilde{\lambda}_i$ will typically be allocated more permits. In addition, poor countries face in general lower marginal abatement cost functions and therefore they abate more. As a result, poor countries are expected to be rather permit exporters. Based on analogous reasoning, rich countries on the other hand are expected to be permit importers. Hence, the covariance is likely to be negative, resulting in an upward pressure on the permit price. This reasoning however neglects the presence of participation constraints. Due to these constraints, it might be the case that richer countries are allocated more permits so that they import less or even might become a permit exporter. This would exert an upward pressure on the covariance or might it even turn it into a positive figure which would result in a lower permit price. Furthermore the second term between square brackets in (38) also plays a role. This weighted sum of marginal benefits will tend to be smaller (larger) than the unweighted sum if high marginal benefit regions face a lower (higher) $\tilde{\lambda}_i$ and low marginal benefit regions have a higher (lower) $\tilde{\lambda}_i$. All these different interfering factors prevent us from drawing definite conclusions with respect to the change in the permit price due to constrained allocations.

Another way to assess the results of the previous sections is to consider how the different components of the countries' pay off are affected if the permit price changes. We distinguish between three different effects due to an increase (decrease) in the permit price: (i) all regions face a higher (lower) cost of abatement since a higher (lower) permit price implies that regions will abate more (less) (see condition (19)), (ii) permit *selling* countries receive more (less) revenues and permit *buying* countries face a higher (lower) cost of purchasing permits, (iii) all regions face less (more) environmental damage or more (less) benefits from emission reduction bearing in mind that a higher price implies more abatement (see condition (21)).

Let us focus on the case of a permit price increase with respect to the first best solution. The first and the third effect work in opposite directions (respectively welfare deteriorating and welfare improving) but do not depend on whether a region is a net permit buyer or a net permit seller. The second effect on the contrary, influences the welfare of net permit buyers negatively whereas it increases the welfare of net permit sellers. This result is summarized in Table 1.

**Table 1: Effect of a permit price increase on regions' welfare**

| | **Net permit buyer** | **Net permit seller** |
|---|---|---|
| | Effect on region's welfare | Effect on region's welfare |
| Abatement cost | − | − |
| Net permit trading revenue | − | + |
| Environmental benefit | + | + |

In the case of binding positivity constraints we found that we wanted to reduce the welfare of the constrained region(s). Being constrained, such regions receive an emission permit endowment of zero and hence are (net) permit buyers. From Table 1, we see that a reduction in welfare for the constrained regions can be realized by an increase in the permit price, i.e. by distributing fewer permits in total, if the extra costs due to this measure are not outweighed by the resulting environmental benefit. If the environmental benefit due to a price increase would be larger than the incurred costs, a price decrease would be more appropriate.

For regions with binding 'no hot air' constraints on the contrary, we wanted to increase welfare. These regions will be net permit sellers since they receive an endowment exactly equal to their business as usual emissions. From Table 1 it can be seen that this can be achieved by increasing the permit price if the resulting increased abatement cost does not outweigh the increased environmental benefit and permit trading revenues for the constrained regions. This will always be the case because regions will not sell emission permits if the cost to reduce these emissions exceeds the revenues they can get from it.

An empirical application should provide us with more insight in the effect on the global abatement target and the permit price of imposing both restrictions simultaneously. Intuitively, one would predict an increase in the permit price through a reduction in the number of permits distributed. Indeed, if the marginal benefit of emission reduction is not too high for the countries with binding positivity constraints, both constraints call for an increase in the permit prise (if they are binding). In addition, the positivity constraints are expected to be less restrictive than the no hot air constraints since the presence of participation constraints will probably withhold us from allocating negative endowments to most regions.

# 5. SOME EMPIRICAL APPLICATIONS

## *5.1. Model description*

As mentioned before, an empirical simulation is indispensable to gain more insight in how the imposition of positivity and 'no hot air' constraints influences the global abatement target and the permit price. We tried to use as well as possible the information available in the literature.

We divided the world into 16 homogeneous blocks of countries. Table 2 summarizes some relevant information on those regions[4] for the reference year 2010. Data are based on IEA[5] statistics (2001) for 1995 on which we applied growth rates calculated from one of the IPCC[6] emission scenario's[7] (2000). Percentage shares in world GDP, in world carbon

[4] For more details on geographical coverage, see Appendix E :.

[5] International Energy Agency

[6] Intergovernmental Panel on Climate Change

[7] We used the A1B-AIM scenario belonging to the A1 scenario family which describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid

emissions and in world population are reported in the first three columns of Table 2. Also GDP per capita, per capita carbon emissions and the ratio of emissions over GDP are shown.

**Table 2:Regional characteristics (2010)**

| | **GDP** (%) | **emissions** (%) | **population** (%) | **GDP/cap** (US$/cap) | **emis./cap** (ton C/cap) | **emis./GDP** (kg C/US$) |
|---|---|---|---|---|---|---|
| CAN | 1.61 | 1.41 | 0.46 | 24322.32 | 4.38 | 0.18 |
| USA | 20.36 | 15.96 | 4.08 | 34378.86 | 5.53 | 0.16 |
| JPN | 14.25 | 3.54 | 1.95 | 50421.58 | 2.57 | 0.05 |
| EU15 | 23.88 | 9.62 | 5.80 | 28400.88 | 2.35 | 0.08 |
| OEU | 1.28 | 0.22 | 0.18 | 48668.94 | 1.73 | 0.04 |
| CEA | 1.57 | 2.03 | 1.41 | 7685.69 | 2.04 | 0.27 |
| FSU | 2.46 | 6.65 | 4.22 | 4025.46 | 2.23 | 0.55 |
| AUZ | 1.21 | 0.95 | 0.34 | 24765.78 | 3.99 | 0.16 |
| MED | 1.98 | 3.44 | 3.99 | 3420.92 | 1.22 | 0.36 |
| MEA | 2.71 | 7.17 | 3.14 | 5935.86 | 3.23 | 0.54 |
| AFR | 1.77 | 4.00 | 12.22 | 997.11 | 0.46 | 0.46 |
| CHN | 5.24 | 20.16 | 20.86 | 1730.46 | 1.37 | 0.79 |
| IND | 2.20 | 5.41 | 16.01 | 948.83 | 0.48 | 0.50 |
| RAS | 9.37 | 7.86 | 13.19 | 4897.45 | 0.84 | 0.17 |
| SAM | 9.61 | 9.44 | 10.08 | 6573.73 | 1.33 | 0.20 |
| ROW | 0.50 | 2.15 | 2.07 | 1676.50 | 1.47 | 0.88 |
| **world** | **100.00** | **100.00** | **100.00** | **6895.20** | **1.41** | **0.21** |

*(source: IEA (2001) and IPCC (2000))*

CAN = Canada
USA = United States of America
JPN = Japan
EU15 = European Union
OEU = Other Europe
CEA = Central
FSU = Eastern Europe
AUZ = Australia and New Zealand
MED = Mediterranean
MEA = Middle East
AFR = Africa
CHN = China
IND = India
RAS = Rest of Asia
SAM = South America
ROW = Rest of the world

GDP per capita is highest in Japan and in the other European countries whereas in India and Africa GDP per capita is lowest. Also from this table we can read that the USA and China emit most in absolute values. In terms of emissions per capita however, Canada and the USA emit most while the largest emitters in terms of emissions per GDP are China and the 'rest of the world', indicating that they are inefficient carbon users.

Preferences of different regions are represented by the following constant elasticity of marginal utility specification:

$$U_i = \frac{1}{1-\varepsilon}\left(\frac{\overline{Y}_i - C_i\left(a_i\right) - p\left[\overline{E}_i - a_i - \omega_i\right]}{pop_i}\right)^{(1-\varepsilon)} \qquad \forall i \in N \tag{39}$$

introduction of new and more efficient technologies. In particular, A1B describes a balanced technological change across all sources where balanced is defined as not relying too heavily on one particular energy source (IPCC, 2001). The model used to develop the scenario is the Asian Pacific Integrated Model (AIM) from the Institute of Environmental Studies in Japan (Morita et al., 1994) where $pop_i$ denotes the exogenous population and the parameter $\varepsilon$ determines the concavity of the utility function and can be interpreted as a measure of inequality aversion in a welfare maximization framework. The larger $\varepsilon$, the more weight we will attach to poorer countries when maximizing the group welfare function. Indeed from specification (39) it can be seen that in the utility function each region's GDP per capita is weighted by its own GDP per capita to the power $(-\varepsilon)$. Hence we can state each region's weight in the social welfare function is given by the following specification[8]:

$$\left(\frac{\overline{Y}_i / pop_i}{\overline{Y}_p / pop_p}\right)^{-\varepsilon} \qquad (40)$$

where $\overline{Y}_i$ is the baseline GDP per capita for region i and the subscript *p* refers to the poorest region. The division by the poorest nation's GDP per capita is done in order to normalize the weights so that the poorest region always gets a weight equal to one for all values of $\varepsilon$. We derived specification (40) from our constant elasticity of marginal utility specification but a combination of linear utility functions and a concave parameterisation of social welfare W as a function of GDP per capita would result in the same weighting scheme. In Table 3 the pattern of weights for different values of $\varepsilon$ is shown. For our purposes we put $\varepsilon = 0.5$ throughout the paper but in section 5.5 this figure will be submitted to a sensitivity analysis.

For the marginal cost functions we use the following specification from Nordhaus (1991) calibrated to the simulation results obtained with the OECD-GREEN model Burniaux et al. (1992) by Eyckmans et al. (1993).

$$\ln\left(1 - \frac{a_i}{\overline{E}_i}\right) = \beta_i C_i^{'} \qquad \forall i \in N$$

Since our model contains a larger number of regions than the one of Eyckmans et al. (1993), we replicated for the new regions the parameter $\beta_i$ from the geographically matching region.

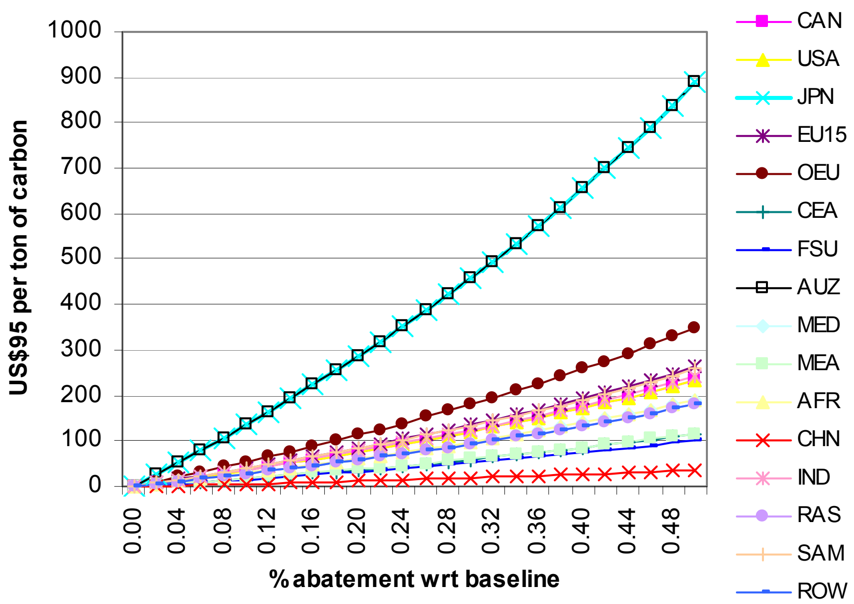
[8] This is an approximation, based on the assumption that the abatement cost and the revenue or cost of permit trading together are not large enough to change a country's position in the GDP per capita ranking.

**Table 3: Distributional weights**

| | $\varepsilon$ | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **0.01** | **0.10** | **0.30** | **0.40** | **0.50** | **1.00** | **1.50** | **2.00** | **2.50** |
| CAN | 0.97 | 0.72 | 0.38 | 0.27 | 0.20 | 0.04 | 0.01 | 0.00 | 0.00 |
| USA | 0.96 | 0.70 | 0.34 | 0.24 | 0.17 | 0.03 | 0.00 | 0.00 | 0.00 |
| JPN | 0.96 | 0.67 | 0.30 | 0.20 | 0.14 | 0.02 | 0.00 | 0.00 | 0.00 |
| EU15 | 0.97 | 0.71 | 0.36 | 0.26 | 0.18 | 0.03 | 0.01 | 0.00 | 0.00 |
| OEU | 0.96 | 0.67 | 0.31 | 0.21 | 0.14 | 0.02 | 0.00 | 0.00 | 0.00 |
| CEA | 0.98 | 0.81 | 0.53 | 0.43 | 0.35 | 0.12 | 0.04 | 0.02 | 0.01 |
| FSU | 0.99 | 0.87 | 0.65 | 0.56 | 0.49 | 0.24 | 0.11 | 0.06 | 0.03 |
| AUZ | 0.97 | 0.72 | 0.38 | 0.27 | 0.20 | 0.04 | 0.01 | 0.00 | 0.00 |
| MED | 0.99 | 0.88 | 0.68 | 0.60 | 0.53 | 0.28 | 0.15 | 0.08 | 0.04 |
| MEA | 0.98 | 0.83 | 0.58 | 0.48 | 0.40 | 0.16 | 0.06 | 0.03 | 0.01 |
| AFR | 1.00 | 1.00 | 0.99 | 0.98 | 0.98 | 0.95 | 0.93 | 0.91 | 0.88 |
| CHN | 0.99 | 0.94 | 0.84 | 0.79 | 0.74 | 0.55 | 0.41 | 0.30 | 0.22 |
| IND | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| RAS | 0.98 | 0.85 | 0.61 | 0.52 | 0.44 | 0.19 | 0.09 | 0.04 | 0.02 |
| SAM | 0.98 | 0.82 | 0.56 | 0.46 | 0.38 | 0.14 | 0.05 | 0.02 | 0.01 |
| ROW | 0.99 | 0.94 | 0.84 | 0.80 | 0.75 | 0.57 | 0.43 | 0.32 | 0.24 |

Figure 1 shows the resulting marginal abatement cost functions. It is immediately obvious that there exist huge differences between regions: in Japan, Australia and New Zealand, reducing emissions is most expensive whereas in China and in the former Soviet Union it is cheapest.

**Figure 1: Marginal abatement cost functions**




Abatement benefits are assumed linear in global emission reduction, hence marginal benefits are constant. Ayres and Walter (1991) proposed a central estimate of 35 US$ per ton of carbon abated. Finus et al. (2003) obtained a marginal damage value of 137.13

US$ per ton carbon[9], based on estimates of Tol (1997). For our empirical exercise we follow a "revealed references approach" and pick a value for the marginal benefits so as to obtain an optimal emission reduction of 5% with respect to 1990 by the Annex B countries as agreed upon in the Kyoto protocol. This leads to a value of 43 US$ for the marginal benefits per ton carbon abated. This figure is in line with results by Plambeck and Hope (1996) who report that their best estimates of marginal benefits in a regional scenario fall within the range of 36.67 to 176.00 US$ per ton carbon[10]. For the disaggregation of benefits over different regions, we adopted the simple assumption that benefits are disaggregated according to the region's share in world GDP (see Table 2).

## 5.2. Non-cooperative Nash outcome

In Table 4 the non-cooperative outcome is reported. The first column shows the emission reduction in percentage of the projected 2010 baseline emissions, the second and the third column report respectively the marginal abatement cost and benefit and the last column contains the pay off in US$ per capita. These pay offs will be used as the deviation pay offs when we impose that the IEA should satisfy individual rationality.

**Table 4: Non-cooperative outcome**

| | ABATEMENT (%) | C′ (US$/TON C) | B′ (US$/TON C) | PAY OFF/CAP (US$/CAP) |
|---|---|---|---|---|
| CAN | 0.20 | 0.69 | 0.69 | 4.11 |
| USA | 2.56 | 8.76 | 8.76 | 5.19 |
| JPN | 0.48 | 6.13 | 6.13 | 8.48 |
| EU15 | 2.67 | 10.27 | 10.27 | 4.48 |
| OEU | 0.11 | 0.55 | 0.55 | 8.23 |
| CEA | 0.41 | 0.67 | 0.67 | 1.30 |
| FSU | 0.73 | 1.06 | 1.06 | 0.67 |
| AUZ | 0.04 | 0.52 | 0.52 | 4.19 |
| MED | 0.31 | 0.85 | 0.85 | 0.58 |
| MEA | 0.69 | 1.16 | 1.16 | 0.99 |
| AFR | 0.28 | 0.76 | 0.76 | 0.17 |
| CHN | 4.27 | 2.25 | 2.25 | 0.23 |
| IND | 0.27 | 0.95 | 0.95 | 0.16 |
| RAS | 1.54 | 4.03 | 4.03 | 0.80 |
| SAM | 1.10 | 4.13 | 4.13 | 1.08 |
| ROW | 0.08 | 0.22 | 0.22 | 0.28 |
| **WORLD** | **1.92** | **4.05** | **43.00** | **1.10** |

Differences in abatement efforts follow from differences in the share of regions in global abatement benefits on the one hand and from the convexity of their cost function on the other hand. China for instance reduces most because abatement is cheap and abatement benefits are substantial. The second and the third column reveal that indeed each region abates emissions up to the point where its marginal cost is equal to its marginal benefit

[9] The exact number they report is 37.40 US$ per ton $CO_2$. Multiplying with a factor $\frac{44}{12}$ we obtained the figure of 137.13 US$.

[10] They report estimates within the range of 10 to 48 US$ per ton $CO_2$.

and hence does not internalize environmental damages caused to other regions. The consequence is that the marginal costs are not equalized across regions what implies a significant lack of efficiency. The resulting emission reductions as reported in the first column and the pay off per capita in the last column are fairly low. This outcome clearly shows that an IEA to coordinate emission reduction efforts across regions is desirable since the same emission reduction could be achieved at a much lower cost.

## 5.3. First best outcome

In Table 5 we present the first best command-and-control solution without transfers. From the first column we can see immediately that the amount of emission reduction undertaken is much higher than in the non-cooperative outcome. Furthermore, we can conclude from the second and the third column that the result is efficient: the marginal cost of each region is equal to the sum of marginal benefits over all regions. As a consequence, the world pay off per capita is now almost seven times higher than in the Nash outcome.

The benefits from emission reduction however are not well distributed: we see that the countries in the shaded cells not only receive less than in the non-cooperative outcome, but they even get a negative pay off. The reason is that these countries have the cheapest carbon abatement possibilities and therefore they are required to abate a lot in the Pareto efficient solution. It is obvious that these countries would never agree on this particular IEA if they do not get compensated. This result clearly illustrates the need for international transfers in order to make all countries willing to cooperate in an IEA. The participation problem will be taken care of in the next section where we allow for permit trading among countries.

**Table 5: First best solution**

| | ABATEMENT (%) | C′ (US$/TON C) | B′ (US$/TON C) | PAY OFF/CAP (US$/CAP) |
|---|---|---|---|---|
| CAN | 11.95 | 43.00 | 0.69 | 37.75 |
| USA | 11.95 | 43.00 | 8.76 | 55.02 |
| JPN | 3.30 | 43.00 | 6.13 | 99.28 |
| EU15 | 10.73 | 43.00 | 10.27 | 51.63 |
| OEU | 8.16 | 43.00 | 0.55 | 94.58 |
| CEA | 22.84 | 43.00 | 0.67 | 5.81 |
| FSU | 25.61 | 43.00 | 1.06 | -3.60 |
| AUZ | 3.30 | 43.00 | 0.52 | 46.84 |
| MED | 14.53 | 43.00 | 0.85 | 3.15 |
| MEA | 22.57 | 43.00 | 1.16 | -3.09 |
| AFR | 14.53 | 43.00 | 0.76 | 0.59 |
| CHN | 56.56 | 43.00 | 2.25 | -10.87 |
| IND | 11.65 | 43.00 | 0.95 | 0.73 |
| RAS | 15.22 | 43.00 | 4.03 | 7.14 |
| SAM | 10.88 | 43.00 | 4.13 | 10.14 |
| ROW | 15.22 | 43.00 | 0.22 | -1.32 |
| **WORLD** | **22.72** | **43.00** | **43.00** | **7.49** |

## 5.4. Emissions trading

In this section we report some results on the emissions trading model. We assume that emission permits are allocated for free and that the endowment of emission permits is used as a redistribution instrument across nations in order to stabilize the IEA. The two stability concepts elaborated in section 3.3 will be considered successively. If there is still some scope left after satisfying the participation constraints, the permit distribution will be manipulated further in order to deal with equity issues. The inequality aversion parameter will be the relevant criterion in this respect.

### 5.4.1. Individual rationality

#### a) Full cooperation

##### *(1) Unconstrained endowments*

Table 6 contains the simulation results from permit trading among all regions when the agreement must satisfy individual rationality but no constraints are imposed on the allocation of permits. That is, we allow for negative permit endowments as well as for the allocation of 'hot air'.

The first two columns show the abatement and endowment of each region relative to the base year 2010. The next two columns include the endowment and emissions in million tons of carbon. The difference between these two columns results in the volume of trade, reported in the fifth column. A positive figure denotes the amount of permits a region sells whereas a negative figure denotes the number of permits to be bought. Accordingly an *S* in front of a row denotes that the country is a permit seller. When a region receives exactly the same pay off as in the non-cooperative equilibrium this is indicated with an asterisk (*) in the end of the row. This means that for this region the participation constraint is binding.

**Table 6: Emissions trading – I.R. – unconstrained endowments** $(\varepsilon = 0.5)$

| | ABAT. (%) | ENDOW. (%) | ENDOW. (MIO TON C) | EMISSIONS (MIO TON C) | VOL. TRADE (MIO TON C) | C′ (US$/TON C) | PAY OFF/CAP (US$/CAP) | |
|---|---|---|---|---|---|---|---|---|
| CAN | 11.95 | 70.18 | 99.57 | 124.93 | -25.36 | 43.00 | 4.11 | * |
| USA | 11.95 | 67.09 | 1077.43 | 1414.04 | -336.61 | 43.00 | 5.19 | * |
| JPN | 3.30 | 14.46 | 51.46 | 344.24 | -292.78 | 43.00 | 8.48 | * |
| EU15 | 10.73 | 42.56 | 411.86 | 863.93 | -452.08 | 43.00 | 4.48 | * |
| OEU | 8.16 | -24.28 | -5.41 | 20.47 | -25.88 | 43.00 | 8.23 | |
| CEA | 22.84 | 72.03 | 147.45 | 157.96 | -10.51 | 43.00 | 1.30 | * |
| *S* FSU | 25.61 | 78.85 | 527.30 | 497.50 | 29.80 | 43.00 | 0.67 | * |
| AUZ | 3.30 | 71.84 | 68.78 | 92.59 | -23.80 | 43.00 | 4.19 | * |
| MED | 14.53 | 80.55 | 278.70 | 295.72 | -17.02 | 43.00 | 0.58 | * |
| *S* MEA | 22.57 | 80.37 | 579.87 | 558.65 | 21.22 | 43.00 | 0.99 | * |
| AFR | 14.53 | 83.35 | 335.43 | 343.99 | -8.55 | 43.00 | 0.17 | * |
| *S* CHN | 56.56 | 62.32 | 1264.41 | 881.35 | 383.06 | 43.00 | 0.23 | * |
| *S* IND | 11.65 | 279.66 | 1523.72 | 481.39 | 1042.33 | 43.00 | 40.09 | |
| RAS | 15.22 | 67.29 | 531.93 | 670.21 | -138.28 | 43.00 | 0.80 | * |
| SAM | 10.88 | 73.22 | 695.64 | 846.67 | -151.03 | 43.00 | 1.08 | * |
| *S* ROW | 15.22 | 87.31 | 189.14 | 183.65 | 5.49 | 43.00 | 0.28 | * |
| **WORLD** | **22.72** | **77.28** | **7777.28** | **7777.28** | **0.00** | **43.00** | **7.49** | |

From the marginal costs we see immediately that the solution is still *first best*: marginal costs across regions are equalised to the sum of marginal benefits. Indeed, a comparison with Table 5 shows that exactly the same amount of emissions is abated as in the Pareto efficient solution. The resulting average pay off per capita is also *first best*. Only the distribution of the pay offs has changed: all countries except India receive an amount of permits exactly large enough to ensure their non-cooperative pay off. This implies a negative permit endowment only for the 'other European countries' region (OEU). Apparently the individual rationality constraint ensures for all other regions that they receive a positive permit endowment. The remainder of the permits to be distributed are all allocated to the poorest country. This results in a large amount of hot air for India: it receives an allocation of not less than 279.66% of its business as usual emissions.

### *(2) Constrained endowments*

Next we consider what happens when we impose positivity and 'no hot air' constraints simultaneously on the permit allocation, still in the case of full cooperation. The requirement that the agreement must be individually rational still holds. The results are reported in Table 7.

Due to the positivity constraint, the 'OEU' region now gets exactly zero endowments, what results in a pay off per capita larger than its Nash pay off. In addition, the 'no hot air' constraint imposes that India's 'hot air' is taken away and is allocated conform our inequality aversion to the second, the third and the fourth poorest country. All these nations receive a permit endowment of exactly their business as usual emissions what yields them a pay off per capita well above their non-cooperative pay off. A new permit seller in this equilibrium is Africa.

**Table 7: Emissions trading – I.R. – no neg. endowments and no hot air** $(\varepsilon = 0.5)$

| | ABAT. (%) | ENDOW. (%) | ENDOW. (MIO TON C) | EMISSIONS (MIO TON C) | VOL. TRADE (MIO TON C) | C′ (US$/TON C) | PAY OFF/CAP (US$/CAP) |
|---|---|---|---|---|---|---|---|
| CAN | 12.77 | 70.02 | 99.35 | 123.78 | -24.43 | 46.14 | 4.11 * |
| USA | 12.77 | 66.98 | 1075.70 | 1400.96 | -325.27 | 46.14 | 5.19 * |
| JPN | 3.53 | 15.29 | 54.41 | 343.39 | -288.98 | 46.14 | 8.48 * |
| EU15 | 11.47 | 42.78 | 414.01 | 856.80 | -442.80 | 46.14 | 4.48 * |
| OEU | 8.73 | 0.00 | 0.00 | 20.34 | -20.34 | 46.14 | 26.75 |
| CEA | 24.29 | 71.42 | 146.20 | 154.99 | -8.80 | 46.14 | 1.30 * |
| S FSU | 27.20 | 78.05 | 521.98 | 486.87 | 35.11 | 46.14 | 0.67 * |
| AUZ | 3.53 | 72.02 | 68.96 | 92.36 | -23.40 | 46.14 | 4.19 * |
| MED | 15.50 | 80.18 | 277.39 | 292.35 | -14.96 | 46.14 | 0.58 * |
| S MEA | 24.01 | 79.67 | 574.86 | 548.31 | 26.54 | 46.14 | 0.99 * |
| S AFR | 15.50 | 100.00 | 402.44 | 340.07 | 62.37 | 46.14 | 3.81 |
| S CHN | 59.12 | 100.00 | 2028.85 | 829.31 | 1199.54 | 46.14 | 25.06 |
| S IND | 12.44 | 100.00 | 544.86 | 477.06 | 67.80 | 46.14 | 3.41 |
| RAS | 16.24 | 67.03 | 529.94 | 662.18 | -132.25 | 46.14 | 0.80 * |
| SAM | 11.63 | 73.07 | 694.26 | 839.58 | -145.32 | 46.14 | 1.08 * |
| S ROW | 16.24 | 100.00 | 216.62 | 181.45 | 35.17 | 46.14 | 9.22 |
| **WORLD** | **23.99** | **76.01** | **7649.81** | **7649.81** | **0.00** | **46.14** | **7.46** |

A quick look at the marginal costs immediately reveals that the result is cost efficient but not *first best*. Each country still abates up to the point where its marginal cost equalizes the permit price. This permit price is however not equal to the aggregated marginal benefits but about 3 US$ higher. A higher equilibrium marginal abatement cost of each region implies that each region abates more. This can be verified by comparing the first column in Table 7 with the first column in Table 6.

The intuition behind the increase in the permit price is the following. On the one hand we would like to give one nation, i.e. OEU a negative endowment but we are not allowed to because of the positivity constraint. A way to deal with this could be to increase the permit price; the country with an endowment of zero now has pay a higher permit price for each ton of carbon it emits. We found however that if only the positivity constraints are imposed, welfare is extracted from the constrained country by *de*creasing the permit price by 0.05 US$ compared to the first best outcome. The explanation is that although the region now faces a lower abatement cost and a lower cost of purchasing permits, it now bears more environmental damage. In our empirical exercise with an aggregate marginal benefit from emission reduction of 43 US$, this loss in environmental damage outweighs the reduced costs of OEU (see Table 1).

On the other hand, optimality requires that India is allocated ‘hot air’ but also this is ruled out. A means of compensating this is a raise in the permit price: the nation with an allocation of 100% of its business as usual emissions can sell its permits now at a higher price. We found that imposing only ‘no hot air’ constraints, increased the permit price by 3.28 US$.

Hence the no 'hot air' and positivity restrictions have an opposite effect on the permit price. Imposing them together on the maximization problem, results in a slightly more moderate increase in the permit price as reported in Table 7. A price increase can only be achieved by making the permits scarcer, i.e. by distributing less of them. This is confirmed if we compare the endowment in Table 7 with the one in Table 6. The loss in the pay off from abatement policy due to the imposition of no hot air and positivity constraints, amounts to approximately 0.37% with respect to the first best scenario.

Finally we should note that the increase in the permit price strokes with our intuition behind condition (38). From Table 7 we see that the permit sellers belong to the poorest regions. Therefore the covariance between $\tilde{\lambda}$ and $NIM$ will be negative what explains the increase in the permit price.

## b) Partial cooperation – the Kyoto coalition

### *(1) Unconstrained endowments*

In Table 8 we report the results of an individually rational permit trading agreement among the Annex B countries of the Kyoto protocol, which in our set up roughly corresponds to coalition:

$$S = \{CAN, USA, JPN, EU15, OEU, CEA, FSU, AUZ\}$$

No constraints are imposed yet on the permit allocations. The symbols used in the table have the same meaning as before.

First, one should note that the result can be considered as a Nash equilibrium in which the coalition of cooperating countries behaves as one player. Indeed, within the coalition the benefits from emission abatement are completely internalised: each coalition member puts its marginal cost equal to the sum of marginal benefits over all coalition partners. All the outsiders from the coalition follow their Nash strategy and abate until their marginal cost is equal to their marginal benefit.

In addition, an abatement percentage of 9.25% with respect to the 2010 business usual emissions is undertaken within the coalition. This is equivalent to an emission reduction of 5% with respect to 1990 emissions[11] as imposed by the Kyoto protocol. Furthermore, each member of the coalition exactly receives its non-cooperative pay off, except for the former Soviet Union. Since this is the poorest country in the coalition, it is allocated an amount of hot air. This means that our welfare economics model provides a justification

[11] 1990 emissions amount to approximately 3880.41 million ton carbon (IEA, 2001).

for the controversial allocation of hot air to Russia[12]. For negative endowments there is no scope since this cannot be done without making a region worse off compared to its Nash outcome.

**Table 8: Emissions trading in Kyoto coalition**
**I.R. – unconstrained endowments - $(\varepsilon = 0.5)$**

| | ABAT. (%) | ENDOW. (%) | ENDOW. (MIO TON C) | EMISSIONS (MIO TON C) | VOL. TRADE (MIO TON C) | C′ (US$/TON C) | B′ (US$/TON C) | PAY OFF/CAP (US$/CAP) |
|---|---|---|---|---|---|---|---|---|
| **CAN** | 8.13 | 90.75 | 128.77 | 130.35 | -1.58 | 28.65 | 0.69 | 4.11 * |
| **USA** | 8.13 | 89.76 | 1441.46 | 1475.41 | -33.95 | 28.65 | 8.76 | 5.19 * |
| **JPN** | 2.21 | 80.73 | 287.40 | 348.11 | -60.71 | 28.65 | 6.13 | 8.48 * |
| **EU15** | 7.28 | 84.68 | 819.54 | 897.30 | -77.76 | 28.65 | 10.27 | 4.48 * |
| **OEU** | 5.51 | 71.28 | 15.89 | 21.06 | -5.17 | 28.65 | 0.55 | 8.23 * |
| S **CEA** | 15.86 | 88.37 | 180.90 | 172.23 | 8.66 | 28.65 | 0.67 | 1.30 * |
| S **FSU** | 17.89 | 108.27 | 724.07 | 549.13 | 174.94 | 28.65 | 1.06 | 12.93 |
| **AUZ** | 2.21 | 93.17 | 89.20 | 93.63 | -4.42 | 28.65 | 0.52 | 4.19 * |
| MED | 0.31 | 0.00 | 0.00 | 344.90 | 0.00 | 0.85 | 0.85 | 1.48 |
| MEA | 0.69 | 0.00 | 0.00 | 716.55 | 0.00 | 1.16 | 1.16 | 2.56 |
| AFR | 0.28 | 0.00 | 0.00 | 401.33 | 0.00 | 0.76 | 0.76 | 0.43 |
| CHN | 4.27 | 0.00 | 0.00 | 1942.20 | 0.00 | 2.25 | 2.25 | 0.68 |
| IND | 0.27 | 0.00 | 0.00 | 543.37 | 0.00 | 0.95 | 0.95 | 0.41 |
| RAS | 1.54 | 0.00 | 0.00 | 778.40 | 0.00 | 4.03 | 4.03 | 2.10 |
| SAM | 1.10 | 0.00 | 0.00 | 939.62 | 0.00 | 4.13 | 4.13 | 2.82 |
| ROW | 0.08 | 0.00 | 0.00 | 216.44 | 0.00 | 0.22 | 0.22 | 0.73 |
| **S** | **9.25** | **90.75** | **3687.22** | **3687.22** | **0.00** | **28.65** | **28.65** | **6.77** |
| **WORLD** | **4.91** | **36.64** | **3687.22** | **9570.04** | **0.00** | **12.44** | **43.00** | **2.22** |

Finally, we should point to the fact that all the outsiders from the coalition are better off than in the non-cooperative outcome (see Table 4) although they follow exactly the same strategy. This illustrates that they free ride on the abatement efforts undertaken by the coalition members.

### *(2) Constrained endowments*

We now impose that allocating hot air or negative endowments is not allowed. The results are reported in Table 9. From the third column we see that the hot air is taken away from the former Soviet Union and given to the second poorest coalition member i.e. the central European countries. FSU and CEA are now the only coalition members that receive more than in the non-cooperative equilibrium.

As in the full cooperation case, the permit price now also has increased. This illustrates that the Samuelson rule for optimal emission reductions by the coalition (see equation (32) ) breaks down as predicted in section 4.2.2. The resulting emission reduction within the coalition is more than 1% higher than in the case where hot air is allowed. This leads to a

[12] The Kyoto Protocol calls for an emission reduction by Russia to 100% of 1990 emissions in the period 2008-2012. However, as a result of the decline in economic activity, the Russian federation has projected 2010 carbon emissions lower than in 1990.

reduction in the pay off by 1.5% for the Kyoto group compared to the case with unconstrained allocations and an increase in the pay off by 4.4% for the world as a whole.

**Table 9: Emissions trading in Kyoto coalition**
**I.R. – no neg. endowments and no hot air - $(\varepsilon = 0.5)$**

| | ABAT. (%) | ENDOW. (%) | ENDOW. (MIO TON C) | EMISSIONS (MIO TON C) | VOL. TRADE (MIO TON C) | C′ (US$/TON C) | B′ (US$/TON C) | PAY OFF/CAP (US$/CAP) |
|---|---|---|---|---|---|---|---|---|
| **CAN** | 9.41 | 89.98 | 127.67 | 128.54 | -0.87 | 33.38 | 0.69 | 4.11 * |
| **USA** | 9.41 | 89.02 | 1429.67 | 1454.89 | -25.22 | 33.38 | 8.76 | 5.19 * |
| **JPN** | 2.57 | 80.15 | 285.31 | 346.83 | -61.52 | 33.38 | 6.13 | 8.48 * |
| **EU15** | 8.43 | 83.90 | 812.01 | 886.16 | -74.15 | 33.38 | 10.27 | 4.48 * |
| **OEU** | 6.40 | 70.24 | 15.65 | 20.86 | -5.21 | 33.38 | 0.55 | 8.23 * |
| S **CEA** | 18.23 | 98.44 | 201.52 | 167.39 | 34.12 | 33.38 | 0.67 | 9.08 |
| S **FSU** | 20.52 | 100.00 | 668.76 | 531.54 | 137.22 | 33.38 | 1.06 | 9.87 |
| **AUZ** | 2.57 | 92.86 | 88.90 | 93.28 | -4.38 | 33.38 | 0.52 | 4.19 * |
| MED | 0.31 | 0.00 | 0.00 | 344.90 | 0.00 | 0.85 | 0.85 | 1.65 |
| MEA | 0.69 | 0.00 | 0.00 | 716.55 | 0.00 | 1.16 | 1.16 | 2.86 |
| AFR | 0.28 | 0.00 | 0.00 | 401.33 | 0.00 | 0.76 | 0.76 | 0.48 |
| CHN | 4.27 | 0.00 | 0.00 | 1942.20 | 0.00 | 2.25 | 2.25 | 0.77 |
| IND | 0.27 | 0.00 | 0.00 | 543.37 | 0.00 | 0.95 | 0.95 | 0.46 |
| RAS | 1.54 | 0.00 | 0.00 | 778.40 | 0.00 | 4.03 | 4.03 | 2.34 |
| SAM | 1.10 | 0.00 | 0.00 | 939.62 | 0.00 | 4.13 | 4.13 | 3.15 |
| ROW | 0.08 | 0.00 | 0.00 | 216.44 | 0.00 | 0.22 | 0.22 | 0.81 |
| **S** | **10.67** | **89.33** | **3629.50** | **3629.50** | **0.00** | **33.38** | **28.65** | **6.67** |
| **WORLD** | **5.48** | **36.06** | **3629.50** | **9512.32** | **0.00** | **14.14** | **43.00** | **2.32** |

## *5.4.2. Internal stability*

In Appendix F : and Appendix G : we illustrate that neither the grand coalition nor the Kyoto coalition are internally stable. In both cases cooperation between the coalition members does not generate enough surpluses to compensate all regions that have an incentive to deviate in order to free ride on the remaining coalition's effort. This illustrates that internal stability is a more stringent requirement than individual rationality.

In order to focus on the most interesting potentially internally stable coalitions, we used an algorithm (Eyckmans, 2001) to check which potentially stable coalitions generate the largest surplus in terms of world abatement. The result is reported in Table 10. Under each region, the number indicates whether the region belongs to a coalition: a "1" means that the corresponding region is a member of the coalition; a "0" denotes that it does not belong to that coalition. Together these digits form the key that describes the composition of the coalition. The last two columns give the abatement in percentage of 2010 emissions for the coalition and for the world as a whole.

We see that the largest coalition in terms of abatement consists of only three members: USA, EU15 and CHN. The abatement percentage resulting from this coalition structure is far below the one undertaken in the first best full cooperation scenario (see Table 6) but significantly larger than the percentage resulting from the efficient (i.e. with unconstrained endowments) permit trading agreement within the Kyoto coalition (see Table 8). The other nine largest potentially stable coalitions contain at least 6 and at most 8 members. It is worth noting that the CAN, JPN, RAS and SAM belong to none of the coalitions in Table 10 whereas EU15 and CHN belong to all of the ten coalitions. This can probably be explained by the fact that CHN has the lowest marginal abatement costs. Hence including CHN in the permit agreement makes emission reduction cheaper. EU15 on the other hand, has the highest marginal abatement benefit. If they would leave, the permit price would fall resulting in less emission reduction while they have a high interest in emission reduction taking place.

**Table 10: Ten biggest potentially internally stable coalitions in terms of world abatement**

| CAN | USA | JPN | EU15 | OEU | CEA | FSU | AUZ | MED | MEA | AFR | CHN | IND | RAS | SAM | ROW | coal.abat. (%) | world abat. (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | **1** | 0 | **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **1** | 0 | 0 | 0 | 0 | 18.78 | 8.70 |
| 0 | 0 | 0 | **1** | 0 | 0 | **1** | 0 | 0 | **1** | **1** | **1** | **1** | 0 | 0 | **1** | 14.50 | 8.67 |
| 0 | 0 | 0 | **1** | 0 | **1** | **1** | 0 | 0 | **1** | 0 | **1** | **1** | 0 | 0 | **1** | 14.89 | 8.60 |
| 0 | 0 | 0 | **1** | 0 | **1** | **1** | 0 | **1** | **1** | **1** | **1** | 0 | 0 | 0 | **1** | 14.87 | 8.59 |
| 0 | 0 | 0 | **1** | **1** | **1** | **1** | 0 | 0 | **1** | **1** | **1** | 0 | 0 | 0 | 0 | 15.73 | 8.52 |
| 0 | 0 | 0 | **1** | 0 | **1** | **1** | **1** | 0 | **1** | **1** | **1** | 0 | 0 | 0 | 0 | 15.49 | 8.51 |
| 0 | 0 | 0 | **1** | 0 | **1** | **1** | 0 | **1** | **1** | 0 | **1** | 0 | 0 | 0 | **1** | 15.29 | 8.51 |
| 0 | 0 | 0 | **1** | 0 | **1** | **1** | 0 | 0 | **1** | **1** | **1** | 0 | 0 | 0 | **1** | 15.12 | 8.51 |
| 0 | 0 | 0 | **1** | 0 | 0 | **1** | 0 | 0 | **1** | 0 | **1** | **1** | 0 | 0 | **1** | 14.84 | 8.48 |
| 0 | 0 | 0 | **1** | 0 | 0 | **1** | 0 | **1** | **1** | 0 | **1** | **1** | 0 | 0 | 0 | 14.84 | 8.46 |

As an illustration, the stability analysis for the largest potentially stable coalition is reported in Table 11. The first column contains the coalition key[13]. The first line shows the pay off for the different members of the coalition in the PANE w.r.t. coalition "0101000000010000" without any transfers or emissions trading. The second line contains the pay off for the PANE w.r.t. the two player coalition "0001000000010000", i.e. the remaining coalition after USA has left the original coalition "0101000000010000". Hence it is assumed in line 2 that the two remaining regions continue to cooperate but they reoptimize their emission strategies among themselves. According to Table 11 USA cannot improve its pay off by defecting from the coalition. Line 3 shows a similar result for EU15. The fourth line illustrates what happens with the pay off for the coalition members of "0101000000010000" when CHN deviates. I.e. it contains the pay off for the PANE w.r.t. coalition "0101000000000000". We see that CHN could improve its pay off by defecting from the original coalition provided the remaining coalition stays together. Hence CHN needs to be compensated in order to be willing to stay in the coalition. The question is whether the coalition generates enough surpluses in order to do that. This is

[13] Remember that we have 12 regions ordered in the following way:

$$N = \{CAN, USA, JPN, EU15, OEU, CEA, FSU, AUZ, MED, MEA, AFR, CHN, IND, RAS, SAM, ROW\}$$

verified in the last line of Table 11. It contains for each region the minimal transfer needed to stabilize the coalition. We read from the table that keeping CHN in the coalition requires a transfer of 5313.65 million US$. From USA and EU15 we can subtract respectively 2009.27 million US$ and 3367.17 US$ without giving them an incentive to defect from the coalition. The lower right cell shows the sum of all transfers needed to stabilize the coalition. The negative figure indicates that there is still some surplus left to be distributed. From this we can conclude that the coalition is potentially internally stable.

**Table 11: Stability analysis for** $S = \{USA, EU15, CHN\}$

| COALITION | USA | EU15 | CHN | |
|---|---|---|---|---|
| 0101000000010000 | 6636.59 | 8434.33 | -4822.61 | |
| 0001000000010000 | 4627.32 | 5439.96 | -1390.22 | |
| 0100000000010000 | 4152.50 | 5067.16 | -929.54 | |
| 0101000000000000 | 1458.12 | 2234.04 | 491.04 | |
| **min. stabilizing transfer** | -2009.27 | -3367.17 | 5313.65 | **-62.79** |

We now allow for emissions trading among regions within the coalition. The permits are distributed for free over the coalition members in such a way that no region has an incentive to defect from the coalition assuming that the remaining coalition stays together. The results are reported in Table 12.

**Table 12: Emissions trading in coalition** $S = \{USA, EU15, CHN\}$

**I.S. – unconstrained endowments -** $(\varepsilon = 0.5)$

| | ABAT. (%) | ENDOW. (%) | ENDOW. (MIO TON C) | EMISSIONS (MIO TON C) | VOL. TRADE (MIO TON C) | C′ (US$/TON C) | B′ (US$/TON C) | PAY OFF/CAP (US$/CAP) |
|---|---|---|---|---|---|---|---|---|
| CAN | 0.20 | 0.00 | 0.00 | 141.60 | 0.00 | 0.69 | 0.69 | 18.67 |
| **USA** | 6.10 | 88.02 | 1413.52 | 1507.97 | -94.45 | 21.27 | 8.76 | 15.93 ** |
| JPN | 0.48 | 0.00 | 0.00 | 354.28 | 0.00 | 6.13 | 6.13 | 38.68 |
| **EU15** | 5.46 | 78.18 | 756.66 | 914.94 | -158.28 | 21.27 | 10.27 | 12.29 ** |
| OEU | 0.11 | 0.00 | 0.00 | 22.26 | 0.00 | 0.55 | 0.55 | 37.37 |
| CEA | 0.41 | 0.00 | 0.00 | 203.88 | 0.00 | 0.67 | 0.67 | 5.90 |
| FSU | 0.73 | 0.00 | 0.00 | 663.91 | 0.00 | 1.06 | 1.06 | 3.08 |
| AUZ | 0.04 | 0.00 | 0.00 | 95.70 | 0.00 | 0.52 | 0.52 | 19.02 |
| MED | 0.31 | 0.00 | 0.00 | 344.90 | 0.00 | 0.85 | 0.85 | 2.63 |
| MEA | 0.69 | 0.00 | 0.00 | 716.55 | 0.00 | 1.16 | 1.16 | 4.54 |
| AFR | 0.28 | 0.00 | 0.00 | 401.33 | 0.00 | 0.76 | 0.76 | 0.77 |
| S **CHN** | 33.80 | 78.66 | 1595.83 | 1343.10 | 252.73 | 21.27 | 2.25 | 0.37 |
| IND | 0.27 | 0.00 | 0.00 | 543.37 | 0.00 | 0.95 | 0.95 | 0.73 |
| RAS | 1.54 | 0.00 | 0.00 | 778.40 | 0.00 | 4.03 | 4.03 | 3.73 |
| SAM | 1.10 | 0.00 | 0.00 | 939.62 | 0.00 | 4.13 | 4.13 | 5.02 |
| ROW | 0.08 | 0.00 | 0.00 | 216.44 | 0.00 | 0.22 | 0.22 | 1.29 |
| **S** | **18.18** | **81.82** | **3766.01** | **3766.01** | **0.00** | **21.27** | **21.27** | **4.69** |
| **WORLD** | **8.70** | **37.42** | **3766.01** | **9188.26** | **0.00** | **10.05** | **43.00** | **4.11** |

We observe that the coalition members internalise the benefits from emission reduction. Each region abates until its marginal cost equals the aggregated marginal benefits within the coalition. Furthermore, USA and EU15 receive exactly enough permits so that their pay offs are equal to the one they would have if they left the coalition unilaterally, provided the remaining coalition stays together. This is indicated with a double asterisk in the end of the row. The rest of the permits is allocated to the poorest coalition region, i.e. CHN. The question of whether or not to allocate hot air or negative endowments does not apply here: the Samuelson condition for the optimal emission reduction by the coalition $\{USA, EU15, CHN\}$ is fulfilled and does not require the allocation of hot air nor a negative amount of emission permits. With a percentage of 88% w.r.t. business as usual emissions the USA gets the largest relative endowment. Finally we should point to the fact that CHN is the only permit selling region in this PANE. This raises the issue of market power and non-competitive behaviour in a permit trading agreement which we do not deal with in this paper. It might however call for a consideration of the second largest potentially internally stable coalition since it contains 6 members and thus possibly more permit sellers as we see from Table 10.

The internal stability analysis which is included in Appendix H : confirms that this coalition "0001001001111001" can be internally stabilized through the right transfers. In Table 13 we report the optimal permit allocations and the results of emissions trading within this coalition. First we note that in the equilibrium only EU15 is a permit buyer. In addition we see once more from the marginal costs and benefits columns that the Samuelson rule is satisfied within the coalition. Furthermore the asterisks indicate that again all countries except the poorest receive exactly their deviation pay off. As in the previously discussed three-member coalition also here neither hot air nor negative permit amounts are allocated.

**Table 13: Emissions trading in coalition** $S=\{EU15, FSU, MEA, AFR, CHN, IND, ROW\}$

**I.S. – unconstrained endowments -** $(\varepsilon = 0.5)$

| | ABAT. (%) | ENDOW. (%) | ENDOW. (MIO TON C) | EMISSIONS (MIO TON C) | VOL. TRADE (MIO TON C) | C′ (US$/TON C) | B′ (US$/TON C) | PAY OFF/CAP (US$/CAP) |
|---|---|---|---|---|---|---|---|---|
| CAN | 0.20 | 0.00 | 0.00 | 141.60 | 0.00 | 0.69 | 0.69 | 18.61 |
| USA | 2.56 | 0.00 | 0.00 | 1564.89 | 0.00 | 8.76 | 8.76 | 25.69 |
| JPN | 0.48 | 0.00 | 0.00 | 354.28 | 0.00 | 6.13 | 6.13 | 38.54 |
| **EU15** | 4.30 | 67.58 | 654.07 | 926.14 | -272.07 | 16.66 | 10.27 | 9.90 ** |
| OEU | 0.11 | 0.00 | 0.00 | 22.26 | 0.00 | 0.55 | 0.55 | 37.24 |
| CEA | 0.41 | 0.00 | 0.00 | 203.88 | 0.00 | 0.67 | 0.67 | 5.88 |
| S **FSU** | 10.83 | 93.43 | 624.79 | 596.32 | 28.47 | 16.66 | 1.06 | 2.69 ** |
| AUZ | 0.04 | 0.00 | 0.00 | 95.70 | 0.00 | 0.52 | 0.52 | 18.95 |
| MED | 0.31 | 0.00 | 0.00 | 344.90 | 0.00 | 0.85 | 0.85 | 2.62 |
| S **MEA** | 9.44 | 94.13 | 679.16 | 653.42 | 25.73 | 16.66 | 1.16 | 3.96 ** |
| S **AFR** | 5.90 | 96.40 | 387.96 | 378.69 | 9.26 | 16.66 | 0.76 | 0.72 ** |
| S **CHN** | 27.61 | 81.80 | 1659.61 | 1468.67 | 190.95 | 16.66 | 2.25 | 0.49 ** |
| S **IND** | 4.69 | 97.39 | 530.63 | 519.33 | 11.31 | 16.66 | 0.95 | 0.71 |
| RAS | 1.54 | 0.00 | 0.00 | 778.40 | 0.00 | 4.03 | 4.03 | 3.72 |
| SAM | 1.10 | 0.00 | 0.00 | 939.62 | 0.00 | 4.13 | 4.13 | 5.00 |
| S **ROW** | 6.20 | 96.73 | 209.55 | 203.19 | 6.35 | 16.66 | 0.22 | 1.25 ** |
| **S** | **14.05** | **85.50** | **4745.76** | **4745.76** | **0.00** | **16.66** | **16.66** | **1.77** |
| **WORLD** | **8.67** | **47.16** | **4745.76** | **9191.30** | **0.00** | **11.16** | **43.00** | **4.34** |

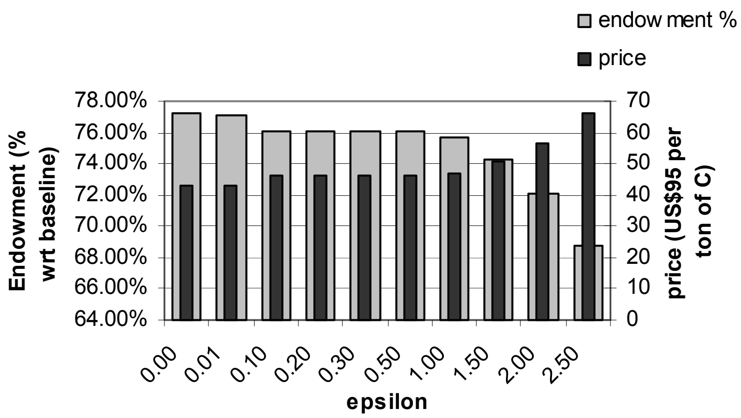
The reason why we find optimality to require an allocation of hot air if the agreement has to be individually rational whereas this is not the case when we impose the internal stability restriction is the following. Being inequality averse, we want to give the surplus of cooperation after the internal stability restrictions are satisfied to the poorest region in the form of emission permits. The internal stability restriction however is more demanding than the individual rationality constraint. Therefore the surplus left to be distributed is not likely to be large enough to provide the poorest region with 'hot air' or there is less scope for equity considerations in the allocation of permits.

## *5.5. Sensitivity analysis*

Because of the large uncertainty w.r.t. the aggregated marginal benefit from emission reduction, a sensitivity analysis with respect this figure is appropriate. We found that for low values of the aggregate marginal benefit (i.e. roughly below 37 US$), binding positivity constraints had a positive effect on the permit price. For a figure above 37 US$, binding positivity constraints exerted a downward pressure on the permit price. The reason is that if marginal benefits are relatively high, the way to extract income from the positivity constrained regions is by distributing more permits (i.e. by allowing for more environmental damage) with a lower permit price as a result. When we imposed the positivity and no hot air constraints simultaneously, the value of the aggregate marginal benefit had only quantitative, no qualitative effect on our results. Lower marginal benefits just result in less emission reduction to be undertaken, hence more permits to be distributed. Furthermore we found that for lower values of the aggregated marginal benefit, the positivity restriction on permit allocations was not binding anymore for the grand coalition.

Figure 2 illustrates the effect of a varying degree of inequality aversion on the total amount of permits distributed (light shaded bars) and on the permit price (dark shaded bars) in the case of full cooperation, individual rationality and both the positivity and the no hot air constraints imposed on the permit endowments. We see that the amount of permits distributed decreases as the global planner becomes more inequality averse. The reason is that at a higher degree of inequality aversion we want to give a larger compensation to poorer regions and subtract more income from richer regions. Since this can only be done to a limited extent through the distribution of permits, it is achieved by adapting the permit price. A higher permit price means that the rich permit buying countries face more expensive permit prices whereas the poor permit selling regions receive more revenues for the permits they sell. A higher permit price implies higher marginal abatement costs since each abating region still follows the decentralised permit market equilibrium condition (see condition (17)). Thus they don't equalise marginal abatement costs with the sum of marginal abatement benefits or the Samuelson condition for the optimal provision of emission abatement breaks down.

**Figure 2: Effect of a varying degree of inequality aversion (full cooperation - constrained endowments)**




A similar graph could be drawn for the case of a PANE where permit trading takes place within a coalition under individual rationality and constrained emission endowments. However, if we vary the degree of inequality aversion in the case of a PANE w.r.t. a coalition on which we impose internal stability, this will in most cases have no effect on the permit price or total endowment since the no hot air constraint is not likely to be binding in this case.

# 6. CONCLUSION

In this paper we explored the equity and efficiency properties of self-enforcingly designed international carbon agreements. We used a welfare economics framework while focusing on one particular type of agreement i.e. an international tradable permit agreement. While the decentralised permit market equilibrium ensures that cost efficiency prevails, the allocation of tradable quotas over the different regions is used to compensate regions that otherwise would not be willing to participate in or comply with the agreement. Then, if there is some scope left, the permit distribution is manipulated further in order to deal with equity issues. In order to study partial cooperation between regions as is observed in reality (the Kyoto Protocol is an example), we adopted the Partial Agreement Nash Equilibrium concept which roughly comes down to a Nash equilibrium where the players are coalitions instead of individual countries. Two stability concepts i.e. individual rationality and internal and external stability were considered.

We found that if we allowed for negative permit endowments and for the allocation of hot air, the Samuelson rule for the optimal provision of carbon emission reduction was preserved. If however the allocation of hot air or negative endowments was ruled out, the allocation of permits could be considered as a limited international redistribution instrument and the Samuelson condition broke down. This could be seen from the marginal social values of income that were not equalized in the equilibrium for regions that faced a binding constraint on their endowment.

A simulation model with 16 aggregate regions was used to illustrate the different solution concepts and to gain more insight in the effect on welfare of binding permit allocation constraints. The non-cooperative Nash solution yielded a very modest overall carbon emission abatement of 1.92% with respect to the reference business as usual emissions in 2010. Mainly regions with high marginal abatement benefits and cheap carbon abatement possibilities contributed to this result.

A tradable permit agreement among all regions with unconstrained endowments in which the assignment of permits was used to make the agreement individually rational, resulted in a first best abatement percentage of 22.72% w.r.t. 2010 emissions. When we imposed no hot air and positivity constraints on the endowments, the total amount of permits distributed decreased and the permit price increased. The resulting abatement undertaken amounted to 23.99%. Although this is positive from an environmental perspective, it implied a lower social welfare due to the inefficiency of the result.

A simulation of emissions trading under individual rationality within the Kyoto coalition yielded some interesting results. First, we found that the former Soviet Union, the poorest region in the Kyoto coalition in terms of GDP per capita, was allocated hot air. Hence our model provides a justification for the allocation of hot air to Russia in the Kyoto Protocol. Secondly, the imposition of constraints on the endowments yielded qualitatively the same result as in the full cooperation case. Remarkably was however that although the Kyoto coalition faced a reduction in its average pay off due to these constraints, the welfare of the world as a whole increased. Furthermore the positivity constraints were not binding in this case.

Next we checked some tradable permit agreements on their internal stability. Neither the grand coalition nor the Kyoto coalition appeared to be potentially internally stable. Both coalitions did not generate enough surpluses in order to compensate the regions that have an incentive to free ride on the coalition's efforts. The largest potentially internally stable coalition in terms of world abatement yielded an abatement effort of 8.70% w.r.t. 2010 and consisted only of three regions: the USA, the European Union and China. Permit trading within the coalition showed that neither the positivity constraints nor the no hot air constraints were binding.

In summary we can conclude that ruling out negative or hot air allocations reduces welfare if at least one of these constraints is binding. However when more stringent stability concepts are adopted, the constraints on endowments become less binding. A sensitivity analysis revealed that the welfare loss due to these constraints gets larger as we become more inequality averse.

We are well aware of the aspects that require further investigation. First, concerning participation in international environmental agreements, we did not consider the concept of coalitional stability. This allows for coalitions of two or more regions not to agree upon the agreement if they find that their joint pay off in a partial agreement Nash would be higher than the pay off they obtain under the current agreement. We did not consider this concept since it would imply that in our empirical exercise with 16 regions, $2^{16}$ different coalitions have to be checked what was beyond the scope of this paper. Secondly, the model should be extended to a dynamic setting in order to include intertemporal flexibility mechanisms such as the banking of permits. A dynamic emission model would also allow for a better incorporation of the main physical features of the global warming problem. Thirdly, we did not take into account non-competitive behaviour of permit trading firms that might result from market power when there are only a limited number of permit sellers. Finally, an update of the marginal abatement cost functions should be carried out.

# APPENDICES

## *Appendix A : First order conditions of the unconstrained allocation problem*

$$\mathcal{L}\left(\omega_1,...,\omega_s,\pi_1,...,\pi_s\right)$$
$$=\sum_{j\in S}\left(\lambda_j+\pi_j\right)U_j\left[\overline{Y}_j-C_j\left[\alpha_j\left(\rho(\omega_S)\right)\right]-\rho(\omega_S)\left(\overline{E}_j-\alpha_j\left(\rho(\omega_S)\right)-\omega_j\right),\sum_{k\in S}\alpha_k\left(\rho(\omega_S)\right)\right]$$
$$-\sum_{j\in S}\pi_j U_j^{TP}$$

Deriving this Lagrangian with respect to $\omega_i$ gives:

$$\begin{aligned}&\sum_{j\in S}\left(\lambda_j+\pi_j\right)\frac{\partial U_j}{\partial X_j}\left(-C_j'(.)\alpha_j'(.)\rho'(\omega_S)-\rho'(\omega_S)NIM_j+\rho(\omega_S)\alpha_j'(.)\rho'(\omega_S)\right)\\&+\left(\lambda_i+\pi_i\right)\frac{\partial U_i}{\partial X_i}\rho(\omega_S)+\sum_{j\in S}\left(\lambda_j+\pi_j\right)\frac{\partial U_j}{\partial a}\left(\sum_{k\in S}\alpha_k'(.)\rho'(\omega_S)\right)=0\quad\forall i\in S\end{aligned}\tag{41}$$

where $NIM_j=\overline{E}_j-\alpha_j\left(\rho(\omega_S)\right)-\omega_j$ denotes net permit imports of region j. Equation (41) can be simplified as follows:

$$\begin{aligned}\tilde{\lambda}_i\rho(\omega_S)=&\sum_{j\in S}\tilde{\lambda}_j\alpha_j'(.)\rho'(\omega_S)\left(C_j'-\rho(\omega_S)\right)+\sum_{j\in S}\tilde{\lambda}_j\rho'(\omega_S)NIM_j\\&-\sum_{j\in S}\tilde{\lambda}_j\left(\frac{\partial U_j}{\partial a}\Big/\frac{\partial U_j}{\partial X_j}\right)\left(\sum_{k\in S}\alpha_k'(.)\rho'(\omega_S)\right)\quad\forall i\in S\end{aligned}\tag{42}$$

where $\tilde{\lambda}_i\equiv\left(\lambda_i+\pi_i\right)\left(\frac{\partial U_i}{\partial X_i}\right)$ again should be interpreted as the marginal social value to region i of an additional unit of income. The first term on the right hand side cancels out because of the firms' profit maximizing behaviour, given by condition (17). Furthermore, we know from (25) that $\rho'(\omega_S)=\frac{-1}{\sum_{j\in S}\alpha_j'\left(\rho(\omega_S)\right)}$. In addition, we can define $B_j'\equiv\left(\frac{\partial U_j}{\partial a}\Big/\frac{\partial U_j}{\partial X_j}\right)$ again as the marginal benefit of abatement to region j expressed in terms of income. Using this information, we can rewrite the first order conditions as follows:

$$\tilde{\lambda}_i=\frac{\left[\rho'(\omega_S)\sum_{j\in S}\tilde{\lambda}_j NIM_j+\sum_{j\in S}\tilde{\lambda}_j B_j'\right]}{\rho(\omega_S)}\quad\forall i\in S\tag{43}$$

## *Appendix B : Samuelson rule under positivity constraints*

Call the set of unconstrained regions *U* and the set of constrained regions *C*, both being a subset of $S$. Then, using (17), the first order conditions in (43) become

$$C_i' = \rho'(\omega_S)\left(\sum_{j\in U} NIM_j + \sum_{j\in C}\frac{\tilde{\lambda}_j}{\tilde{\lambda}_+^{UC}} NIM_j\right) + \sum_{j\in U} B_j' + \sum_{j\in C}\frac{\tilde{\lambda}_j}{\tilde{\lambda}_+^{UC}} B_j' \quad \forall i\in U \tag{44}$$

$$C_i' = \rho'(\omega_S)\left(\sum_{j\in U}\frac{\tilde{\lambda}_+^{UC}}{\tilde{\lambda}_i} NIM_j + \sum_{j\in C}\frac{\tilde{\lambda}_j}{\tilde{\lambda}_i} NIM_j\right) + \sum_{j\in U}\frac{\tilde{\lambda}_+^{UC}}{\tilde{\lambda}_i} B_j' + \sum_{j\in C}\frac{\tilde{\lambda}_j}{\tilde{\lambda}_i} B_j' \quad \forall i\in C \tag{45}$$

In order to get a better insight in to how these two expressions are related to each other, it is useful to focus on the case where there is only one nation k for which the positivity constraint is binding. Expression (44) and (45) then reduce to:

$$C_i' = \rho'(\omega_S)\left(\sum_{j\in U} NIM_j + \frac{\tilde{\lambda}_k}{\tilde{\lambda}_+^{UC}} NIM_k\right) + \sum_{j\in U} B_j' + \frac{\tilde{\lambda}_k}{\tilde{\lambda}_+^{UC}} B_k' \quad \forall i\in U \tag{46}$$

$$C_k' = \rho'(\omega_S)\left(\frac{\tilde{\lambda}_+^{UC}}{\tilde{\lambda}_k}\sum_{j\in U} NIM_j + NIM_k\right) + \frac{\tilde{\lambda}_+^{UC}}{\tilde{\lambda}_k}\sum_{j\in U} B_j' + B_k' \quad k\in C \tag{47}$$

It is easily checked that since for $k\in C$, $\frac{\tilde{\lambda}_k}{\tilde{\lambda}_+^{UC}} < 1$, the two last terms in equation (47) exceed the two last terms in (46). Furthermore, the sum of net imports among unconstrained regions is negative because the constrained region with zero endowment is a permit importer and is excluded from the sum. Therefore, one can verify that the first term between brackets in condition (47) is negative and smaller than the one in condition (46). Since $\rho'(\omega_S) < 0$, equation (47) must exceed equation (46). This means that ideally, the constrained region should have to face a higher marginal abatement cost in order to compensate for the fact that it receives too much permits. However, since the abatement efforts are determined in a decentralised way via the permit market, i.e. each firm freely chooses its own abatement effort such that its marginal abatement costs are equal to the permit price, this correction via abatement efforts will not take place.

## *Appendix C : Samuelson rule under 'no hot air' constraints*

Using (17), condition (36) can also be interpreted as follows:

$$\tilde{\lambda}_{BAU}^{UC} C_i' = \rho'(\omega_S)\sum_{j\in S}\tilde{\lambda}_j NIM_j + \sum_{j\in S}\tilde{\lambda}_j B_j' + \phi_i \quad \forall i\in S \tag{48}$$

If we again consider the special case where for only one region k the allocation faces a binding constraint by its business as usual emissions and we denote the set of unconstrained regions with *U* and the set of constrained regions with *C*, both being a subset of $S$, condition (48) becomes

$$C_i' = \rho'(\omega_S)\left(\sum_{j\in U} NIM_j + \frac{\tilde{\lambda}_k}{\tilde{\lambda}_{BAU}^{UC}} NIM_k\right) + \sum_{j\in U} B_j' + \frac{\tilde{\lambda}_k}{\tilde{\lambda}_{BAU}^{UC}} B_k' \quad \forall i \in U \tag{49}$$

$$C_k' = \rho'(\omega_S)\left(\frac{\tilde{\lambda}_{BAU}^{UC}}{\tilde{\lambda}_k}\sum_{j\in U} NIM_j + NIM_k\right) + \frac{\tilde{\lambda}_{BAU}^{UC}}{\tilde{\lambda}_k}\sum_{j\in U} B_j' + B_k' + \frac{\phi_k}{\tilde{\lambda}_k} \quad k \in C \tag{50}$$

Since for $k \in C$ $\frac{\tilde{\lambda}_k}{\tilde{\lambda}_{BAU}^{UC}} > 1$, the two last terms in equation (49) exceed the second and the third one in equation (50). In order to compare the first term between brackets in both equations, we should note that the unweighted sum of net imports among *un*constrained regions will be positive since the constrained region is an exporter. This implies that in both (49) and (50), the first term between brackets is again negative but now the first term in (49) is larger than the one in (50) after multiplication with $\rho'(\omega_S)$. Because of the presence of the positive term $\frac{\phi_k}{\tilde{\lambda}_k} = \frac{\tilde{\lambda}_k - \lambda_{BAU}^{UC}}{\tilde{\lambda}_k}$ in condition (50), we cannot conclude in general that optimally the marginal abatement cost of unconstrained regions should exceed the marginal cost of the constrained region. However, since $\frac{\phi_k}{\tilde{\lambda}_k}$ takes a value smaller than 1, this will hold in most cases.

## *Appendix D : Covariance between* $\tilde{\lambda}$ *and* $NIM$

$$\operatorname{cov}\left(\tilde{\lambda}, NIM\right) = \frac{1}{s}\sum_{j\in S}\left(\tilde{\lambda}_j - \bar{\tilde{\lambda}}\right)\left(NIM_j - \overline{NIM}\right)$$

where $\bar{\tilde{\lambda}} = \frac{1}{s}\sum_{j\in S}\tilde{\lambda}_j$ and $\overline{NIM} = \frac{1}{s}\sum_{j\in S} NIM_j = 0$

Hence $\operatorname{cov}\left(\tilde{\lambda}, NIM\right) = \frac{1}{s}\sum_{j\in S}\left(\tilde{\lambda}_j NIM_j - \bar{\tilde{\lambda}} NIM_j\right)$

$$= \frac{1}{s}\sum_{j\in S}\tilde{\lambda}_j NIM_j - \frac{1}{s}\bar{\tilde{\lambda}}\sum_{j\in S} NIM_j$$

$$= \frac{1}{s}\sum_{j\in S}\tilde{\lambda}_j NIM_j$$

## *Appendix E : Geographical coverage*

| LABEL | NAME | COMPOSITION |
|---|---|---|
| CAN | Canada | |
| USA | USA | |
| JPN | Japan | |
| EU15 | European Union | |
| OEU | Other Europe | Iceland, Norway, Switzerland |
| CEA | Eastern Europe | Bulgaria, Czech-Rep, Hungary, Poland, Romania, Slovak-Rep, Slovenia |
| FSU | Former Soviet Union | |
| AUZ | Australazia | Australia and New Zealand |
| MED | Mediterranean | Turkey, Morocco, Algeria, Egypt, Libya, Tunisia |
| MEA | Middle East | Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen |
| AFR | Africa | Angola, Benin, Botswana, Burkina-Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Republic of Congo, Djibouti, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea Bissau, Ivory coast, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, reunion, Rwanda, Senegal, Seychelles, Sierra-Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe |
| CHN | China | China, Hong Kong |
| IND | India | |
| RAS | Rest of Asia | South Korea, Indonesia, Malaysia, Philippine, Singapore, Thailand, Vietnam, Taiwan, Sri-Lanka, Bangladesh, Nepal, Pakistan |
| SAM | South America | Costa-Rica, Cuba, Dominican Republic, El Salvador, Guatemala, Haití, Honduras, Jamaica, Antilles, Nicaragua, Panamá, Trinidad-Tobago, Venezuela, Colombia, Bolivia, Ecuador, Perú, Argentina, Brasil, Chile, Uruguay, Paraguay |
| ROW | Rest of the world | |

## Appendix F : Stability analysis for the grand coalition

| GRAND COALITION | CAN | USA | JPN | EU15 | OEU | CEA | FSU | AUZ | MED | MEA | AFR | CHN | IND | RAS | SAM | ROW | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1223.53 | 15983.13 | 13765.88 | 21286.34 | 1218.81 | 581.62 | -1079.80 | 1123.90 | 895.75 | -690.89 | 513.87 | -16134.38 | 829.63 | 6698.40 | 7269.39 | -194.29 | |
| 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1549.152 | 15712.27 | 13497.72 | 20891.23 | 1195.239 | 579.352 | -1026.35 | 1102.563 | 889.241 | -645.129 | 516.699 | -15728.6 | 827.883 | 6592.881 | 7150.205 | -183.223 | |
| 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1009.81 | 15531.28 | 10838.4 | 17010.43 | 961.853 | 579.641 | -409.518 | 891.827 | 846.932 | -111.417 | 570.807 | -10964.6 | 837.759 | 5598.628 | 6010.335 | -58.529 | |
| 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1128.412 | 14654.75 | 12358.11 | 19079.45 | 1080.455 | 636.932 | -510.118 | 1001.065 | 933.065 | -176.614 | 619.574 | -12306.4 | 916.423 | 6248.646 | 6714.451 | -78.073 | |
| 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 | 1022.433 | 13238.41 | 10793.35 | 18190.59 | 958.673 | 624.207 | -234.783 | 890.516 | 895.309 | 55.391 | 629.292 | -9946.46 | 900.775 | 5695.07 | 6088.502 | -23.597 | |
| 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 1 | 1215.27 | 15866.73 | 13621.81 | 21088.10 | 1243.87 | 587.47 | -1025.22 | 1112.82 | 900.23 | -641.23 | 524.75 | -15785.99 | 838.99 | 6660.07 | 7221.35 | -183.02 | |
| 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 1 | 1183.57 | 15462.51 | 13324.69 | 20600.17 | 1179.71 | 1493.77 | -1058.55 | 1087.82 | 864.48 | -680.23 | 494.41 | -15803.91 | 800.23 | 6477.50 | 7032.12 | -189.81 | |
| 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 1 | 1097.32 | 14361.66 | 12510.86 | 19266.77 | 1106.97 | 485.06 | 2199.69 | 1019.45 | 768.29 | -781.58 | 413.34 | -15823.36 | 696.27 | 5981.41 | 6517.29 | -207.27 | |
| 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 1 | 1214.74 | 15860.62 | 13620.80 | 21084.15 | 1206.16 | 586.23 | -1029.54 | 1178.57 | 898.81 | -645.44 | 523.13 | -15807.39 | 837.19 | 6656.46 | 7218.10 | -183.91 | |
| 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 1 | 1179.20 | 15403.34 | 13263.33 | 20511.12 | 1174.33 | 559.84 | -1043.79 | 1082.98 | 1876.31 | -667.32 | 495.96 | -15697.61 | 800.81 | 6455.13 | 7006.39 | -186.77 | |
| 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 1 | 1101.97 | 14418.37 | 12538.78 | 19321.64 | 1109.55 | 492.23 | -1124.37 | 1022.04 | 776.78 | 2423.41 | 422.21 | -15736.54 | 706.54 | 6010.38 | 6545.35 | -203.20 | |
| 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 1 | 1174.79 | 15349.41 | 13235.92 | 20458.09 | 1171.80 | 553.22 | -1061.69 | 1080.46 | 855.90 | -685.28 | 1670.61 | -15774.60 | 791.35 | 6427.78 | 6979.79 | -190.44 | |
| 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 1 | 487.54 | 6611.54 | 6953.34 | 10049.17 | 609.26 | -80.95 | -1935.77 | 549.50 | 47.64 | -1674.01 | -215.06 | 2539.63 | -95.88 | 2447.05 | 2873.87 | -369.05 | |
| 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 1 | 1169.36 | 15276.78 | 13164.02 | 20352.14 | 1165.48 | 552.63 | -1047.31 | 1074.73 | 854.16 | -672.97 | 488.57 | -15664.68 | 2070.58 | 6399.50 | 6947.83 | -187.47 | |
| 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 1 | 1100.00 | 14335.12 | 12169.82 | 18917.34 | 1078.37 | 560.17 | -790.12 | 996.41 | 847.32 | -446.95 | 519.34 | -13803.29 | 806.41 | 8111.47 | 6540.12 | -134.88 | |
| 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 1 | 1108.25 | 14437.68 | 12230.79 | 19026.92 | 1083.91 | 570.68 | -765.65 | 1001.79 | 860.04 | -421.91 | 531.88 | -13707.04 | 821.30 | 6098.15 | 8362.91 | -129.89 | |
| 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 | 1198.22 | 15657.90 | 13513.47 | 20880.59 | 1196.32 | 562.40 | -1092.02 | 1102.90 | 870.35 | -708.41 | 493.93 | -16068.96 | 803.12 | 6554.75 | 7118.61 | 486.08 | |
| **Min. stabilizing transfer** | **325.63** | **-451.84** | **-1407.77** | **-3095.76** | **25.06** | **912.16** | **3279.49** | **54.67** | **980.56** | **3114.30** | **1156.74** | **18674.01** | **1240.95** | **1413.07** | **1093.53** | **680.37** | **27995.14** |

## Appendix G : Stability analysis for the Kyoto coalition

| KYOTO COALITION | CAN | USA | JPN | EU15 | OEU | CEA | FSU | AUZ | |
|---|---|---|---|---|---|---|---|---|---|
| **11111111**00000000 | 178.51 | 2481.57 | 2915.79 | 4074.68 | 254.19 | -118.37 | -1134.31 | 227.19 | |
| **0**1111111**1**00000000 | 327.82 | 2396.26 | 2801.52 | 3920.77 | 244.28 | -111.18 | -1080.90 | 218.45 | |
| **10111111**00000000 | 150.44 | 2739.09 | 1988.56 | 2933.59 | 174.75 | -0.58 | -478.47 | 159.02 | |
| **11011111**00000000 | 183.53 | 2462.74 | 2526.04 | 3616.94 | 216.20 | -7.29 | -615.53 | 196.44 | |
| **11101111**00000000 | 169.77 | 2243.32 | 2066.22 | 3406.30 | 182.24 | 38.90 | -349.82 | 167.08 | |
| **11110111**00000000 | 179.03 | 2480.00 | 2871.20 | 4029.87 | 267.24 | -107.52 | -1083.70 | 224.18 | |
| **11111011**00000000 | 158.75 | 2221.23 | 2680.25 | 3716.78 | 233.39 | 306.65 | -1103.54 | 208.12 | |
| **11111101**00000000 | 104.42 | 1527.45 | 2164.77 | 2873.86 | 187.34 | -170.94 | 389.34 | 164.84 | |
| **11111110**00000000 | 178.37 | 2472.07 | 2867.91 | 4022.81 | 250.15 | -108.70 | -1087.30 | 252.96 | |
| **Min. stabilizing transfer** | 149.315 | 257.519 | -389.755 | -668.379 | 13.051 | 425.018 | 1523.66 | 25.77 | **1336.19** |

## Appendix H : Stability analysis for coalition

$$S = \{EU15, FSU, MEA, AFR, CHN, IND, ROW\}$$

| COALITION | EU15 | FSU | MEA | AFR | CHN | IND | ROW | |
|---|---|---|---|---|---|---|---|---|
| 000**1**00**1**00**1111**00**1** | 8615.48 | 331.97 | 457.80 | 467.37 | -2451.96 | 615.611 | 78.27 | |
| 000**0**00**1**00**1111**00**1** | 4081.66 | 343.13 | 392.12 | 282.33 | 182.49 | 357.05 | 72.12 | |
| 000**1**00**0**00**1111**00**1** | 7541.84 | 806.42 | 397.95 | 408.46 | -2205.09 | 538.29 | 68.10 | |
| 000**1**00**1**00**0111**00**1** | 7546.73 | 294.14 | 886.63 | 410.80 | -2157.26 | 540.83 | 69.41 | |
| 000**1**00**1**00**1011**00**1** | 8090.20 | 325.58 | 443.03 | 621.69 | -2218.77 | 582.88 | 76.23 | |
| 000**1**00**1**00**1101**00**1** | 3512.16 | -58.57 | 6.33 | 131.81 | 729.99 | 189.35 | -3.75 | |
| 000**1**00**1**00**1110**00**1** | 8003.85 | 328.15 | 443.98 | 440.55 | -2153.59 | 766.04 | 76.57 | |
| 000**1**00**1**00**1111**00**0** | 8395.20 | 323.07 | 445.77 | 455.37 | -2399.89 | 599.84 | 184.11 | |
| **min. stabilizing transfer** | -4533.82 | 474.44 | 428.83 | 154.32 | 3181.95 | 150.43 | 105.83 | **-38.01** |

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