# A note on optimal transfer schemes, stable coalition for environmental protection and joint welfare maximization assumption

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**Abstract**

Transfers play an important role in modeling International Environmental Agreements (IEA). We examine the implementation mechanism of Optimal Transfer Sharing Scheme (Carraro et al., 2006) which try to enable the existence of stable coalitions for environmental protection by side transfers. There are many coalitions where the OPTS can possibly be implemented. However, the implementation mechanism is almost impossible as it requests the flow of welfare from a few countries to the rest of coalition members, which is unrealistic. If the joint welfare maximization assumption is replaced with the assumption that the emission levels of coalition members are uniformly deceased by a constant percentage in comparison to fully non-cooperative coalition structure, then the free riding incentives are significantly weakened. As a consequence there are possibilities to implement an OPTS and enable existence of stable coalitions.

**Keywords:** stable international environmental agreements, climate policy, coalition formation, transfers, integrated assessment modeling.

**JEL: C71, C72, H23, Q58**

## 1 Introduction

The body of literature on International Environmental Agreements (IEA) has two conflicting views. One view is rooted in the non-cooperative game theory and became the dominant path in the literature (Barrett, 1994, 2003; Botteon and Carraro, 2001; Osmani and Tol, 2005; Finus et al., 2006;

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Rubio and Ulph, 2006; McGinty, 2007). The usual approach of non-cooperative game theory to stable IEAs is based on the idea developed for cartel stability (d'Aspremont et al., 1983) and requires so-called internal and external stability. Internal stability means that a country does not have an incentive to leave the coalition, while external stability means that a country does not have an incentive to join the coalition. This part of the literature reaches the conclusion that the size of a stable coalition is typically very small, thus representing a pessimistic view of global environmental goods.

The other view is rooted in the cooperative game theory and concludes that the grand coalition (or at least big coalitions) is stable by implementing ex-ante and ex-post transfers as benefits and costs from pollution abatement are asymmetric (see Finus (2004) for an overview). Ex-ante implies that countries commit to a specific transfer rule before they decide upon their participation in a coalition for environmental protection. Ex-post implies that after a stable coalition for environmental protection has built, transfers are used to expand an existing stable coalition. This represents an optimistic view of the possibility of international cooperation on solving global environmental problems.

Carraro and Siniscalco (1993) analyze the possibility of enlarging a stable coalition through ex-post transfers if members refund non-participants for joining the coalition for environmental protection. An enlargement is considered as successful if it indicates a Pareto improvement to all coalition members, and if the larger coalition is internally stable despite old signatories transfer some of the additional welfare gains from cooperation to new coalition members. Their analysis concludes that self-financed transfers can only enlarge a coalition in the case of heterogeneous countries.

A part of literature uses the $\gamma$-core concept and implements transfers to solve the asymmetry of costs and benefits of the countries involved. In order to deter free-riding they assume that after a deviation, the remaining countries break up into singletons, where each singleton maximizes its individual payoff.(Chander and Tulkens, 1995, 1997, 2006; Eyckmans and Tulkens, 2003; Chander, 2007).

Jeppesen and Andersen (1998) demonstrate that if some countries are committed to cooperation concerning their abatement implies that this group of countries presupposes a leader role in forming the coalition. The leading role allows them to evaluate potential aggregate benefits from increasing the coalition and device side payments to countries that have a follower role in order to attain optimum membership. Their results are not surprising and commitment is not compatible with the notion of self-enforcing IEAs. Therefore, Botteon and Carraro (1997) show that the enlargement of coalitions through ex-post transfers may also be possible without commiHoel and Schneider (1997) integrate *a non-environmental cost function* from not signing the IEA which they call "non-material payoff". They find that, even in the absence of side payments the number of signatories is not very small.

More recent papers have investigated the effect of different transfer schemes on the success of coalition formation (Bosello et al., 2003, 2004; Carraro and Siniscalco, 2001; Eyckmans and Finus, 2004; Weikart et al., 2006; Altamirano-Cabrera and Finus, 2006). Most of these papers employ integrated assessment models. They used not only stylized transfer schemes obtained from cooperative game theory, but also considered schemes that are based on different equity and fairness principles. Their research stresses that transfers have an essential impact on building of self-enforcing agreements, but the results are sensible to the design of transfer scheme, model structure and the data set.

This paper use a game-theoretic approach, and *Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model* (see Section 2) provide the cost-benefit functions (payoff functions) of pollution abatements. The main contribution of this research is the analysis of implementation mechanism of Optimal Transfer Scheme (Carraro et al., 2006). The transfer schemes usually presume that there is no free-riding[1], or use ad-hoc assumption [2] in order to deter it. On the opposite, the Optimal Transfers Scheme (OPTS) aims to deter free-riding and enable existence of stable coalitions. All profitable and non-profitable Potential Internal Stable Coalitions for two different year horizons 2005 and 2045 are found[3]. Potential Internal Stable (PIS) coalitions are coalitions where the OPTS can be applied. There are few big profitable PIS coalitions, but it is optimistic as there are many non-profitable big PIS coalitions. However, the close investigation of the OPTS transfer scheme for those coalitions shows that *it is almost impossible to realize the OPTS under joint welfare maximization assumption.* It is infeasible as the OPTS always requests the flow of welfare from a few countries to the rest of the world. No one can imagine an environmental agreement like Kyoto protocol based on a transfer scheme that transfer the welfare from only a few countries (sometimes only one country) to the rest of the world. However, *if the joint welfare maximization assumption is replaced with the assumption that coalition members reduce their abatement levels with the same percentage in comparison to fully non-cooperative coalition structure* (all countries are single players), then the free riding incentives are strongly declined. It follows that an OPTS under the new assumption requests the flow of welfare from rest of the world to a few countries, which is realistic. As a result there is space for implementation of OPTS, which can enable existence of stable coalitions.

In section two the FUND model is briefly introduced. The next section presents the game-theoretic model. The fourth section gives a short description of Shapley Value, Nash Bargaining Solution and Consensus Value. The following section introduces the Potential Internal Stable coalitions and Optimal Transfer Scheme (OPTS). Section six examines the implementation mechanism of OPTS and free riding incentives under joint welfare assumption and under assumption that coalition members decrease their emission levels with the same percentage. The seventh section provides our conclusions. In Appendix eight our data, results and figures are presented.

## 2 FUND model

This paper uses version 2.8 of the Climate Framework for Uncertainty, Negotiation and Distribution (FUND). Version 2.8 of FUND corresponds to version 1.6, described and applied by Tol (1999a,b, 2001, 2002c), except for the impact module, which is described by Tol (2002a,b) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. Finally, the model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by Tol (2006).

Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America (USA), Canada (CAN), Western Europe (WEU), Japan and South Korea (JPK), Australia and New Zealand (ANZ), Central and Eastern Europe (EEU), the former Soviet Union (FSU), the Middle East (MDE), Central America (CAM), South America (LAM), South Asia (SAS), Southeast Asia (SEA), China (CHI), North Africa (NAF), Sub-Saharan Africa (SSA), and Small Island States (SIS). The model runs from 1950 to 2300 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. The period of 1950-1990 is used for the calibration of the model, which is based on the IMAGE 100-year database (Batjes and Goldewijk, 1994). The period 1990-2000 is based on observations of the World Resources Databases (W.R.I., 2001). The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al., 1992). The

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[1] Such as Shapley Value, Nash Bargaining Solution and Consensus Value.

[2] Chander and Tulkens (1995, 1997) use the $\gamma$ core concept and assume that the coalition breaks down if a coalition member free-rides.

[3] The data for year horizon 2025 are sometimes used.

2000-2010 period is interpolated from the immediate past, and the period 2100-2300 extrapolated. The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress,malaria, and tropical cyclones.

The endogenous parts of FUND consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean surface temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt et al. (1992). The model also contains sulphur emissions (Tol, 2006).

The climate impact module, based on Tol (2002b,c) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C) or the level of change (benchmarked at 1.0°C).

## 2.1 Welfare function of FUND model

For the analysis of coalition formation, we approximate the FUND model with a linear quadratic structure. Specifically, the abatement cost function is represented as:

$$C_i = \alpha_i R_i^2 Y_i \tag{1}$$

where C denotes cost, R relative emission reduction, and Y gross domestic product; i indexes regions; $\alpha$ is the cost parameter. The benefit function is approximated as:

$$B_i = \beta_i \sum_j^n R_j E_j \tag{2}$$

where B denotes benefit and E unabated emissions. Tables 19, 20 and 21 in Appendix give the parameters of Equations (1) and (2) for years 2005, 2025 and 2045 as estimated by or specified in FUND. Moreover the profit $P$ is given as:

$$P_i = B_i - C_i = \beta_i \sum_j^n R_j E_j - \alpha_i R_i^2 Y_i \tag{3}$$

Non-cooperative optimal emission reduction is then:

$$dP_i/dR = \beta_i E_i - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = \beta_i E_i/(2\alpha_i Y_i) \tag{4}$$

If region i is in a coalition with region j, optimal emission reduction is:

$$dP_{i+j}/dR_i = 0 \Rightarrow E_i(\beta_i + \beta_j) - 2\alpha_i R_i Y_i = 0 \Rightarrow R_i = (\beta_i + \beta_j)E_i/(2\alpha_i Y_i) \tag{5}$$

The price for entering a coalition is therefore higher emission abatement at home. The return is that the coalition partners also raise their abatement efforts.

Note that our welfare functions are orthogonal, this indicates that the emissions change of a country do not affect the marginal benefits of other countries (independence assumption). In our game, countries outside the coalition benefit from the reduction in emissions achieved by the cooperating countries but they cannot affect the benefits derived by the members of the coalition. As our cost-benefit function are orthogonal our approach does not capture the effects of emissions leakage. But our cost benefit function are sufficiently realistic as they are approximation of complex model FUND and our procedure of dealing with farsighted stability is general and appropriate for non-orthogonal functions also.

## 3 Our model

There are 16 world regions (we name the set of all regions by $N_{16}$) in our game theoretic model of IEA's (or coalitions), which are shown in first column of Table 19. At the first level, the link between the economic activity and the physical environment is established in order to generate the economical-ecological model. This link is established through a social welfare function of FUND model, see 3. The social welfare function captures the difference between the profit from pollution and the environmental damage. Following this approach, countries play a two stage-game. In the first stage, each country decides to join the coalition $C \subseteq N_{16}$ and become a signatory (or coalition member) or stay singleton and non-signatory (*membership game*). These decisions lead to *coalition structure* $S$ with $c$ coalition-members ($c$ denotes the cardinality of $C$) and 16-c non-members. *A coalition structure* simply fully describes how many coalitions (at the moment we assume that we have one coalition) are formed, how many members each coalition has and how many singleton players are. Given the simple coalition structure $S$ is fully characterized by coalition $C$. In the second stage, every country decides on emissions (*strategic game*). Within the coalition, players play cooperatively (by maximizing their joint welfare) while the coalition and single countries compete in a non cooperative way (by maximizing their own welfare). Every coalition $C$ is assigned a real number $\upsilon(C)$ (called characteristic function).

**Definition 3.1** *By the* ***characteristic function*** *of our 16-player game (played by c and* $16 - c$ *players, where c is cardinality of coalition C) we mean a real-valued function* $\upsilon(C) : C \to R$,
$\upsilon(C) = max(\sum_1^c \pi_i) \quad \forall i \in C, \quad C \subset N_{16}, \quad c \leq 16$.

Characteristic function is simple the total profit that coalition-member reach by maximizing their joint welfare. As $\pi$ are strictly concave, their sum is strictly concave also, which simplifies the maximization problem. The game satisfies the superadditivity property:

**Definition 3.2** *A game is superadditive if for any two coalitions,* $C_1 \subset N_{16}$ *and* $C_2 \subset N_{16}$ :
$\upsilon(C_1 \cup C_2) > \upsilon(C_1) + \upsilon(C_2) \quad C_1 \cap C_2 = \emptyset$.

The *superadditivity property* means that if $C_1$ and $C_2$ are disjoint coalitions (here $C_1$ and $C_2$ can be single players too), it is clear that they should accomplish at least as much as by joining forces as by remaining separate. But the game *almost always (with some exceptions)* exhibits *positive spillovers:*

**Definition 3.3** *A game exhibits positive spillover property if and only if for any two coalitions* $C_1 \subset N_{16}$ *and* $C_2 \subset N_{16}$ *such as* $C_1 \nsubseteq C_2$ *and* $C_2 \nsubseteq C_1$ *we have:*
$\forall k \notin C_1 \cup C_2 \quad \upsilon_k(C_1 \cup C_2) > \upsilon_k(C_1) \wedge \upsilon_k(C_1 \cup C_2) > \upsilon_k(C_2)$

It indicates that there is an external gain ($C_1$ and $C_2$ can be single players too) or a positive spillover from cooperation, making free-riding (i.e., not joining $C_1 \cup C_2$) attractive. It just implies that every player $k \notin C_1 \cup C_2$ has higher profit when two coalitions $C_1$ and $C_2$ cooperate compared to the situation where two coalitions stay separated. It indicates that from a non-signatory's point of view (player $k$ here), the most favorable situation is the one in which all other countries take part in the coalition (except $k$). As we have already mentioned the positive spillover property is almost always satisfied with the exception of some coalitions that contain as members Japan & South Korea or Australia & New Zealand which have negative marginal benefits (negative $\beta$'s) from pollution abatement.

# 4 Different sharing schemes

This section presents shortly Shapley Value, Nash Bargaining solution and Consensus Value.

## 4.1 Shapley Value

Suppose we form a coalition $C$ by entering the players into this coalition one at a time; $v(C)$ is the *characteristic function* of coalition $C$, see definition 3.1; $|C|$ is cardinality of coalition $C$, and $n$ is total number of players. As each player enters the coalition, he receives the amount by which his entry increases the value of the coalition he enters. The Shapley value (Shapley, 1953) is just the average payoff to the players if the players are entered in completely random order.

**Definition 4.1** *The Shapley value is given by, $\phi = (\phi_1, ..., \phi_n)$ where for $i = 1, ..., n$:*

$$\phi_i(v) = \sum_{C \subset N, i \subset C} \frac{(|C|-1)!(n-|C|)!}{n!}(v(C) - v(C - \{i\})) \tag{6}$$

The interpretation of this formula is as follows. Suppose we choose a random order of the players with all n! orders (permutations) of the players equally likely. Then we enter the players according to this order. If, when player $i$ enters, he forms coalition $C$ (that is, if he finds $C - \{i\}$ there already), he receives the amount $(v(C) - v(C - \{i\}))$. The probability that when $i$ enters he will find coalition $C - \{i\}$ there already is $\frac{(|C|-1)!(n-|C|)!}{n!}$. The denominator is the total number of permutations of the n players. The numerator is number of these permutations in which the $|C| - 1$ members of $C - \{i\}$ come first $((|C| - 1)!$ ways), then player $i$, and then the remaining $n - |C|$ players $((n - |C|)!$ ways). So this formula shows that $\phi_i(v)$ is just the average amount player $i$ contributes to the coalitions if the players sequentially form those coalitions in a random order (and in all possible ways).

## 4.2 Nash Bargaining solution

The axiomatic theory of bargaining originated in a fundamental paper by Nash (1950). If a part (or all) of countries (suppose that there are $n$ countries) agree to form a coalition and behave cooperatively and the rest of countries optimize their own welfare function. The scenario is that $n$ world regions have access to any of the alternatives in some set $\Re^n$, called the feasible utility set. Their preferences over the alternatives in the utility set are given by welfare function $P_i$, see equation 3.

If no coalition is formed, they end up at a pre-specified alternative in the feasible set called the disagreement point, which is denoted by vector $d$. In our model $d$ is *profit vector of atom structure* with $n$ elements where every country optimize his own profits. More formally, a bargaining problem is defined by the tuple $(\Re^n; d)$ where the utility set $(\Re^n)$ has to be (and is) a non-empty, convex, and compact subset. We further assume that there exists an $p \in \Re^n$, such that $p \gg d$. In our case, Nash bargaining solution, denoted $f_N(\Re^n; d)$ is given by

$f_N(\Re^n; d) = \arg\max \prod_{i=1\dots n}(P_i - d_i) \quad where \quad P_i = B_i - C_i = \beta_i \sum_j^n R_j E_j - \alpha_i R_i^2 Y_i$

This means simply we need to find the abatement level R of $n$ coalition members that maximize $f_N$ (as $P_i$ is function of $R$). Note than the abatement level R of ten remaining countries are known as they simply maximize their own welfare function (we need them in order to calculate the benefit function $B_i = \beta_i \sum_j^n R_j E_j$).

## 4.3 Consensus Value

Let us consider an arbitrary 2-person cooperative TU game with player set $N = \{1, 2\}$ and characteristic function $v$ determined by the values: $v(\{1\}), v(\{2\})$ and $v(\{1, 2\})$. A reasonable solution is that player 1 gets:

$$v(\{1\}) + [v(\{1, 2\}) - v(\{1\}) - v(\{2\})]/2$$

and player 2 gets:

$$v(\{2\}) + [v(\{1, 2\}) - v(\{2\}) - v(\{1\})]/2$$

That is, the (net) surplus generated by the cooperation between player 1 and 2, $v(\{1, 2\}) - v(\{2\}) - v(\{1\})$, is equally shared between the two players. This solution is called the standard solution for 2-person cooperative games. Ju et al. (2004) provide a generalization of the standard solution for 2-person games into n-person cases. Consider a n-person game $(N, v)$ while the grand coalition $C_n = \{1, 2, .., n\}$ is formed than the player $(n + 1)$ (let call the new player just player (n+1)) joins the coalition and the coalition $C_{n+1} = \{1, 2, .., n, n + 1\}$ is formed. The generalization of player $(n + 1)$ share is:

$$\underbrace{v(\{n+1\})}_{v\ of\ the\ single\ player\ (n+1)} + \underbrace{[v(\{1, ..., n+1\}) - v(\{n+1\}) - v(\{1, .., n\})]}_{the\ surplus\ from\ cooperation\ of\ C_n\ and\ player\ (n+1)} \cdot 1/2$$

The interpretation of above formula is as follows. We can see the above situation as 2-person game. The coalition $C_n = \{1, 2, .., n\}$ is considered as one player and the next player is the new player $(n + 1)$ that joins the coalition. The (net) surplus generated by the cooperation between coalition $C_n$ and the new player is $v(\{1, ..., n+1\}) - v(\{n+1\}) - v(\{1, .., n\})$. The equation above says that the new player take the amount he gets alone $v(\{n + 1\})$ plus the half of the surplus.

$$\underbrace{v(\{i \mid i \in C_n\})}_{v\ of\ a\ member\ of\ C_n} + \underbrace{[v(\{1, ..., n+1\}) - v(\{n+1\}) - v(\{1, .., n\})]}_{the\ surplus\ from\ cooperation\ of\ C_n\ and\ player\ (n+1)} \cdot 1/2 \cdot 1/n$$

Each of n-players that was already in coalition $C_n$ gets his payoff as member of coalition $C_n$ plus half of the surplus divided by n.

# 5 Optimal Transfer Sharing Scheme

I will begin by introducing definition of Potentially Internally Stable coalition (Botteon and Carraro, 1997; Eyckmans and Finus, 2004; Carraro et al., 2006):

**Definition 5.1** *A coalition C is said to be Potentially Internally Stable (PIS) if and only if:*

- $\sum \pi_i(C) \geq \sum \pi_i(C \ \setminus \{i\}) \quad \forall i \in C$

- $\pi_i$ *is profit of country* i, $\pi_i(C)$ *refers to situations with country* i *is member of coalition* $C$, *and* $\pi_i(C \ \setminus \{i\})$ *with country* i *as free-rider.*

Consequently a coalition C is PIS if it generates sufficient welfare to distribute each of its members at least its free riding payoff. Thus, if C is PIS there exist a transfer scheme which guarantees internal stability to all members of S. Such a transfer scheme is constructed by donating every member of S at least his free-rider payoff $\pi_i(C \setminus \{i\})$.

**Definition 5.2** *A transfer scheme is called optimal if it satisfies:*

- $\forall\, C \subseteq N,\ \forall i \in C : \pi^i_{OPT} = \pi_i(C \setminus \{i\}) + \lambda_i\big[\sum_{j\in C} \pi_j(C) - \sum_{j\in C} \pi_j(C \ \setminus \{i\})\big],$ $\forall \lambda_j \in \Re_+ | \sum_{j\in C} \lambda_j = 1\}.$

It is evident that any transfer scheme which belongs to the class of optimal transfer scheme (OPTS) will make any PIS coalition internally stable. It is easy to see that there is much freedom in choosing weights $\lambda(C)$. Provided that the surplus of cooperation exceeds the free-riding payoffs, as well as all weights $\lambda(C)$, are positive, the following allocation will be internally stable independent of the choice of weights.

It is essential to note that sharing schemes always *assume that free-riding is deterred* (like Shapley Value, Nash bargaining solution and Consensus Value), and share the emissions burden. On the opposite, the OPTS *aims to deter free-riding and enable existence of stable coalitions.*

# 6 Burden Sharing Emissions in Potentially Internally Stable Coalitions

The number of *big profitable* Potentially Internal Stable (PIS) Coalitions for years 2005 and 2045 is small (only one coalition with 5 members), while the number of *big non-profitable* Potentially Internal Stable Coalitions for years 2005 and 2045 is large, see Table 1 and Table 2. It is an optimistic result as there are a lot of non-profitable coalitions that are PIS. But, as I am going to clarify below, there are still hidden barriers for the implementation of OPTS. Our numerical computation advices us to distinguish two different situations; the first situation when *coalition members maximize their joint welfare* and the second situation when *coalition members decrease uniformly their emission levels by a constant percentage.*

Let me begin with the situation under joint welfare maximization assumption. Assume we have the 10-members coalition (USA, CAN, JPK, ANZ, EEU, FSU, LAM, SAS, CHI, SIS) which I have inspected that is PIS. Coalition members can be divided in two types; type one, the countries that *have no incentive to free-ride*; type two, the countries that *have incentives to free-ride.* China (CHI) and USA have no incentives to free-ride, while the rest of countries has incentives to free-ride, see Table 3. It is evident that the majority of countries have incentives to free-ride. The first type of countries increases slightly their abatement levels when the coalition is formed. On the other hand, indirectly force other countries (second type of countries) to increase their abatement levels significantly, as it is less expensive to reduce emissions in second type countries compare to the first type countries (because of economic structure). This becomes clear when we compare the abatement levels of our coalition members with China and without China as a coalition member, see Table 4. Table 4 shows that the abatement levels of every coalition member are at least doubled when China is a coalition member in comparison to the situation when China is not a coalition member. On the other hand, China increases its abatement level only by 50 %. So, in the PIS coalitions the welfare is transferred from the second type countries (all coalition members except China and USA) to the first type of countries (China and USA in our coalition) when the OPTS is not applied. As a consequence this leaves the burden emissions, mostly at the country of second types, where is less expensive to reduce pollution. On the opposite side, the OPTS transfers welfare from China and USA to the rest of coalition member in order to deter free riding, and this is a general feature and the main drawback of OPTS when joint welfare maximization assumption is applied. With general feature, I mean that it does not depend on our setting and FUND model, while with main drawback, I indicate that it is impossible to realize the OPTS scheme under joint welfare maximization assumption. One cannot imagine any realistic International Environmental Agreements that have as an essential argument distributing its welfare from a few countries (sometime only one country) to the rest of world. In order to illustrate further my argument, I have presented some other coalitions where the same analysis is valid, see Tables 5, 6, 7 and 8. The joint welfare maximization generates not only the largest welfare[4] but also generates strong incentives to free ride, which make OPTS impossible to implement.

There is no 13-members PIS coalition in year 2005, where USA, WEU, FSU and CHI are coalition-members simultaneously, and there is only one coalition that contains three of them, namely USA, FSU, CHI as coalition member, see Table 13. As a consequence the OPTS usually leaves out two of the essential player of games of climate change. A simple numerical exercise is performed in order to receive some possible explanations why it is hard to have three of big players in one coalition. I take the 13 member PIS coalition of Table 7, and add WEU as coalition member. It is checked that the resulting 14 member coalition is not PIS, see Table 9 for profit of coalition members as free-riders. Table 10 presents the abatement levels of coalition members that are raised by 50 % when WEU is a coalition member in comparison to the situation when WEU is not a coalition member. On the opposite WEU tripled its abatement level. When CHI is a member of 13-member PIS coalition (but WEU not), it realizes sufficient welfare to compensate the gains from free-riding of the rest of coalition members. As it is already explained this happened as the rest of coalition member almost tripled their abatement levels, while China only raises with 50 %. However, as coalition members have tripled their abatement levels their marginal abatement costs are increased, and as a consequence it is not any longer cheaper to reduce the pollution in those countries. And finally there is no more space for WEU to realize welfare and compensate the free-riders.

There are only few really big profitable (only one 5 member coalition in year 2045, see Tables 11 and 12) coalitions, which are potentially internal stable, because in most profitable coalitions every country has an incentive to free ride, which implies that they cannot be usually potentially internal stable. It is clear than an OPTS for profitable coalitions has the same drawbacks as an OPTS for non-profitable coalitions.

If the joint welfare optimization assumption is replaced with the assumption that the emission levels of coalition members are uniformly reduced by a constant percentage term[5] in comparison to fully non-cooperative coalition structure then, the number of countries that profit from free riding is drastically reduced. This implies that there is space for implementation of OPTS schemes. Tables 14, 15 and 16 show that for 15 member PIS coalitions (which are the largest PIS coalitions) in year horizons 2005, 2025 and 2045, there are at most two countries that have incentives to free-ride[6]. These are favorable circumstances for implementation of OPTS, as the welfare transfers occur from majority of world regions to some of the world regions. This sounds realistic, and a

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[4] The hessian matrix of second derivatives of welfare functions is negative definite, so we have a unique maximum for welfare.

[5] All results that are presented to this paper, coalition members reduce uniformly their emission levels by 50%. Even so, I have performed other numerical computations when coalition members decrease their emissions level by 30%. The results are qualitatively similar when coalition members reduce their emissions level by 50% or 30%.

[6] The 15 member coalitions for year 2045 have no country that has an incentive to free-ride. It implies that they are already stable coalitions and no OPTS is needed.

coalition for environmental protection can work in this way. Furthermore, there are two 15 member coalitions, which are simultaneously PIS coalitions during all year horizons 2005, 2025 and 2045. This indicates that OPTS scheme can possibly build incentives for almost all countries[7] of the world to take part in coalitions for environmental protection. Clearly, the last conclusion depends on FUND model structure and assumptions. In order to receive a rough measure of free-riding incentives, we calculated the number of free-riders for 10 member coalitions for year horizons 2005, 2025 and 2045, see Table 17. The first column of Table 17 presents different year horizons 2005, 2025 and 2045. The second column of Table 17, $C_t$ displays the total number of 10 member coalitions, while the third column $C_p$ presents the total number of PIS coalitions. The columns four to nine displays the number of PIS coalition with equal number of free riders; the column four, $C_{PFr=0}$ presents the number of coalitions with no free riders, and column nine, $C_{PFr=9}$ presents the number of coalitions with nine riders. Table 17 shows that there are many PIS coalitions, and more than half of them have at most two countries that have incentives to free-ride. This indicates that there is a big space for implementation of OPTS schemes, which requests the flow of welfare from majority of world regions to few of them. This sounds reasonable and is quite feasible. Table 18 is identical with Table 17 but it presents numerical results for 8 member coalitions. The same conclusions as for 10 member coalitions of Table 17 hold. The uniformed reduction emissions level assumption does not generate the largest possible welfare, but it reduces considerably the incentives to free ride, which makes OPTS possible to implement.

# 7 Conclusions

The paper investigates the PIS coalitions and the OPTS. The common transfer schemes like Shapley Value, Nash Bargaining solution and Consensus Value assumes there is no free-riding while OPTS try to deter free-riding and enable the existence of internal stable coalitions. FUND model provides the cost-benefit functions for our game theoretic approach.

There are many non-profitable PIS coalitions but only few big profitable coalitions. In spite that there are many PIS coalitions, the implementation of the OPTS scheme within these coalitions is impossible when joint welfare maximization assumption is applied. The OPTS scheme transfer the welfare from a few countries (that have no incentive to free-ride) to the rest of countries (that have incentives to free-ride) which is an almost an impossible task. On the other hand, the PIS coalitions usually do not have simultaneously as coalition members some essential players of climate change like: USA, WEU, China or FSU. This is another shortcoming of OPTS under joint welfare maximization assumption.

Nevertheless, if the joint welfare maximization assumption is substituted with the assumption that coalition members decrease uniformly their abatement levels by the same percentage compared to fully non-cooperative coalition structure, then the free riding incentives are considerably decreased. As a result there is space for implementation of OPTS. The main conclusion of our analysis is that, the OPTS scheme can enable existence of stable coalitions and deter free riding only if joint welfare maximization assumption is replaced by assumption that coalition members equally reduce their emissions by the same percentage.

Further research is necessary in order to incorporate future in the decision process, equity preferences, other integrate assessment models and political commitment to cooperation.

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[7] The grand coalitions for every year horizons 2005, 2025 and 2045 is not PIS coalition. However, the ratio $\frac{\sum \pi_i(C \setminus \{i\}) - \sum \pi_i(C)}{\sum \pi_i(C \setminus \{i\})}$ stay (see definition 5.1 of PIS coalitions) in interval $10^{-3} - 2 \cdot 10^{-3}$, which is a small value.

# 8 Appendix

Table 1: Number of *profitable coalitions* which are potentially internally stable.

| $Year$ | $P_9$ | $P_8$ | $P_7$ | $P_6$ | $P_5$ | $P_4$ | $P_3$ |
|---|---|---|---|---|---|---|---|
| Year 2005 | - | - | - | 0 | 0 | 5 (from 15) | 16 (from 16) |
| Year 2045 | 0 | 0 | 0 | 0 | 1 (form 90) | 38 (from 106) | 64 (from 65) |

Table 2: Number of *non-profitable coalitions* which are potentially internally stable.

| $Year$ | $P_{16}$ | $P_{15}$ | $P_{14}$ | $P_{13}$ | $P_{12}$ | $P_{11}$ | $P_{10}$ | $P_9$ | $P_8$ | $P_7$ | $P_6$ | $P_5$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year 2005 | 0 | 0 | 0 | 23 | 266 | 1220 | 3172 | 5336 | 6436 | 6115 | 4929 | 3923 |
| Year 2045 | 0 | 0 | 0 | 0 | 8 | 111 | 531 | 1480 | 2723 | 3553 | 3456 | 2407 |

Table 3: Profit $P$ of coalition members ($C_{memb}$) in year 2045, for *a 10 member non-profitable coalition* which is potentially internal stable, when coalition is formed ($P_{coal}$), and when coalition members free-ride ($Pfreerid$).

| $C_{memb}$ | USA | CAN | JPK | ANZ | EEU | FSU | LAM | SAS | CHI | SIS |
|---|---|---|---|---|---|---|---|---|---|---|
| $P_{coal}$ | **1.23** | 0.08 | 0.04 | 0.06 | -0.02 | -1.51 | 0.15 | -0.06 | **4.8** | 0.04 |
| $P_{freerid}$ | **1.21** | 0.1 | 0.08 | 0.08 | 0.11 | 0.4 | 0.19 | 0.36 | **2.15** | 0.08 |

Table 4: Relative emission reduction $R$ of coalition members ($C_{memb}$) in year 2045, for *a 10 member non-profitable coalition* which is potentially internal stable, when China is a coalition-member ($RCHI-in$), and when China is not a coalition-member ($RCHI-out$).

| $C_{memb}$ | USA | CAN | JPK | ANZ | EEU | FSU | LAM | SAS | CHI | SIS |
|---|---|---|---|---|---|---|---|---|---|---|
| $R_{CHI-in}$ | 0.03 | 0.03 | 0.011 | 0.03 | 0.08 | 0.27 | 0.025 | 0.1 | 0.09 | 0.12 |
| $R_{CHI-out}$ | 0.01 | 0.01 | 0.004 | 0.01 | 0.03 | 0.1 | 0.009 | 0.03 | 0.06 | 0.04 |

Table 5: Profit $P$ of coalition members ($C_{memb}$) in year 2045, for *a 12 member non-profitable coalition* which is potentially internal stable, when coalition is formed ($P_{coal}$), and when coalition members free-ride($P_{freerid}$).

| $C_{memb}$ | CAN | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | CHI | SSA | SIS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_{coal}$ | 0.04 | 0.01 | 0.03 | -0.05 | -0.12 | 0.05 | 0.08 | -0.16 | 0.22 | **2.46** | 0.23 | 0.01 |
| $P_{freerid}$ | 0.06 | 0.05 | 0.05 | 0.06 | 0.18 | 0.08 | 0.11 | 0.2 | 0.31 | **1.38** | 0.26 | 0.05 |

Table 6: Relative emission reduction $R$ of coalition members ($C_{memb}$) in year 2045, for *a 12 member non-profitable coalition* which is potentially internal stable, when China is a coalition-member ($R_{CHI-in}$), and when China is not a coalition-member ($R_{CHI-out}$).

| $C_{memb}$ | CAN | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | CHI | SSA | SIS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $R_{CHI-in}$ | 0.026 | 0.01 | 0.028 | 0.074 | 0.093 | 0.042 | 0.023 | 0.089 | 0.041 | 0.083 | 0.047 | 0.11 |
| $R_{CHI-out}$ | 0.008 | 0.003 | 0.009 | 0.023 | 0.028 | 0.013 | 0.007 | 0.027 | 0.013 | 0.058 | 0.014 | 0.03 |

Table 7: Profit $P$ of coalition members ($C_{memb}$) in year 2005, for *a 13 member non-profitable coalition* which is potentially internal stable, when coalition is formed ($P_{coal}$), and when coalition members free-ride($P_{freerid}$).

| $C_{memb}$ | CAN | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | CHI | NAF | SSA | SIS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_{coal}$ | 0.03 | **-0.87** | -0.04 | -0.004 | -0.2 | 0.009 | 0.11 | -0.1 | 0.31 | **1.64** | **0.47** | **0.51** | 0.009 |
| $P_{freerid}$ | 0.048 | **-0.77** | -0.03 | 0.05 | 0.02 | 0.034 | 0.13 | 0.15 | 0.33 | **0.98** | **0.44** | **0.47** | 0.03 |

Table 8: Relative emission reduction $R$ of coalition members ($C_{memb}$) in year 2005, for *a a 13 member non-profitable coalition* which is potentially internal stable, when China is a coalition-member ($R_{CHI-in}$), and when China is not a coalition-member ($R_{CHI-out}$).

| $C_{memb}$ | CAN | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | CHI | NAF | SSA | SIS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $R_{CHI-in}$ | 0.03 | 0.01 | 0.04 | 0.1 | 0.16 | 0.07 | 0.04 | 0.16 | 0.07 | 0.14 | 0.11 | 0.11 | 0.16 |
| $R_{CHI-out}$ | 0.01 | 0.004 | 0.01 | 0.03 | 0.05 | 0.02 | 0.01 | 0.05 | 0.02 | 0.09 | 0.04 | 0.04 | 0.05 |

Table 9: Profit $P$ of coalition members ($C_{memb}$) in year 2005, for *a 14 member non-profitable coalition which is not potentially internal stable*, when coalition is formed ($P_{coal}$), and when coalition members free-ride($P_{freerid}$).

| $C_{memb}$ | CAN | WEU | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | CHI | NAF | SSA | SIS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_{coal}$ | 0.04 | **2.31** | **-1.12** | -0.06 | -0.05 | -0.45 | -0.005 | 0.14 | -0.36 | 0.39 | **1.85** | 0.6497 | 0.7 | -0.002 |
| $P_{freerid}$ | 0.07 | **1.66** | **-1.19** | -0.04 | 0.07 | 0.03 | 0.049 | 0.19 | 0.22 | 0.49 | **1.53** | 0.6498 | 0.71 | 0.04 |

Table 10: Relative emission reduction $R$ of coalition members ($C_{memb}$) in year 2005, for *a 14 member non-profitable coalition* which *is not potentially internal stable*, when Western European Union (WEU) is a coalition-member ($R_{WEU-in}$), and when WEU is not a coalition-member ($R_{WEU-out}$).

| $C_{memb}$ | CAN | WEU | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | CHI | NAF | SSA | SIS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $R_{WEU-in}$ | 0.05 | 0.02 | 0.02 | 0.06 | 0.14 | 0.24 | 0.1 | 0.05 | 0.23 | 0.1 | 0.2 | 0.16 | 0.16 | 0.24 |
| $R_{WEU-out}$ | 0.03 | 0.006 | 0.01 | 0.04 | 0.1 | 0.16 | 0.07 | 0.04 | 0.16 | 0.07 | 0.14 | 0.11 | 0.11 | 0.16 |

Table 11: Profit $P$ of coalition members ($C_{memb}$) in year 2045, for *a 5 member profitable coalition* which is potentially internal stable, when coalition is formed ($P_{coal}$), and when coalition members free-ride($P_{freerid}$).

| $C_{memb}$ | USA | CAN | ANZ | LAM | SEA |
|---|---|---|---|---|---|
| $P_{coal}$ | **0.37** | 0.025 | 0.019 | 0.047 | 0.14 |
| $P_{freerid}$ | **0.36** | 0.026 | 0.02 | 0.049 | 0.143 |

Table 12: Relative emission reduction $R$ of coalition members ($C_{memb}$) in year 2045, for *a 5 member non-profitable coalition* which is potentially internal stable, when USA is coalition-member ($R_{USA-in}$), and when USA is not coalition-member ($R_{USA-out}$).

| $C_{memb}$ | USA | CAN | ANZ | LAM | SEA |
|---|---|---|---|---|---|
| $R_{USA-in}$ | 0.008 | 0.0075 | 0.008 | 0.007 | 0.012 |
| $R_{USA-out}$ | 0.005 | 0.003 | 0.003 | 0.003 | 0.005 |

Table 13: All 13-member non-profitable coalitions which are potentially internal stable for year 2005. There is no coalition where USA, WEU, CHI and FSU participate simultaneously, and there are only two coalitions, where three of them (namely USA, FSU and CHI) takes part simultaneously.

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CAN | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | **CHI** | NAF | SSA | SIS |
| CAN | JPK | ANZ | EEU | **FSU** | CAM | LAM | SAS | SEA | **CHI** | NAF | SSA | SIS |
| CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | SAS | SEA | **CHI** | NAF | SSA | SIS |
| CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SEA | **CHI** | NAF | SSA | SIS |
| CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | **CHI** | NAF | SSA | SIS |
| CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | SEA | NAF | SSA | SIS |
| CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | SEA | **CHI** | SSA | SIS |
| CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | SEA | **CHI** | NAF | SIS |
| CAN | **WEU** | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | NAF | SSA | SIS |
| CAN | **WEU** | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | **CHI** | NAF | SIS |
| CAN | **WEU** | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | NAF | SSA | SIS |
| CAN | **WEU** | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | SEA | SSA | SIS |
| CAN | **WEU** | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | SEA | NAF | SIS |
| **USA** | CAN | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | **CHI** | NAF | SSA | SIS |
| **USA** | CAN | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | NAF | SSA | SIS |
| **USA** | CAN | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | **CHI** | SSA | SIS |
| **USA** | CAN | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | **CHI** | NAF | SIS |
| **USA** | CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | NAF | SSA | SIS |
| **USA** | CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | **CHI** | NAF | SIS |
| **USA** | CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | SEA | SSA | SIS |
| **USA** | CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | SEA | NAF | SIS |
| **USA** | CAN | JPK | ANZ | EEU | **FSU** | MDE | CAM | LAM | SAS | SEA | **CHI** | SIS |

Table 14: Number of *15 member coalitions* which are potentially internally stable in year 2005, as well as *free-riding members in bold letters*, when coalition members decrease equally the abatement levels by 50 %.

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CAN | WEU | **JPK** | **ANZ** | EEU | FSU | MDE | CAM | LAM | SAS | SEA | CHI | NAF | SSA | SIS |
| USA | CAN | WEU | **JPK** | **ANZ** | EEU | MDE | CAM | LAM | SAS | SEA | CHI | NAF | SSA | SIS |
| USA | CAN | WEU | **JPK** | **ANZ** | EEU | FSU | MDE | CAM | LAM | SAS | SEA | NAF | SSA | SIS |

Table 15: Number of *15 member coalitions* which are potentially internally stable in year 2025, as well as *the free-riding members in bold letters* when coalition members decrease equally the abatement levels by 50 %.

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CAN | WEU | **JPK** | ANZ | EEU | FSU | MDE | CAM | LAM | SAS | SEA | **CHI** | NAF | SSA | SIS |
| USA | CAN | WEU | **JPK** | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | CHI | NAF | SSA | SIS |
| USA | CAN | WEU | **JPK** | ANZ | EEU | FSU | MDE | CAM | LAM | SAS | SEA | NAF | SSA | SIS |

Table 16: Number of *15 member coalitions* which are potentially internally stable in year 2045, as well as *the free-riding members in bold letters* when coalition members decrease equally the abatement levels by 50 %.

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| USA | CAN | WEU | JPK | ANZ | EEU | MDE | CAM | LAM | SAS | SEA | CHI | NAF | SSA | SIS |
| USA | CAN | WEU | JPK | ANZ | EEU | FSU | MDE | CAM | LAM | SAS | SEA | NAF | SSA | SIS |

Table 17: Number of *10 member coalitions* which are potentially internally stable, and the number of free-riding members when coalition members decrease equally the abatement levels by 50 %.

| $Year$ | $C_t$ | $C_P$ | $C_{PFr=0}$ | $C_{PFr=1}$ | $C_{PFr=2}$ | $C_{PFr=3}$ | $C_{PFr=4}$ | $C_{PFr=5}$ |
|---|---|---|---|---|---|---|---|---|
| Year 2005 | 8008 | 1709 | 0 | 516 | 809 | 384 | 0 | 0 |
| Year 2025 | 8008 | 1830 | 0 | 603 | 753 | 364 | 110 | 0 |
| Year 2045 | 8008 | 2884 | 0 | 495 | 1483 | 846 | 60 | 0 |

Table 18: Number of *8 member coalitions* which are potentially internally stable, and the number of free-riding members when coalition members decrease equally the abatement levels by 50 %.

| $Year$ | $C_t$ | $C_P$ | $C_{PFr=0}$ | $C_{PFr=1}$ | $C_{PFr=2}$ | $C_{PFr=3}$ | $C_{PFr=4}$ | $C_{PFr=5}$ | $C_{PFr=6}$ | $C_{PFr=7}$ | $C_{PFr=8}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 12870 | 3279 | 0 | 434 | 1686 | 1124 | 14 | 0 | 14 | 7 | 0 |
| 2025 | 12870 | 2677 | 0 | 743 | 1332 | 541 | 61 | 0 | 0 | 0 | 0 |
| 2045 | 12870 | 2453 | 0 | 712 | 1439 | 302 | 0 | 0 | 0 | 0 | 0 |

Table 19: Our data from year 2005, $\alpha$ abatement cost parameter (unitless), $\beta$ marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) $E$ carbon dioxide emissions (in billion metric tonnes of carbon) $Y$ gross domestic product, in billion US dollar. Source: FUND

| | $\alpha$ | $\beta$ | $E$ | $Y$ |
|---|---|---|---|---|
| USA | 0.01515466 | 2.19648488 | 1.647 | 10399 |
| CAN | 0.01516751 | 0.09315600 | 0.124 | 807 |
| WEU | 0.01568000 | 3.15719404 | 0.762 | 12575 |
| JPK | 0.01562780 | -1.42089104 | 0.525 | 8528 |
| ANZ | 0.01510650 | -0.05143806 | 0.079 | 446 |
| EEU | 0.01465218 | 0.10131831 | 0.177 | 407 |
| FSU | 0.01381774 | 1.27242378 | 0.811 | 629 |
| MDE | 0.01434659 | 0.04737632 | 0.424 | 614 |
| CAM | 0.01486421 | 0.06652486 | 0.115 | 388 |
| LAM | 0.01513700 | 0.26839935 | 0.223 | 1351 |
| SAS | 0.01436564 | 0.35566631 | 0.559 | 831 |
| SEA | 0.01484894 | 0.73159104 | 0.334 | 1094 |
| CHI | 0.01444354 | 4.35686225 | 1.431 | 2376 |
| NAF | 0.01459959 | 0.96627119 | 0.101 | 213 |
| SSA | 0.01459184 | 1.07375825 | 0.145 | 302 |
| SIS | 0.01434621 | 0.05549814 | 0.038 | 55 |

Table 20: Our data from year 2025, $\alpha$ abatement cost parameter (unitless), $\beta$ marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) $E$ carbon dioxide emissions (in billion metric tonnes of carbon), $Y$ gross domestic product (in billion US dollar). Source: FUND

| | $\alpha$ | $\beta$ | $E$ | $Y$ |
|---|---|---|---|---|
| USA | 0.015229 | 1.76 | 1.926 | 16199 |
| CAN | 0.015244 | 0.1 | 0.146 | 1277 |
| WEU | 0.015646 | 2.86 | 0.889 | 18781 |
| JPK | 0.01568 | -0.44 | 0.676 | 14408 |
| ANZ | 0.015196 | 0.03 | 0.102 | 785 |
| EEU | 0.014777 | 0.11 | 0.262 | 780 |
| FSU | 0.013979 | 0.95 | 1.339 | 1249 |
| MDE | 0.014528 | 0.26 | 0.690 | 1335 |
| CAM | 0.014985 | 0.12 | 0.160 | 733 |
| LAM | 0.015216 | 0.22 | 0.310 | 2519 |
| SAS | 0.01458 | 0.39 | 0.883 | 1858 |
| SEA | 0.014967 | 0.64 | 0.575 | 2535 |
| CHI | 0.014666 | 5.56 | 2.228 | 5420 |
| NAF | 0.014853 | 0.71 | 0.139 | 481 |
| SSA | 0.014865 | 0.64 | 0.196 | 694 |
| SIS | 0.014498 | 0.07 | 0.058 | 107 |

Table 21: Our data from year 2045, $\alpha$ abatement cost parameter (unitless), $\beta$ marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) $E$ carbon dioxide emissions (in billion metric tonnes of carbon), $Y$ gross domestic product (in billion US dollar). Source: FUND

| | $\alpha$ | $\beta$ | $E$ | $Y$ |
|---|---|---|---|---|
| USA | 0.015241 | 1.33 | 2.402 | 22029 |
| CAN | 0.015253 | 0.09 | 0.183 | 1739 |
| WEU | 0.01559 | 2.35 | 1.111 | 25495 |
| JPK | 0.01568 | 0.07 | 0.846 | 20794 |
| ANZ | 0.015229 | 0.07 | 0.128 | 1136 |
| EEU | 0.014842 | 0.1 | 0.414 | 1429 |
| FSU | 0.014107 | 0.71 | 2.093 | 2281 |
| MDE | 0.01473 | 0.33 | 0.976 | 2707 |
| CAM | 0.015084 | 0.13 | 0.222 | 1332 |
| LAM | 0.015291 | 0.17 | 0.429 | 4554 |
| SAS | 0.014753 | 0.37 | 1.224 | 3545 |
| SEA | 0.015088 | 0.51 | 0.795 | 4826 |
| CHI | 0.014785 | 5.28 | 3.428 | 10560 |
| NAF | 0.015029 | 0.51 | 0.192 | 1005 |
| SSA | 0.015039 | 0.41 | 0.271 | 1456 |
| SIS | 0.014648 | 0.07 | 0.082 | 196 |

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