ENVIRONMENTAL COALITIONS WITH HETEROGENEOUS COUNTRIES: BURDEN-SHARING AND CARBON LEAKAGE

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Abstract

In this paper a simple model is used to analyse the strategic behaviour of countries that bargain over CO_2 emission reductions. Five main world regions are considered and their incentives to sign an international agreement on climate change control are analysed. A non-cooperative approach to coalition formation is used to analyse profitability and stability of the agreement. The main focus of the paper is on the role of carbon leakage. On the one hand, by offsetting the effort of signatory countries, carbon leakage reduces the size of the equilibrium coalition and even the likelihood of a successful negotiation. On the other hand, by increasing the profitability of large coalitions, carbon leakage may stabilise agreements signed by many countries. The paper shows that both the size of leakage and the burden-sharing rule used to share the gains from cooperation among signatory countries are crucial variables which explain the type and size of the equilibrium coalitions.

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1. Introduction

The objective of current negotiations on climate change control is to adopt a “protocol or another legal instrument” draft by the Ad hoc Group on the Berlin Mandate (AGBM), a subsidiary body established by the Conference of Parties first session in order to define new commitments for the post-2000 period. More precisely, under the Rio Convention, developed countries agreed to take measures aimed at returning their greenhouse gases (GHG) emissions to 1990 levels by the year 2000. However, at the first session of the Conference of Parties in 1995, governments recognised that stronger measures were needed for minimising the risk of climate change. In order to mitigate the adverse effects of climate change, the IPCC Second Assessment Report states that a stabilisation of atmospheric concentration of carbon dioxide (CO_2), which is one of the major GHG, at 550 parts per million by volume (ppmv) would be necessary, which implies global emissions to be less than 50 per cent of current levels. In this context, the Berlin Mandate is about defining “quantified legally-binding objectives for emission limitations and significant overall reductions within specified time frames” for Annex I countries[1].

The central issue is the question of what the precise targets and timetables for emission reductions should be. Countries’ proposals differ both on reduction percentage and on time-frame. In particular, a number of governments (including some members of the European Union) call for 10% reductions in CO_2 by the year 2005 (short term); some (such as the low-lying island states) call for even more ambitious cut of 20% by this date; others (including Australia, Canada, Japan and the US) have argued that a 2005 date is unrealistic and have proposed objectives for the 2010-2015 period (medium-long term). However, the targeted reductions and time frames are likely to be the final pieces of the negotiating puzzles, since critical issues regarding the nature of the targets (timing and location) are still unresolved.

The first relevant issue about QELROs (quantified emission limitation and reduction objectives, i.e. target and timetables) is **flexibility**. Governments must decide on the following questions:

- the use of *multi-year “budgets”* in the timetable: should a target be expressed as a certain level to be achieved by a specific date, or as a "budget" to be achieved over a period of several years?

- *emission banking and borrowing*: should it be possible to “bank” any over-achievement in a given period for future use or to "borrow" (with a penalty charge) from the next budget period to cover under-achievement during the current one?

- *emission trading and activities implemented jointly*: should developed countries be allowed to achieve part or all of their committed emission reductions at less cost - and less political pain - through joint implementation (JI) or emissions trading?

The second key issue is **differentiation** of targets and timetables. Governments must determine whether the same target will apply to all Annex I Parties (or at least to those that are OECD members, as opposed to those with economies in transition) or whether each developed country will have an individual target that reflects its economic features (emissions intensity of GDP, for example), so as to equalise the economic costs to each country of achieving its target. There are differing points of view. In particular it could be fairer allowing countries to have different commitments based on various possible formulae (e.g. per-capita targets), but on the other hand some criticisms have been raised against differentiation since it poses too many methodological and political problems.

How these targets will be achieved is less clear and the debate on whether they should be accomplished through mandatory and harmonised **policies and measures** or whether each country should be allowed the maximum flexibility to meet the agreed targets as it thinks best has always been at the forefront of the negotiations. If the text prescribed internationally co-ordinated and legally binding policies, countries could maintain a "level playing field" in their external trade and avoid distorting competition. On the other hand, if the text allowed maximum flexibility for each country, a more cost-efficient abatement policy could spread out, since climate change is a new policy area (unlike trade for example) and countries are still exploring a wide range of policies.

This paper aims at providing an economic analysis of some of the above issues by using recent developments in the theory of coalition formation, i.e. the analysis of the economic incentives that may lead country to sign (or not to sign) an international agreement on climate change. The theoretical framework proposed in this paper also accounts for countries' asymmetries, a crucial feature of current GHG negotiations.

The problem of coalition formation has recently attracted the attention of game-theorists and economists. In particular, a new approach has emerged in which coalition formation is the outcome of a non-cooperative strategic behaviour of the players involved in the negotiations. This approach has been proposed both in games without spillovers (Le Breton and Weber, 1993) and in games with positive or negative spillovers (Barrett, 1994; Bloch, 1994, 1997; Carraro and Siniscalco, 1993).[2]

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[2] It must be acknowledged that the first results on the non-cooperative formation of coalitions in the presence of positive spillovers can be found in the oligopoly literature on stable cartels. See D'Aspremont and

In the case of climate change, positive spillovers are the environmental benefit received by non-signatories when a group of countries decide to cooperage in order to reduce GHG emissions. The literature on environmental negotiations (e.g. Barrett, 1994, Carraro and Siniscalco, 1993) has emphasised the importance to model the decision process through which countries decide to join an environmental coalition as a non cooperative game. The goal is to determine the so-called "self-enforcing agreements", i.e. agreements which are not based on the countries' commitment to cooperation. The game is therefore a two-stage game: in the first stage -- the coalition game -- countries decide non-cooperatively whether or not to sign the agreement (join the coalition) given the burden-sharing rule which is adopted by the signatories countries; in the second stage – the emission game -- countries set their emission levels (their environmental policy) by maximising their welfare function given the decision taken in the first stage and the adopted burden-sharing rule.

The main feature of the first stage, when countries decide whether or not to sign the agreement, is the free-riding incentive that characterises countries' decision. A non-signatory achieves indeed the same environmental benefit as signatories, without paying any cost. This may lead the coalition to be unstable, i.e. to an equilibrium in which no cooperative abatement is actually carried out. The main feature of the second stage of the game is the large cross country differences in terms of emissions, economic growth, abatement costs, technical progress, perceived damages from climate changes.

This second problem – heterogeneity -- has not emerged in most theoretical literature which usually assumes symmetric countries, i.e. that negotiating countries have the same economic structure and the same preferences for the environment, which implies that their payoff functions are all the same. Even if the analysis of the symmetric case is very informative on the mechanisms that lead to the formation of environmental coalitions,[3] it prevents from assessing the sensitivity of the coalition size to the burden-sharing rule. Moreover, it does not enable us to identify which countries are going to join the coalition and which other countries are going to free-ride.

This paper attempts to provide a first contribution to the above issues by considering a model in which countries' asymmetries are explicitly account for. However, the implied mathematical coalition problem becomes quickly very cumbersome. It is therefore necessary to use numerical simulations to discuss the issues raised by countries' asymmetry.[4] Instead of assuming hypothetical countries whose characteristics are often unrealistic, in this paper we propose to analyse the problem of environmental coalition formation by focusing on a few countries with explicit and measurable environmental features.

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[3] A survey of the literature is provided in Carraro (1997).

To this aim, we have used the statistical information provided by Musgrave (1994) to calibrate the payoff function of five world regions that are assumed to be formed by countries whose interests are homogenous and which can therefore be aggregated. These five countries or regions are: 1) Japan; 2) US and Canada; 3) the European Union; 4) Eastern Europe and Russia; 5) India and China. Then, using a standard formulation of the environmental game that can be found in Carraro and Siniscalco (1992), Barrett (1994), Chander and Tulkens (1994), we have computed the payoff achieved by all possible coalitions among the five groups of countries, the incentives to free-ride (i.e. to exit the coalition) and the incentives to broaden a stable coalition. These results have been derived both in the case in which the burden-sharing rule is based on the Nash-bargaining concept and in the case in which it is based on the Shapley value concept[5].

As said above, another important feature of the game which captures countries' interaction in climate negotiations is the incentive to free-ride, given the public good nature of climate. It has already been shown that this incentive may not prevent the formation of an environmental coalition (a group of signatories) even if full co-operation (all countries sign the agreement) remains very unlikely. It has also been argued that all coalitions, even those formed by a few countries, are very unlikely when countries' reaction functions in the emission game are negatively sloped (Carraro and Siniscalco, 1993). In economic terms, this means that when non signatories increase their own emissions (e.g. because energy prices are lower) as a response to a group of countries' emission reduction, then this latter group is less likely to sign the agreement. By contrast, if non signatories enjoy a cleaner environment without damaging the cooperating countries, than the latter have a larger incentive to sign the agreement.

The crucial variable which captures the above effects is the so called "carbon leakage". If leakage is large, then any emission reduction in the cooperating countries is partially offset by an emission increase in the non-cooperating ones. This is likely to reduce the incentive to sign the agreement, i.e. the likelihood of an equilibrium characterised by a non-trivial coalition structure.[6]

In this paper, we would like to assess whether the above claim holds even in the presence of heterogeneous countries and above all which type of countries (large vs. small; high damage vs. low damage; high abatement cost vs. low abatement costs; etc.) is most likely to suffer from the presence of carbon leakage. Moreover, we would like to understand whether the burden-sharing rule can partially offset the negative effects of leakage on the size of the environmental coalition.

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[5] Numerical simulations which assess the existence of stable coalitions when the burden sharing rule is based on the Shapley-value concept can also be found in Barrett (1997).

[6] A trivial coalition structure is the one in which all countries behave as singletons. Further effects

The conclusions are very interesting and add further insights to the analysis of environmental coalitions. First, our results confirm the main theoretical conclusion derived for the symmetric case, i.e. coalitions involving more than 3 countries are never stable.[7] Moreover, they also show that leakage has only a small negative impact on the coalition size. This impact is completely ruled out by the use of the Shapley value burden sharing rule.

The structure of the paper is as follows: in the next section we introduce the basic theoretical concept, the model which will be used to describe the negotiation process, and the data used to calibrate the countries' payoff functions. In section 3, we present the results of our numerical simulations, and we discuss the impact on the existence and size of stable coalitions of the two burden-sharing rules and of countries' heterogeneity. Moreover, we analyse the impact of different degrees of carbon leakage on the size of the stable coalition. Finally, some concluding remarks and policy discussions are contained in section 4.

2. An economic model of international agreements on CO_2 emission reduction

Consider n countries (n≥2) that bargain over CO_2 emission control in order to mitigate their impact on climate. Let $W_i(x_1 \ldots x_n)$ be a country's welfare function, where x_i, i=1,2,...,n, denotes a vector containing country i's CO_2 emissions and all other economic variables affecting abatement costs and the environmental damage perceived in each country. The function $W_i(.)$, i=1,2,...,n, captures countries' interaction in a global environment, as welfare depends on all countries' emissions as well as on other trans-national variables (e.g. trade policy variables). Let us assume that in the second stage of the game -- the emission game – countries set optimally their emission levels (and all other relevant economic variables). Formally, we assume that the Nash equilibrium in the second stage is unique. As a consequence, the value of the welfare function in the first stage only depends on the coalition *s* which is formed. Let $P_i(s)$ denote the value of country i's welfare when it decides to join the coalition *s*, whereas $Q_i(s)$ is the value of its welfare when country i does not join the coalition *s*. Hence, $P_i(\ )$, i=1,2,...,n, is a country' s non-cooperative payoff (the non-cooperative Nash equilibrium payoff when all countries behave as singletons), whereas $P_i(S)$ is country i's payoff when all countries decide to cooperate (the grand-coalition *S* is formed).

Notice that when a country joins the environmental coalition, it determines its optimal emission level by maximising a function reflecting the agreed-upon burden sharing rule (i.e. in the case of the Nash-bargaining rule, emissions are determined by maximising the product of the deviation of cooperative countries' emissions from the non cooperative level). When a country does not join the coalition, it

[7] This conclusion is quite robust as it has been found for different functional form specifications of countries'

sets emissions by maximising its own welfare function given the emissions levels of all other countries (emissions are therefore defined by its own best-reply function). This behavioural assumption also defines the concept of γ-characteristic function and γ-core in Chander and Tulkens (1994).

Moreover, let us assume that:

- All countries decide <u>simultaneously</u> in both stages;[8]
- Countries are proposed to sign a <u>single agreement</u> on CO_2 emission control. Hence, those which do sign cannot propose a different agreement. From a game-theoretic viewpoint this implies that only one coalition can be formed, the remaining defecting players playing as singletons.
- When defecting from a coalition *s*, each country assumes that the other countries belonging to *s* <u>remain</u> in the coalition.[9]
- Each country's payoff function <u>increases monotonically</u> with respect to the coalition size (the number of signatories in the symmetric case).[10]

Given these assumptions, we say that:

- A coalition *s* is profitable iff $P_i(s) \geq P_i(\quad)$, i *s*, where $P_i(s)$ is country i's payoff when coalition *s* forms.
- A coalition *s* is <u>stable</u> iff:

(i) there is no incentive to free-ride, i.e. $Q_i(s \backslash i) - P_i(s) \leq 0$ for each country i belonging to *s*, where $Q_i(s \backslash i)$ is country i's payoff when it defects from coalition *s;*

(ii) there is no incentive to broaden the coalition, i.e. $P_i(s \quad i) - Q_i(s) \leq 0$ for each country i which does not belong to *s*.[11]

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[8] By contrast, Barrett (1994) assumes that the group of signatories is Stackelberg leader with respect to non-signatories in the second stage emission game. In Bloch (1997) it is assumed that countries play sequentially in the first stage coalition game.

[9] This assumption is equivalent to the assumption of "Nash conjectures" in a simultaneous oligopoly game where a player assumes no change in the other players decision variable when it modifies its own decision variable. However, coalition theory often uses a different assumption, named coalition unanimity (Cf. Bloch, 1997), where the whole coalition is assumed to collapse when one of its members defects (see Chander and Tulkens, 1993, 1994).

[10] This assumption is quite natural in the case of GHG emission reduction.

[11] As said above, this definition of stability coincides with the definition of a stable cartel provided in the oligopoly literature (D'Aspremont *et al*, 1983) and defines the Nash equilibrium of the first of the game (the one in which countries decide whether or not to sign the agreement). Notice that stability

- A profitable and stable coalition *s* is also <u>Pareto optimal</u> iff there exists no other profitable and stable coalition which provides all countries with a payoff larger than $P_i(s)$, i *s*. Formally, $P_i(s) \geq P_i(s^*)$, i *s*, s $S°$, s^* $S°$ such that i s^*, where $S°$ is the set of all stable and profitable coalitions. Notice that a profitable and stable coalition is also Pareto optimal under the assumption that a country's payoff function increases monotonically with the coalition size.

It has been shown that under fairly general conditions stable coalitions exist (see Donsimoni et al., 1986). However, this does not satisfactorily address the problem of protecting international commons, because, as it has been demonstrated both in the oligopoly and in the environmental literature (see, for example, D'Aspremont et al., 1983; D'Aspremont and Gabszewicz, 1986; Hoel, 1991; Barrett, 1992; Carraro and Siniscalco, 1992), stable coalitions are generally formed by $j < n$ players, where j is a small number, regardless of n. If stable coalitions are small, and countries are symmetric, the impact of their emission reduction on total emissions is likely to be negligible. However, the above-mentioned results concern models in which countries are supposed to be symmetric, i.e. they share the same welfare function. One of the goals of this paper is therefore to verify whether these results hold also in the case of asymmetric countries.

To this aim, asymmetries have to be made explicit. Two problems arise. First, in order to achieve clear results, a specific functional form for the welfare function has to be chosen. Secondly, its parameters have to be calibrated, for numerical simulations to provide information on the identity of countries which non-cooperatively decide to join a coalition. Let us therefore consider the following standard formulation of the environmental game (it can be found in Carraro and Siniscalco, 1992; Barrett, 1994; Chander and Tulkens 1994; and others).

Let the abatement cost function be represented by a concave function which exhibits decreasing returns of environment exploitation. For example:

(1) $$C_i(x_i) = \_ \, c_i(\delta_i - x_i)^2 \qquad i = 1,2, \ldots ,n$$

When emissions produce no damage, the optimal emission level is δ_i, which therefore denotes the maximum level of country i's emissions. This parameter depends on the country's technology, economic structure, development and environmental endowment. By contrast, c_i parametrises total costs from abating emissions (the larger c_i, the larger the cost); it can be seen as a technological parameter.

The environmental damage function is more difficult to specify, being strictly related to the specific pollutant, to adaptation costs, and to country's preferences for a clean environment. As we focus on countries' emissions. Moreover, in order to account for carbon leakage a linear quadratic damage function is chosen:

$$(2) \qquad D_i(X) = m_i(X + \varphi_i X^2/2) \qquad i = 1,2, \ldots ,n$$

where $X = x_1 + x_2 + \ldots + x_n$, m_i -- the marginal damage -- parametrises the level of perceived damage from pollution, and φ_i parametrises the intensity of carbon leakage. The welfare function is therefore a cost function that each country tries to minimise. In other words, each country sets its own policy variables, i.e. the emission level, in order to minimise:

$$(3) \qquad W_i(x_1 \ldots x_n) = \_c_i(\delta_i - x_i)^2 + m_i(X + \varphi_i X^2/2) \qquad i = 1,2, \ldots ,n$$

subject to the decision of whether or not to join the environmental coalition taken by each country, and subject to the burden-sharing rule adopted by the cooperating countries.

Notice that the cost function (3) implies that countries' best-reply functions are non-orthogonal and that their negative slope increases (in absolute value) with the size of carbon leakage.

What is the expected impact of leakage on the equilibrium coalition structure? As said above, one effect is that cooperation is less beneficial, because non-cooperators react by expanding their own emissions. However, there are some additional effects, that deserve a careful analysis. First, the loss suffered by cooperators decrease with the coalition size. When there are many cooperators, total leakage is necessarily low. If the grand coalition is formed, there is no leakage. Hence, gains from cooperation increase with the coalition size for two reasons: (i) because abatement increases (more countries reduce emissions), and (ii) because total leakage decreases (there are less free-riders). Therefore, there are increasing returns from cooperation.

What is the relationship between gains from free-riding and carbon leakage? As usual, they increase with the coalition size (there is more abatement at no cost for free-riders) but at decreasing returns because, in the presence of leakage, the difference between the cooperative and non-cooperative solutions becomes smaller and smaller as the coalition size increases,.

What is the impact of these two effects on the stability of the environmental coalition? Let $L_i(s) = Q_i(s\backslash i) - P_i(s)$ be country i's stability function. This is a useful tool to identify the size of the stable coalition. When positive, it shows that country i has no incentive to defect from coalition s. In the symmetric case, the intersection between $L_i(s)$ and the horizontal axis, where the number of countries is shown, defines the stable coalition which is formed by j* signatories (see Figure 1).

Our guess is that the two effects described above may make the stability function non-monotonic. Without leakage, the stability function is monotonically decreasing with the coalition size. As a consequence, there is one stable coalition, usually formed by a low number of countries (see Figure 1 for the symmetric case). In the presence of leakage, small coalitions are unlikely to be stable because penalised by the emission increase in free-riding countries. By contrast, large coalitions are more likely to be stable, in particular when leakage is large. The reason is that a country leaving a large coalition loses a lot of benefits (as said above there are increasing returns from cooperation) and receives small gains (there are decreasing returns from free-riding). Therefore, $Q_i(s\backslash i) - P_i(s)$ may be positive when s includes all or almost all countries, i.e. the stability function may be positive for large coalition sizes.

As a consequence, the shape of the stability function may be the one shown in Figure 2 for the symmetric case, where there exist several stable coalitions -- a very small one and many large ones (all those coalition sizes above j**) including the grand coalition *S*.

One goal of this paper is to assess the validity of the above conjectures. Therefore, the cost function (3) was calibrated for five groups of countries or regions: 1) Japan; 2) US and Canada; 3) the European Union; 4) Eastern Europe and Russia; 5) India and China. To abbreviate, in the sequel each of the five groups will be referred to as a "country". Table A1 in the Appendix offers some relevant information on the environmental and economic features of the five countries. These data are derived from Musgrave (1994). Let us assume that the average emission level (the fourth row of Table A1) corresponds to optimal emissions when no environmental damage is perceived (the parameter δ_i). Moreover, the fourth row from the bottom and the last row provide the damage per unit of emission (the parameter m_i), and the slope of the marginal abatement cost function (the parameter c_i), respectively.

Following Musgrave (1994), environmental damage is measured in terms of increase in mortality rates. Hence, it has been computed using statistical information on the number of deaths per millions of emissions, based on the aggregate country population and on mortality rates in the different countries. In order to achieve a monetary evaluation of environmental damages, the value of life has been assumed to be a function of average per capita income. However, in order to avoid discrimination across countries, Musgrave assumes the same value of life in all five countries ($349,000). As a consequence, countries with high population (e.g. China + India) are characterised by a large marginal emission damage.

The marginal abatement cost c_i reflects the loss of consumer surplus due to reduced output of the damage-generating activity as well as the loss of surplus in the consumption of substitute products the price of which rise. Musgrave (1994) assumes this marginal cost to be inversely related with

Even if the values chosen for these crucial parameters are largely an approximation of the real values, they are consistent with available information and may be found fairly reasonable. For example, the largest marginal abatement cost has been computed for Japan, whereas the lowest values refer to Russia + Eastern Countries and to India + China. Notice that this parameter is also low for North America. On the other side, the marginal environmental damage is very low in Japan, whereas it achieves very large values in India + China, given the assumption of equal value of life across countries and the expected impact of global warming on mortality rates.[12] Finally, the parameter δ_i reflects both the size and the economic development of a given country. The largest values are therefore calibrated for the U.S. and Russia + Eastern Countries; the lowest value for Japan.

Let us now focus on the leakage parameter. The values assumed in the baseline simulations are shown again in Table A1, where φ_i and the implied degree of leakage are presented in the second and third row from the bottom. It is assumed that leakage is larger in less developed countries, i.e. these countries increase more that the others their emissions when they free-ride on the other countries' cooperative abatement. One reason may be that a lower energy consumption in developed countries reduces oil prices, thus making less costly for developing countries an energy intensive growth path. Alternatively, energy intensive industries may move more easily from developed to developing countries, because in the latter there are additional non-environmental benefits.

Given these values of the model parameters, it is possible to compute the equilibrium values for total costs and emissions when some countries form a coalition, i.e. sign an environmental agreement, whereas other countries decide to free-ride. Given the payoff for each country and for all possible coalitions, it is possible to single out the stable coalitions, where stability has been previously defined. This calculation has been performed both in the case in which the coalition members use the Nash bargaining equilibrium concept to share the cost of reducing emissions, and in the case in which they use the Shapley value. Coalitions have also been computed for different values of φ_i in order to assess the impact of carbon leakage on the equilibrium coalition structure.

3. Environmental coalitions with asymmetric countries under different burden-sharing rules and carbon leakage: some simulation results

Let us start by assuming that countries adopt Nash bargaining as a burden-sharing rule. In this case, countries belonging to the coalition minimise the product of the differences between the cooperative

[12] This implies that this parameter reflects more an "objective" than a "subjective" valuation of the

and non-cooperative cost, given the strategy of the other countries (see Carraro and Siniscalco, 1992 for an explicit analytical derivation of the solution in the case of symmetric countries).

Table A2 in the Appendix presents the equilibrium costs for the five countries for all possible coalition structures. Table A3 contains the corresponding emission levels. Bold figures indicate the cost (emissions) of countries belonging to the coalition, whereas normal figures denote the cost (emissions) for countries outside the coalition. The crucial information to determine which coalitions are stable is provided by Table A4. Here we have $Q_i(s \backslash i) - P_i(s)$ for countries in the coalition (bold figures), and $P_i(s \quad i) - Q_i(s)$ for countries outside the coalition (normal figures). In words, we show both the incentive to exit the coalition (when $Q_i(s \backslash i) - P_i(s)$ is positive for i s) and the incentive to enter the coalition (when $P_i(s \quad i) - Q_i(s) > 0$ for i s).

Definitions provided in section 2 imply that a coalition is stable when there is neither an incentive to exit, nor an incentive to enter the coalition, i.e. when all values in a given row of Table A4 are negative. It is easy to see that this is the case for three coalitions: the ones formed by countries (2,5), (3,5) and (1,4,5). Table 1 summarises these results by showing both the coalitions in which cooperating countries have no incentive to free-ride, but there is an incentive to broaden the coalition, and those which are stable.

Table 1. Stable coalitions - Nash-Bargaining burden-sharing rule

Coalitions without incentive to free-ride	**Stable coalitions (no incentive to free-ride nor to broaden the coalition)**
All 1-country coalitions	
All 2-countries coalitions	{2,5}
	{3,5}
{1,4,5}	{1,4,5}

Notice that all coalitions formed by four countries and the grand coalitions are unstable. This confirms the conclusions achieved in the case of symmetric countries by Carraro and Siniscalco (1992, 1993). Notice also that country 5 – the one with the highest marginal damage -- appears in all stable coalitions and that U.S. and E.U. seem to be ready to sign the agreement unless Eastern countries join it. In this latter case, Japan enter the coalition. The effect of leakage is clear. Without leakage the equilibrium stable coalitions are {1,2,5}, {1,3,5}, {1,4,5} (see Botteon and Carraro, 1997). Hence, in the presence of leakage, Japan would not enter the first two coalitions. As expected, the coalition size becomes smaller.

A similar analysis using the Shapley value as the burden-sharing rule leads to the payoffs (costs) shown in Table A7 in the Appendix, and to the emission levels shown in Table A8. By comparing the incentive to free-ride and the incentive to sign the agreement for all possible coalition structures (see Table A9) it is possible to show that the only stable coalition is formed by countries 2, 4 and 5. Again this confirms the theoretical result contained in Barrett (1997) where it is shown, using the same model, that coalitions formed by four and five countries are unstable. As in the case in which the Nash bargaining rule was used, let Table 2 summarise the results on coalition stability for the case in which the Shapley value defines the burden-sharing rule:

Table 2. Stable coalitions - Shapley value burden-sharing rule

Coalitions without incentive to free-ride	**Stable coalitions (no incentive to free-ride nor to broaden the coalition)**
All 1-country coalitions	
All 2-countries coalitions	
{1,3,5}	
{2,3,5}	
{2,4,5}	{2,4,5}
{3,4,5}	

Notice that in the case in which the Shapley-value burden-sharing rule is used, leakage has no effect on the equilibrium stable coalition, which coincides with the one derived in Botteon and Carraro (1997).

We have therefore achieved three conclusions: first, consistently with previous theoretical findings in the symmetric case, at most three countries decide to sign the environmental agreement; second, the presence of leakage tends to reduce the coalition size. However, this negative effect is offset by the Shapley-value burden-sharing rule; third, the identity of the three signatories, which is crucial to assess the total emission abatement achieved by the coalition in the asymmetric case, depend on the chosen burden-sharing rule. Only country 5 belongs to all stable coalitions that have been single out.

This latter information is relevant. Country 5 is the one with the highest marginal damage from CO_2 emissions. Therefore it has the highest incentive to lead the negotiation process to a successful outcome, i.e. to a stable emission reducing coalition. The conclusion that the country with the highest marginal damage is the pivot around which environmental coalitions can be formed is quite robust. Notice that the fact that China + India seems to be the pivot country only depends on our parametric assumptions on marginal damages in the different countries. The parameters proposed by Musgrave differences between "objective" and "perceived" marginal damage. It is likely that perceived damage in China and India is quite low, thus explaining why in reality these two countries may refuse stringent carbon abatement policies.

Table 3 contains some information about the four stable coalitions. Notice that all countries prefer the coalition {2,4,5}, which is stable when the Shapley value is used as a burden-sharing rule. If the Nash bargaining rule is adopted, Country 4 prefers the coalition {2,5}, whereas the others prefer the coalition {1,4,5}.

Table 3. Stable coalitions - Total costs, emissions and incentives to defect
(N-B = Nash Bargaining, S-V = Shapley Value)

	Countries					
Coalitions	**1**	**2**	**3**	**4**	**5**	*Sum*
	Total costs					
N-B {2,5}	34019	**77174**	104798	102171	**539909**	858070
N-B {3,5}	34089	76381	**106273**	102309	**540218**	859270
N-B {1,4,5}	**33832**	75496	103540	**103042**	**538555**	854465
S-V {2,4,5}	31637	**70019**	99062	**94644**	**527054**	822416
	Emissions					
N-B {2,5}	236.50	**1257.96**	796.15	1232.57	**448.59**	3971.77
N-B {3,5}	236.49	1297.81	**761.26**	1231.91	**453.81**	3981.29
N-B {1,4,5}	**226.94**	1300.37	797.29	**1170.17**	**410.69**	3905.46
S-V {2,4,5}	236.71	**1087.29**	802.16	**977.40**	**519.32**	3622.88
	Incentives to defect					
N-B {2,5}	-0.2	**-659**	-177	-187	**-2234**	-3257
N-B {3,5}	-8	-103	**-953**	-135	**-1903**	-3103
N-B {1,4,5}	**-21**	-591	-861	**-298**	**-1730**	-3501
S-V {2,4,5}	-1262	**-4757**	-1291	**-6447**	**-8929**	-22687

We can therefore conclude that the stable coalition {2,4,5} obtained using the Shapley value dominates the other ones. Moreover, the stable Shapley coalition also yields the lowest aggregate emission level.

The existence of small stable coalitions leads to the following question: can the cooperating countries expand the coalition through self-financed welfare transfers[13] to the remaining players? This issue has been dealt with by Carraro and Siniscalco (1993) who show that, if countries are symmetric, self-financed transfers cannot induce free-riders to sign the environmental agreement, unless some degrees of commitment constrain the strategic choices of cooperating countries.[14] In Botteon and Carraro (1997), we addressed the same issue in the case of heterogeneous countries with orthogonal reaction functions (no leakage). If the damage function is represented by eq. (2), i.e. in the presence of leakage, results are not very different (see Table 4).

Table 4. Transfers-stabilised coalitions

Starting stable coalition	Stabilised coalition without commitment	Stabilised coalition with commitment	Total net gains to expand the coalition
Nash-Bargaining			
{1,4,5}	-	{1,3,4,5}	4235
		{1,2,4,5}	5138
		{1,2,3,4,5}	8290
Shapley value			
{2,4,5}	{1,2,4,5}	{1,2,4,5}	1639
	{2,3,4,5}	{2,3,4,5}	7499
	{1,2,3,4,5}	{1,2,3,4,5}	8658

Notice that, using the Nash bargaining concept, no coalition can be stabilised without commitment, thus confirming again the result proved by Carraro-Siniscalco (1993) for symmetric countries. By contrast, using the Shapley value concept, all four country coalitions that can be achieved from the

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13 Notice that we are not referring to the possibility of using transfers or side-payments to make the agreement profitable to all countries. This latter issue is discussed in Chander and Tulkens (1993, 1994). Here we start from the necessary condition that the agreement is profitable, and we look at the possibility that transfers increase the stability of the agreement.

14 Carraro and Siniscalco (1993) prove the following proposition: if no (symmetric) countries can commit to the cooperative strategy, no self-financed transfer from the j cooperating countries to the other

originally stable coalition {2,4,5}, and the grand coalition, can be stabilised by a system of transfers without commitment. The introduction of a minimum degree of commitment (one country only) is sufficient to stabilise the grand-coalition even in the case in which the burden-sharing rule is defined by the Nash bargaining solution concept.

Let us now analyse how changes in the degree of carbon leakage modify the above conclusions. In Table 5 we increased leakage in some countries and we computed again the equilibrium stable coalitions under both burden-sharing rules. The first two rows of Table 5 show the non-cooperative equilibrium and the baseline case previously discussed, respectively.

Suppose leakage increases in country 5 or in both countries 1 and 5 (rows 3 and 5 of Table 5), i.e. these countries increase even more their emissions when the others cooperate. The equilibrium stable coalitions do not change. By contrast, when both countries 4 and 5 increase leakage (rows 4 and 6), no three country coalition is stable under the Nash bargaining rule, i.e. the coalition size is further reduced by the presence of carbon leakage. If the Shapley value is used, the only stable coalitions remains {2,4,5}.

If leakage is increased in OECD countries, e.g. it becomes much larger in Japan (row 7) and in the E.U. (row 8) then the Shapley value rule leads to an apparently surprising result, i.e. a four country coalition (row 7) and even the grand coalition (row 8) are stable. This is what was previously suggested when analysing the relationship between increasing returns from cooperation and decreasing returns from free-riding. When leakage becomes large in most countries, the payoff from defecting from a large coalition is lower than the payoff from belonging to the coalition. As a consequence, the stability function is positive and even the grand coalition may be stable. Notice that the stability function resulting from our simulations is not U-shaped as in Figure 2, but is increasing with the coalition size (no small coalition is stable), and assumes positive values for coalitions formed by four or all countries.

Notice also that the above conclusions hold in particular when leakage from Japan is large (see the last two rows of Table 5 where the stable coalitions do not change by simply increasing leakage in countries 2 and 3).

Table 5. Stable coalitions and leakage: summary of results

Leakage in Country					Stable coalitions	
1	**2**	**3**	**4**	**5**	**Nash Bargaining**	**Shapley-value**
0	0	0	0	0	{1,2,5} {1,3,5} {1,4,5}	{2,4,5}
1%	7%	7%	15%	15%	{2,5} {3,5} {1,4,5}	{2,4,5}
1%	7%	7%	15%	30%	{2,5} {3,5} {1,4,5}	{2,4,5}
1%	7%	7%	30%	30%	{2,5} {3,5} {4,5}	{2,4,5}
3%	7%	7%	15%	30%	{2,5} {3,5} {1,4,5}	{2,4,5}
3%	7%	7%	30%	30%	{2,5} {3,5} {4,5}	{2,4,5}
5%	7%	7%	15%	15%	{1,3,4,5}	{1,2,4,5}
5%	7%	15%	15%	15%	{1,2,3,4,5}	{1,2,3,4,5}
1%	15%	7%	15%	15%	{2,5} {3,5} {1,4,5}	{2,4,5}
1%	15%	15%	15%	15%	{2,5} {3,5} {1,4,5}	{2,4,5}

5. Conclusions

In this paper we have presented an empirical analysis of the formation of an international agreement on climate change. The analysis has been carried out using two different burden-sharing rules (Nash bargaining and Shapley value) in order to assess the effects of these rules on the stability of the agreement. Even if the model is excessively aggregated - only five main world regions could be considered – the paper provides some interesting insights on the characteristics of countries which are most likely to join the climate coalitions, i.e. to sign the international agreement on CO_2 emission control. The main goal of this paper was the assessment of the relationship between carbon leakage and coalition stability. Our results confirm the ambiguity of this relationship. On the one hand, carbon leakage tends to reduce the size of stable coalitions and even the likelihood of observing a stable coalition at the equilibrium. On the other hand, carbon leakage increases the return from large coalitions, and decreases the return from free-riding when the coalition is large. Therefore, carbon leakage, if sufficiently large, can induce the formation of large environmental coalitions. Therefore, there may be two equilibrium coalition structures: one formed by a small coalition (or by the non-cooperative equilibrium) and one formed by the grand coalition (or a very large one). How to move from one equilibrium to the other is a matter of coordination, which demands for new international institutions.

The above conclusions are just the beginning of a research programme that should achieve two objectives:
(i) to move as much as possible from numerical to general theoretical results on the non-cooperative formation of stable coalitions in the presence of spillovers and heterogeneous countries;
(ii) to assess the impact of institutions, such as the burden-sharing rules, on the achievement of environmental agreements with many signatories.

Moreover, in the model no uncertainty is introduced. As a consequence, the validity of the results should be checked against the presence of economic and scientific uncertainty, the related risk parameters, and the learning process that might take place. Another extension of this paper should account for stocks of pollutants rather than flows only. Finally, the reader may have noticed that we have proposed only a few comments on the empirical implications of the analysis (which countries form the initial stable coalition, which countries are easier to bribe, etc.). The reason is that a careful sensitivity analysis should be carried out in order to verify under what conditions on the parameters of the abatement and damage functions the results still hold.

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APPENDIX

TABLE A1. Countries data set

	Countries				
	1	**2**	**3**	**4**	**5**
World regions	**Japan**	**U.S. and Canada**	**European Union**	**Eastern Europe and Russia**	**China and India**
GDP (billion U.S. dollars)	2779	4920	5141	2800	557
Population (millions)	122	270	373	360	1862
GDP per cap. (U.S. dollars)	22779	18222	13783	7778	299
Emissions (million tons).(_i)	238	1320	815	1263	722
Emissions per cap (tons)	1.951	4.889	2.185	3.508	0.388
Emissions per unit of GDP (tons per million U.S. dollars)	85.64	268.29	158.53	451.07	1296.23
Domestic damage (as no. of deaths per million tons of emissions - the assumed increase of mortality rate is 0.2 per million people)	24.4	54	74.6	72	372.4
Domestic damage (U.S. dollars per ton of emissions - the assumed average value of life is $349,000): m_i	8.51	18.83	26.01	25.10	129.84
φ_i	0.000353	0.0009654	0.0006754	0.001208	0.000107
Leakage	-1.0%	-7.0%	-7.0%	-15.0%	-15.0%
Slope of marginal abatement cost function (c_i)	4.89	0.54	1.02	0.44	0.62

Source: Musgrave (1994).

TABLE A2. Total costs - Nash-Bargaining burden-sharing rule

Coalitions	*Countries* **1**	**2**	**3**	**4**	**5**	*Sum*
Non-cooperative solution	34759	77560	106815	103742	541863	864740
{1}	34759	77563	106819	103745	541885	864771
{2}	34776	77559	106862	103780	542143	865120
{3}	34774	77589	106812	103777	542122	865075
{4}	34776	77592	106863	103741	542153	865125
{5}	34906	77833	107226	104083	541718	865766
{1,2}	34738	77545	106624	103586	540705	863197
{1,3}	34742	77452	106794	103607	540865	863460
{1,4}	34728	77389	106555	103718	540285	862675
{1,5}	34702	77236	106320	103340	541640	863238
{2,3}	34516	77465	106658	103199	537756	859594
{2,4}	34411	77401	105854	103573	535965	857204
{2,5}	34019	77174	104798	102171	539909	858070
{3,4}	34447	76999	106592	103599	536590	858227
{3,5}	34089	76381	106273	102309	540218	859270
{4,5}	33853	75993	104359	103177	539120	856502
{1,2,3}	34530	77405	106557	102886	535274	856653
{1,2,4}	34424	77327	105388	103498	533025	853662
{1,2,5}	34019	77040	104003	101607	539358	856027
{1,3,4}	34462	76711	106474	103528	533775	854950
{1,3,5}	34097	75892	106045	101740	539675	857449
{1,4,5}	33832	75496	103540	103042	538555	854465
{2,3,4}	33894	77031	105925	103192	527066	847108
{2,3,5}	33179	76484	104974	100719	536535	851891
{2,4,5}	32992	76201	102168	102358	534907	848626
{3,4,5}	33030	74756	104626	102444	535410	850266
{1,2,3,4}	33941	76948	105779	103114	523351	843133
{1,2,3,5}	33208	76367	104750	100262	536065	850652
{1,2,4,5}	32971	76087	101392	102268	534461	847179
{1,3,4,5}	33028	74323	104401	102351	534954	849057
{2,3,4,5}	32261	75518	103232	101713	530857	843580
{1,2,3,4,5}	32259	75432	103030	101668	530466	842854

TABLE A3. Emissions (million tons) - Nash-Bargaining burden-sharing rule

Coalitions	*Countries* 1	2	3	4	5	*Sum*
Non-cooperative solution	236.44	1294.81	794.45	1225.76	519.02	4070.48
{1}	236.63	1294.81	794.45	1225.75	519.02	4070.65
{2}	236.44	1297.22	794.41	1225.61	518.97	4072.66
{3}	236.44	1294.74	796.71	1225.62	518.98	4072.49
{4}	236.44	1294.74	794.41	1228.18	518.97	4072.74
{5}	236.43	1294.17	794.12	1224.44	540.45	4089.61
{1,2}	233.31	1287.95	794.61	1226.38	519.22	4061.47
{1,3}	233.57	1295.07	788.58	1226.30	519.20	4062.72
{1,4}	232.70	1295.22	794.66	1216.32	519.30	4058.21
{1,5}	230.77	1295.60	794.86	1227.38	498.41	4047.02
{2,3}	236.46	1276.90	777.44	1227.97	519.74	4038.51
{2,4}	236.47	1272.17	795.24	1200.60	520.05	4024.53
{2,5}	236.50	1257.96	796.15	1232.57	448.59	3971.77
{3,4}	236.46	1296.19	774.45	1202.36	519.94	4029.41
{3,5}	236.49	1297.81	761.26	1231.91	453.81	3981.29
{4,5}	236.51	1298.90	796.54	1180.29	436.90	3949.13
{1,2,3}	229.76	1269.42	770.48	1229.30	520.17	4019.13
{1,2,4}	229.18	1264.46	795.64	1191.69	520.57	4001.53
{1,2,5}	226.79	1248.57	796.86	1235.42	422.74	3930.38
{1,3,4}	229.31	1296.93	767.27	1193.45	520.43	4007.40
{1,3,5}	226.71	1299.18	752.07	1234.72	427.88	3940.56
{1,4,5}	226.94	1300.37	797.29	1170.17	410.69	3905.46
{2,3,4}	236.51	1256.35	758.40	1181.87	521.61	3954.74
{2,3,5}	236.57	1242.88	745.18	1240.63	389.53	3854.79
{2,4,5}	236.59	1243.58	798.63	1167.56	381.50	3827.85
{3,4,5}	236.58	1302.79	744.97	1166.74	382.37	3833.45
{1,2,3,4}	227.59	1249.53	751.84	1174.21	522.27	3925.45
{1,2,3,5}	225.89	1235.63	737.71	1243.85	364.91	3807.99
{1,2,4,5}	226.83	1236.69	799.44	1160.68	357.36	3780.99
{1,3,4,5}	226.44	1304.38	737.69	1159.74	358.01	3786.26
{2,3,4,5}	236.65	1238.76	739.55	1163.96	340.75	3719.67
{1,2,3,4,5}	226.80	1233.64	733.67	1159.69	319.18	3672.98

TABLE A4. Incentives to defect (or to broaden the coalition) - Nash-Bargaining burden-sharing rule

	Countries					
Coalitions	**1**	**2**	**3**	**4**	**5**	*Sum*
{1}	0	18	25	28	245	31
{2}	38	-2	204	208	2234	380
{3}	33	124	-3	179	1903	335
{4}	48	191	271	-1	3033	385
{5}	204	659	953	906	-145	1026
{1,2}	-38	-18	66	87	1346	1444
{1,3}	-33	46	-25	79	1190	1258
{1,4}	-48	62	80	-28	1730	1797
{1,5}	-204	196	275	298	-245	320
{2,3}	-14	-124	-204	7	1221	886
{2,4}	-13	-191	-71	-208	1058	575
{2,5}	-0.2	-659	-177	-187	-2234	-3257
{3,4}	-14	-32	-271	-179	1180	685
{3,5}	-8	-103	-953	-135	-1903	-3103
{4,5}	21	-208	-267	-906	-3033	-4393
{1,2,3}	14	-46	-66	-228	-790	-1117
{1,2,4}	13	-62	-392	-87	-1435	-1964
{1,2,5}	0.2	-196	-747	-661	-1346	-2950
{1,3,4}	14	-238	-80	-79	-1179	-1562
{1,3,5}	8	-475	-275	-611	-1190	-2543
{1,4,5}	-21	-591	-861	-298	-1730	-3501
{2,3,4}	-47	32	71	-7	-3790	-3741
{2,3,5}	-29	103	177	-995	-1221	-1966
{2,4,5}	21	208	-1063	187	-1058	-1705
{3,4,5}	2	-762	267	135	-1180	-1539
{1,2,3,4}	47	238	392	228	-7115	-6210
{1,2,3,5}	29	475	747	-1406	790	635
{1,2,4,5}	-21	591	-1638	661	1435	1030
{1,3,4,5}	-2	-1109	861	611	1179	1539
{2,3,4,5}	2	762	1063	995	3790	6613
{1,2,3,4,5}	-2	1109	1638	1406	7115	11266

TABLE A5. Transfers without commitments - Nash-Bargaining burden-sharing rule

Case 1: Transfers to country 3 from the stable coalition {1,4,5}

	Countries					
	1	**2**	**3**	**4**	**5**	*Sum*
Required transfers $P_i(\{1,3,4,5\})-Q_i(\{1,4,5\})$			860.6			860.6
Available resources $Q_i(\{1,3,4,5\}\backslash i)-P_i(\{1,3,4,5\})$	2.1			-610.8	-1178.8	-1787.5
Partition	-	-	-	-	-	-
Incentives to defect in the expanded coalition	-	-	-	-	-	-

Case 2: Transfers to country 2 from the stable coalition {1,4,5}

	Countries					
	1	**2**	**3**	**4**	**5**	*Sum*
Required transfers $P_i(\{1,2,4,5\})-Q_i(\{1,4,5\})$		591.2				591.2
Available resources $Q_i(\{1,2,4,5\}\backslash i)-P_i(\{1,2,4,5\})$	20.7			-661.4	-1435.3	-2076.0
Partition	-	-	-	-	-	-
Incentives to defect in the expanded coalition	-	-	-	-	-	-

Case 3: Transfers to countries 2 and 3 from the stable coalition {1,4,5}

	Countries					
	1	**2**	**3**	**4**	**5**	*Sum*
Required transfers $P_i(\{1,2,3,4,5\})-Q_i(\{1,2,3,4,5\}\backslash i)$		1108.98	1637.65	-		2746.64
Available resources $Q_i(\{1,2,3,4,5\}\backslash i)-P_i(\{1,2,3,4,5\})$	1.96			-1406.21	-7114.93	-8519.18
Partition	-	-	-	-	-	-
Incentives to defect in the expanded coalition	-	-	-	-	-	-

TABLE A6. Stable coalition commitment and transfers - Nash-Bargaining burden-sharing rule

Case 1: Transfers to country 3 from the stable coalition {1,4,5}

	Countries					
	1	**2**	**3**	**4**	**5**	*Sum*
Required transfers $P_i(\{1,3,4,5\})-Q_i(\{1,4,5\})$			860.6			860.6
Available resources $P_i(\{1,4,5\})-P_i(\{1,3,4,5\})$	803.3			691.0	3601.3	5095.7
Partition	135.7			116.7	608.2	860.6
Net gains to expand the coalition	**667.7**		**0.0**	**574.3**	**2993.1**	4235.1

Case 2: Transfers to country 2 from the stable coalition {1,4,5}

	Countries					
	1	**2**	**3**	**4**	**5**	*Sum*
Required transfers $P_i(\{1,2,4,5\})-Q_i(\{1,4,5\})$		591.2				591.2
Available resources $P_i(\{1,4,5\})-P_i(\{1,2,4,5\})$	860.8			774.1	4094.5	5729.4
Partition	88.8			79.9	422.5	591.2
Net gains to expand the coalition	**772.0**	**0.0**		**694.2**	**3672.0**	5138.2

Case 3: Transfers to countries 2 and 3 from the stable coalition {1,4,5}

	Countries					
	1	**2**	**3**	**4**	**5**	*Sum*
Required transfers $P_i(\{1,2,3,4,5\})-Q_i(\{1,2,3,4,5\}\backslash i)$		1109.0	1637.7	0.0		2746.6
Available resources $P_i(\{1,4,5\})-P_i(\{1,2,3,4,5\})$	1573.0			1374.2	8089.1	11036.3
Partition	391.5			342.0	2013.2	2746.6
Net gains to expand the coalition	**1181.5**	**0.0**	**0.0**	**1032.2**	**6076.0**	8289.7

TABLE A7. Total costs - Shapley value burden-sharing rule

Coalitions	*Countries* 1	2	3	4	5	*Sum*
Non-cooperative solution	34759	77560	106815	103742	541863	864740
{1}	34759	77563	106819	103745	541885	864771
{2}	34776	77559	106862	103780	542143	865120
{3}	34774	77589	106812	103777	542122	865075
{4}	34776	77592	106863	103741	542153	865125
{5}	34906	77833	107226	104083	541718	865766
{1,2}	34739	77539	106581	103551	540445	862856
{1,3}	34740	77463	106793	103621	540964	863580
{1,4}	34730	77359	106508	103712	540001	862310
{1,5}	34178	77413	106591	103559	541137	862878
{2,3}	34478	77395	106649	103115	537104	858742
{2,4}	34412	77395	105857	103577	535983	857224
{2,5}	33417	71828	103231	101091	535987	845554
{3,4}	34399	76914	106590	103519	535769	857191
{3,5}	33985	76209	103874	102106	538780	854954
{4,5}	33045	74776	102300	96453	534430	841005
{1,2,3}	34602	77258	106512	102773	534362	855508
{1,2,4}	34575	77241	105288	103413	532391	852908
{1,2,5}	33585	71235	102526	100655	534833	842835
{1,3,4}	34565	76598	106425	103344	532646	853577
{1,3,5}	33718	75774	103414	101606	537758	852270
{1,4,5}	33438	74390	101601	95713	533139	838281
{2,3,4}	33815	76870	106065	102993	525688	845431
{2,3,5}	32415	70045	102091	99744	531429	835724
{2,4,5}	31637	70019	99062	94644	527054	822416
{3,4,5}	32052	73556	101692	94271	529533	831105
{1,2,3,4}	34325	76630	105815	102716	521573	841059
{1,2,3,5}	33111	69438	101616	99479	529938	833581
{1,2,4,5}	32899	69480	98493	93958	525378	820207
{1,3,4,5}	32974	73276	101228	93527	527942	828948
{2,3,4,5}	30793	68680	100353	92906	521342	814074
{1,2,3,4,5}	32475	68180	99929	92270	519492	812345

TABLE A8. Emissions (million tons) - Shapley value burden-sharing rule

Coalitions	*Countries*					*Sum*
	1	**2**	**3**	**4**	**5**	
Non-cooperative solution	236.44	1294.81	794.45	1225.76	519.02	4070.48
{1}	236.63	1294.81	794.45	1225.75	519.02	4070.65
{2}	236.44	1297.22	794.41	1225.61	518.97	4072.66
{3}	236.44	1294.74	796.71	1225.62	518.98	4072.49
{4}	236.44	1294.74	794.41	1228.18	518.97	4072.74
{5}	236.43	1294.17	794.12	1224.44	540.45	4089.61
{1,2}	234.12	1284.90	794.64	1226.52	519.27	4059.46
{1,3}	232.83	1295.05	790.20	1226.24	519.18	4063.49
{1,4}	233.51	1295.30	794.70	1213.14	519.35	4056.00
{1,5}	213.65	1295.17	794.63	1226.49	529.98	4059.93
{2,3}	236.46	1263.63	785.16	1228.32	519.85	4033.42
{2,4}	236.46	1270.57	795.24	1202.34	520.05	4024.67
{2,5}	236.55	1092.32	797.59	1238.31	523.70	3888.47
{3,4}	236.47	1296.41	782.46	1187.57	520.09	4023.00
{3,5}	236.50	1298.29	687.42	1232.88	512.12	3967.21
{4,5}	236.58	1302.72	798.50	978.03	519.76	3835.59
{1,2,3}	230.52	1252.23	779.12	1229.79	520.33	4011.99
{1,2,4}	231.35	1259.75	795.72	1189.06	520.68	3996.56
{1,2,5}	211.77	1082.47	798.27	1241.05	515.12	3848.69
{1,3,4}	230.00	1297.23	776.63	1174.06	520.63	3998.56
{1,3,5}	210.25	1299.53	681.96	1235.42	503.13	3930.30
{1,4,5}	211.38	1304.12	799.22	967.12	512.02	3793.85
{2,3,4}	236.51	1242.92	774.19	1168.40	521.86	3943.89
{2,3,5}	236.64	1070.42	682.87	1248.34	504.62	3742.88
{2,4,5}	236.71	1087.29	802.16	977.40	519.32	3622.88
{3,4,5}	236.67	1307.69	682.72	956.36	504.38	3687.82
{1,2,3,4}	228.48	1233.78	769.36	1157.19	522.59	3911.39
{1,2,3,5}	209.58	1062.64	678.75	1251.29	497.84	3700.10
{1,2,4,5}	211.60	1080.93	802.92	969.59	513.77	3578.81
{1,3,4,5}	209.66	1309.15	679.14	948.06	498.50	3644.52
{2,3,4,5}	236.80	1079.53	687.69	967.88	512.56	3484.46
{1,2,3,4,5}	210.94	1074.99	685.29	962.31	508.60	3442.13

TABLE A9. Incentives to defect (or to broaden the coalition) - Shapley value burden-sharing rule

Coalitions	*Countries* 1	2	3	4	5	*Sum*
{1}	0	24	26	33	748	831
{2}	36	-2	212	203	6156	6606
{3}	35	193	-3	259	3342	3826
{4}	46	197	273	-1	7723	8237
{5}	728	6005	3352	7630	-145	17570
{1,2}	-36	-24	69	138	5612	5758
{1,3}	-35	204	-26	277	3206	3626
{1,4}	-46	118	83	-33	6863	6984
{1,5}	-728	6178	3177	7846	-748	15725
{2,3}	-125	-193	-212	122	5675	5266
{2,4}	-164	-197	-208	-203	8929	8157
{2,5}	-169	-6005	1139	6447	-6156	-4743
{3,4}	-165	44	-273	-259	6237	5584
{3,5}	267	6164	-3352	7835	-3342	7571
{4,5}	-393	4757	608	-7630	-7723	-10381
{1,2,3}	125	-204	-69	57	4424	4333
{1,2,4}	164	-118	-527	-138	7013	6394
{1,2,5}	169	-6178	909	6697	-5612	-4014
{1,3,4}	165	-33	-83	-277	4704	4476
{1,3,5}	-267	6336	-3177	8078	-3206	7764
{1,4,5}	393	4910	373	-7846	-6863	-9033
{2,3,4}	-510	-44	208	-122	4346	3877
{2,3,5}	-696	-6164	-1139	6838	-5675	-6836
{2,4,5}	-1262	-4757	-1291	-6447	-8929	-22687
{3,4,5}	-922	4876	-608	-7835	-6237	-10725
{1,2,3,4}	510	33	527	-57	2081	3094
{1,2,3,5}	696	-6336	-909	7209	-4424	-3765
{1,2,4,5}	1262	-4910	-1436	-6697	-7013	-18794
{1,3,4,5}	922	5096	-373	-8078	-4704	-7137
{2,3,4,5}	-1682	-4876	1291	-6838	-4346	-16452
{1,2,3,4,5}	1682	-5096	1436	-7209	-2081	-11268

TABLE A10. Transfers without commitments - Shapley value burden-sharing rule

Case 1: Transfers to country 1 from the stable coalition {2,4,5}

	Countries					*Sum*
	1	**2**	**3**	**4**	**5**	
Required transfers $P_i(\{1,2,4,5\})-Q_i(\{2,4,5\})$	1262.5					1262.5
Available resources $Q_i(\{1,2,4,5\}\setminus i)-P_i(\{1,2,4,5\})$		4910.0		6697.2	7012.9	18620.1
Partition	-	332.9	-	454.1	475.5	1262.5
Incentives to defect in the expanded coalition	**0.0**	**-4577.1**	-1436.1	**-6243.1**	**-6537.4**	-18793.6

Case 2: Transfers to country 3 from the stable coalition {2,4,5}

	Countries					*Sum*
	1	**2**	**3**	**4**	**5**	
Required transfers $P_i(\{2,3,4,5\})-Q_i(\{2,4,5\})$			1290.8			1290.8
Available resources $Q_i(\{2,3,4,5\}\setminus i)-P_i(\{2,3,4,5\})$		4876.4		6838.1	4346.1	16060.5
Partition		391.9		549.6	349.3	1290.8
Incentives to defect in the expanded coalition	-1681.8	**-4484.4**	**0.0**	**-6288.5**	**-3996.8**	-16451.5

Case 3: Transfers to countries 1 and 3 from the stable coalition {2,4,5}

	Countries					*Sum*
	1	**2**	**3**	**4**	**5**	
Required transfers $P_i(\{1,2,3,4,5\})-Q_i(\{1,2,3,4,5\}\setminus i)$	1681.8		1436.1			3117.9
Available resources $Q_i(\{1,2,3,4,5\}\setminus i)-P_i(\{1,2,3,4,5\})$		5095.8		7208.9	2081.5	14386.2
Partition		1104.4		1562.4	451.1	3117.9
Incentives to defect in the expanded coalition	**0.0**	**-3991.4**	**0.0**	**-5646.5**	**-1630.4**	-11268.3

TABLE A11. Stable coalition commitment and transfers - Shapley value burden-sharing rule

Case 1: Transfers to country 1 from the stable coalition {2,4,5}

	Countries					*Sum*
	1	**2**	**3**	**4**	**5**	
Required transfers $P_i(\{1,2,4,5\})-Q_i(\{2,4,5\})$	1262.5					1262.5
Available resources $P_i(\{2,4,5\})-P_i(\{1,2,4,5\})$		539.0		686.3	1676.4	2901.7
Partition		234.5		298.6	729.4	1262.5
Net gains to expand the coalition	**0**	**304.5**		**387.7**	**947.1**	1639.3

Case 2: Transfers to country 3 from the stable coalition {2,4,5}

	Countries					*Sum*
	1	**2**	**3**	**4**	**5**	
Required transfers $P_i(\{2,3,4,5\})-Q_i(\{2,4,5\})$			1290.8			1290.8
Available resources $P_i(\{2,4,5\})-P_i(\{2,3,4,5\})$		1339.4		1738.1	5712.1	8789.6
Partition		196.7		255.2	838.8	1290.8
Net gains to expand the coalition		**1142.7**	**0**	**1482.9**	**4873.3**	7498.9

Case 3: Transfers to countries 1 and 3 from the stable coalition {2,4,5}

	Countries					*Sum*
	1	**2**	**3**	**4**	**5**	
Required transfers $P_i(\{1,2,3,4,5\})-Q_i(\{1,2,3,4,5\}\backslash i)$	1681.8		1436.1			3117.9
Available resources $P_i(\{2,4,5\})-P_i(\{1,2,3,4,5\})$		1838.8		2374.2	7562.7	11775.7
Partition		486.9		628.6	2002.4	3117.9
Net gains to expand the coalition	**0**	**1352.0**	**0**	**1745.6**	**5560.3**	8657.9