International Environmental Agreements with Emission, Abatement and Adaptation choices

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Abstract

The present paper examines the formation and the size of stable international environmental agreements on net emission, considering countries' choice of mitigation and adaptation strategies. We assume that countries, before they decide to join or not the coalition, choose their level of emission, abatement and adaptation. The standard non cooperative leadership framework is employed. A coalition is considered stable when no signatories wish to withdraw while no more countries wish to participate. While abatement effort reduces emissions, adaptation effort reduces damages from emissions. We assume specific functions for benefits, damages and costs and we model coalition formation as a three stage game: In the last stage countries choose independently their level of adaptation activities, after observing global net emissions. In the second stage, countries choose their levels of emission and abatement and in the first stage counties choose whether or not to join a coalition that aims at controlling emissions. Within this framework we find that first, assuming adaptation is not very effective, the size of the stable coalition is always larger than in the case in which countries can choose only their emissions level. Second, the size of stable coalition increases as abatement becomes less costly. Finally, as the effectiveness of adaptation effort increases, the incentives to join the coalition decrease and for highly effective adaptation the size of the stable coalition returns to levels commonly reported in the literature without the abatement option.

1 Introduction

Some of the most pressing environmental problems are related to transboundary and/or global pollutants, including global warming, ozone depletion, acid rain, air and water pollution. Transboundary and/or global pollution problems belong to the theory of the voluntary provision of a public good, more specific of a public bad. The absence of a supranational authority that could implement and enforce environmental policies on sovereign countries renters the required intervention very difficult. Thus, any International Environmental Agreement (IEA) has to be designed so that it is self-enforcing, that is, it must be in the self-interest of each country to join and stay in the agreement. An IEA is profitable if the net benefits a country received as a member of the coalition exceed the net benefits it receives outside the coalition. Moreover, an IEA is considered to be stable if none of its signatories has an incentive to withdraw (internal stability) and none of the nonsignatories has an incentive to further participate in the agreement (external stability), assuming that the remaining players do not revise their membership decision (D'Aspremont, Jacquemin and Szewicz 1983).

In examining self-enforcing, stable IEAs, the main part of the literature uses the non-cooperative game theoretic approach and examines both the case that countries move simultaneously and the case that the IEA signatories act as a leader.[1] The simultaneous case has been examined by Carraro and Siniscalco (1993) and resolved by Finus and Rundshagen (2001), Cara and Rotillon and Rubio and Casino (2001), which assuming quadratic cost and benefit functions show that the stable IEA will be signed by no more than two countries. In the leadership approach, Barrett (1994) shows, through simulations of an abatement choice model, that the size of a stable coalition could range between two and the grand coalition depending on the relative size of cost and benefits. On the contrary Diamantoudi and Sartzetakis (2006) find, through analytical solution of an emission choice model, that the size of a stable coalition cannot exceed four countries, regardless of the value of the model's parameters.

The difference in the main result of the above two papers, which model the game with respect to either abatement or emissions, leads us to examine the case in which countries choose emission and abatement levels separately. Given that the consequences of pollution are already present, countries have to develop adaptation strategies to minimize damages, in addition to mitigation measures. Thus, we consider a leadership game in which countries choose independently their level of adaptation activities, after observing global net emissions. In choosing their levels of emission and abatement, counties have the choice of joining a coalition that aims at controlling net emissions. The formation of a coalition is modelled as a three-stage game: In the last stage, countries observe the coalition size and global net emissions and simultaneously choose their adaptation level independently. In the second stage, the mitigation game, signatories behave cooperatively choosing their emission and abatement levels in order to maximize the coalition's welfare taking into account nonsignatories' reactions to their choices. The nonsignatories act noncooperatively as singletons, taking the signatories' choices as given. In the first stage of the game, countries choose whether to sign or not the one and only agreement. To find the size of the self-enforcing, stable coalition we impose the internal and external stability

[1] Formalizing countries' behavior as a cooperative game, it has been shown that an IEA signed by all countries can be stable (chandler and Tulkens (1995) and (1997)).

conditions. We use a quadratic function for benefits derived from emissions, while damages are a quadratic function of net emissions while they decrease linearly with adaptation. Net emission are derived by subtracting abatement from emission and we introduce a quadratic abatement cost function. Adaptation effort involves costs which are quadratic in adaptation effort. We solve the model analytically up to a point and then we resort to numerical simulations in order to derive the size of the stable coalition.

Within this framework we find that the introduction of the abatement as a separate choice variable from emissions allows for larger stable coalitions, assuming that adaptation is not effective. Furthermore, we find that the size of the stable coalition is highly sensitive to the values of the model's parameters. In particular, the lower is the cost of abatement relative to environmental damages –keeping all other parameters constant– the larger is the size of the stable coalition. However, our model always yields a larger stable coalition relative to the case that abatement is not an option. This is true even when the slope of marginal cost of abatement is substantially greater than the slope of environmental damages, within the restrictions derived from the non-negativity constraint on net emissions. However, as the effectiveness of adaptation effort increases, the incentives to join the coalition decrease and for highly effective adaptation the size of the stable coalition returns to levels commonly reported in the literature without the abatement option.

The paper's contribution is twofold: it introduces abatement as a separate variable in the model and also introduces the option of adaptation. With respect to the abatement choice, our results supports Barrett's (1994) suggestion that the size of the stable coalition depends on the model's parameters without the need of allowing for negative net emissions. By introducing the choice of abatement, we can have large coalitions without violating the net emission positivity constraint. As was demonstrated in Diamantoudi and Sartzetakis (2006), assuming positive emission the size of coalition is no more than four. By allowing countries to choose separately their emission and abatement levels, results in a larger coalition size. A critical point is the slope of the best response functions of each country's choice variables to the other countries' choice of net emissions. We find that although each country free rides on other countries' emission reduction efforts, that is, it increases its emissions as the rest of the countries decrease their net emission, it increases its own abatement in response to other countries' reduction in net emissions. With respect to the adaptation choice, we find that as adaptation becomes relatively more effective, the incentives to join the coalition decrease and the size of the stable coalition decreases.

The paper relates to the literature examining the impact of abatement technology on the size of the coalition and also the growing literature on the links between adaptation and mitigation strategies. On abatement technologies, the literature has examined the links between IEAs and technology oriented agreements or R&D cooperation (Katsoulacos (1997), Lessmann and Edenhofer (2010)). In general, technology agreements and R&D cooperation are considered as club goods whose attractiveness may outweigh the incentive to free-ride. If coalition members can secure extra positive externalities among them, by linking for instance an environmental agreement to an R&D one with larger technology spillover effects among the coalition members, the size of the stable coalition will grow (Carraro and Siniscalco (1997)). Moreover, Hoel and Zeeuw (2010) allow the cost of adopting a breakthrough technology to vary with the level of R&D and show that a large stable coalition can result leading to a substantial improvement in average welfare. They find that the stability properties of IEAs improve relative to the case in which treaties focus only on emission reduction. Their result implies that it can indeed be beneficial for IEAs to consider breakthrough technologies and R&D whenever this is appropriate. However, Benchekroun and Chaudhuri (2012) show that technology improvements are not the panacea to all major transboundary pollution problems. They find that eco-innovations can reduce the stability of IEAs when using a farsighted stability concept. Implementing clean technologies may destabilize an otherwise stable grand coalition when countries are farsighted. Goeschl and Perino (2012) illustrate a hold-up problem created in the presence of intellectual property rights regarding new abatement technologies. They find that the presence of intellectual property rights reduces the size of the IEA leading to a reduction of their abatement commitment. Their results has some parallels with Barrett (2006) who finds that a focus on breakthrough technologies cannot improve the performance of IEAs, with the exception of breakthrough technologies that exhibit increasing returns to scale.

The literature examining the effect of adaptation on the size and stability of an IEA has been growing in the recent years and includes theoretical papers and also empirical work based on Integrated Assessment Models. On the theoretical front, Ebert and Welsch (2011 and 2012), have shown that countries' emissions strategies can be complements when adaptation is included as an option. By switching the strategic interaction from substitutability to complementarity, i.e. to upward-sloping reaction functions, the size of stable coalitions increases substantially. More recently Bayramoglu et al. (2018) examine the effect of adaptation on the strategic interaction among players' emission choices and on the size of the stable coalition. They consider both strategic substitutability and complementarity and find, using payoff functions, that if adaptation makes countries' emissions strategic complements coalition sizes increase. They actually show that even the grand coalition is stable under some parameter values. Breton and Sbragia (2017) show that the effect of adaptation on the size of the stable coalition depends on whether adaptation is chosen before or after mitigation. Rubio (2018) uses a model in which emissions are strategic complements and shows that the way in which adaptation reduces the marginal damages of emissions plays an important role in whether adaptation could increase the size of the stable coalition. Benchekroun et al. (2017), using a model where countries' emissions are strategic substitutes, show that as the effectiveness of adaptation technology increases, countries incentives to join the coalition increase leading to larger stable coalitions. Our paper relates more closely to Benchekroun et al. (2017) since we also use a similar damage function and emissions in the mitigation game are strategic substitutes. However, we differ in that we allow countries to choose both emission and abatement levels and we obtain quite different results with respect to the effect of adaptation on the size of the stable coalition.

The rest of the paper is organized as follows. Section 2 lays out the model and presents the case of non-cooperation and full cooperation. Section 3 first describes the coalition formation game and solves analytically for the adaptation and mitigation games. Section 4 derives the size of the stable coalition using numerical simulations. In the same Section the results of numerical simulations for a wide range of acceptable values of the parameters are presented. The last

Section concludes the paper.

2 The Model

We assume that there exist n symmetric countries, $N = \{1, \dots, n\}$. Production and consumption activities in each country i, $i \in N$, generate emissions $e_i > 0$, of a global pollutant. Aggregate emissions of the global pollutant $E = \sum_{i=1}^{n} e_i$, generate damages in each country. Each country, in responding to the adverse effects of emissions, could engage in mitigation and/or adaptation. Mitigation consists of activities that reduce emissions either by reducing production and consumption, or by engaging in abatement $x_i \geqslant 0$. Adaptation v_i consists of activities that ameliorate damages suffered at the country level for any given level of aggregate emissions E. Country i assumes the complete cost of its mitigation effort while the benefits are spread globally: while country i's emissions create a negative externality, its abatement generates a positive externality. On the contrary, adaptation activities reduce only country i's damages from global net emissions and have no effect on other countries. Therefore, countries participate in a decision game with three choice variables: emission, abatement and adaptation.

Country i's social welfare, W_i, is defined as the total benefits country i receives from emitting (that is, from production and consumption activities), $B_i(e_i)$, minus the environmental damages $D_i(NE)$ suffered from the aggregate global net emissions, $NE = E - X$, taking into account country i's adaptation efforts, v_i. Aggregate net emissions are defined as the difference between global emissions E and global abatement $X = \sum_{i=1}^{n} x_i$. To complete the definition of country i's net benefits, we subtract also the cost of abatement, $CA_i(x_i)$, and the cost of adaptation, $CV_i(v_i)$. Thus, country i's welfare is,

$$W_i = B_i(e_i) - D_i(NE, v_i) - CA_i(x_i) - CV_i(v_i).$$

We assume that $B(e_i)$ is strictly concave, that is, $B(0) = 0$, $B' \geq 0$ and $B'' < 0$. We further assume that environmental damages $D(NE, v_i)$ are strictly convex in net emissions , that is, $D(0, v_i) = 0$, $D_{NE}(NE, v_i) > 0$ and $D_{NENE}(NE, v_i) > 0$, while they are decreasing in adaptation effort at a constant rate, that is, $D(NE, 0) > 0$, $D_{v_i}(NE, v_i) < 0$ and $D_{v_i v_i}(NE, v_i) = 0$. Adaptation activities reduce damages generated by a given level of net emissions and also they decrease the marginal damage of net emissions, that is, $D_{NEv_i}(NE, v_i) < 0$. Finally, we assume that both costs are strictly convex, that is $CA(0) = 0$, $CA' \geq 0$ and $CA'' > 0$ and $CV(0) = 0$, $CV' \geq 0$ and $CV'' > 0$.

Following the literature, we employ a quadratic form for country i's benefits, $B_i(e_i) = b(ae_i - \frac{1}{2}e_i^2)$, with $a > 0$ and $b > 0$. Similarly, we use a quadratic function to represent country i's damages from net emissions, $D_i(NE, v_i) = \frac{1}{2}c(NE)^2 - \theta v_i NE = \frac{1}{2}c(\sum_{i=1}^{n}(e_i - x_i))^2 - \theta v_i \sum_{i=1}^{n}(e_i - x_i)$, with $c > 0$ and $\theta > 0$.[2] Notice that $\frac{\partial D_i(NE, v_i)}{\partial NE} = cNE - \theta v_i > 0$, $\forall\ v_i < \frac{c}{\theta}NE$, that is, we assume that adaptation is expensive enough that no country can engage

[2]Note that adaptation enters the damage function additively. This implies that $D_{v_i v_i}(NE, v_i) = 0$ and also that $D_{v_i}(NE, v_i)$ is independent of the country's sensitivity to aggregate net emissions, that is, independent of the parameter c. This type of damage function has been used widely in the literature, see for example Benchekroun (2017). Rubio (2018) compares the additive to a multiplicative functional form for damages.

in levels of adaptation capable of completely eliminating all damages from net emissions. However, adaptation decreases damages, $\frac{\partial D_i(NE,v_i)}{\partial v_i} = -\theta v_i < 0$ and also marginal net emission damages, $\frac{\partial^2 D_i(NE,v_i)}{\partial NE \partial v_i} = -\theta < 0$. Thus, the parameter θ indicates the effectiveness of country i's adaptation effort. We assume that the effectiveness depends on basic technologies widely available across countries, so as it is not country specific. Finally, we use a quadratic formulation for country i's cost of abatement, $CA_i(x_i) = \frac{1}{2}dx_i^2$, with $d > 0$ and its cost of adaptation, $CV_i(v_i) = \frac{1}{2}\omega v_i^2$, with $\omega > 0$. Therefore, country i's social welfare is,

$$W_i = b(ae_i - \frac{1}{2}e_i^2) - \left[\frac{1}{2}c(NE)^2 - \theta v_i NE\right] - \frac{1}{2}dx_i^2 - \frac{1}{2}\omega v_i^2. \tag{1}$$

In what follows we assume that countries are involved in a three stage game. In the first stage each country chooses whether to join a coalition of countries that collectively decide their mitigation efforts; in the second stage countries decide, either individually or collectively depending on their decision in the first stage, their mitigation strategies, e_i and x_i; and in the last stage they decide individually their level of adaptation v_i. The game is solved backwards, with country i choosing v_i to maximize (1), that is,

$$\frac{\partial W_i}{\partial v_i} = 0 \Longrightarrow \theta NE - \omega v_i = 0 \Longrightarrow v_i = \frac{\theta}{\omega} NE. \tag{2}$$

Thus, country i will choose adaptation level $v_i = \frac{\theta}{\omega} NE$, so as to equalize marginal benefit –reductions in damages– to marginal cost, given global net emissions. The level of adaptation depends on the country's cost and effectiveness of adaptation. The more effective adaptation is, relative to its cost, the higher will be country i's adaptation effort for any given level of global net emissions. Adaptation effort increases in global net emissions and is independent of other countries' choice of adoption level. Since we assume completely symmetric countries, the adaptation level, for a given level of net emissions, is equal among all countries.

Before examining the maximum size of stable, self-enforcing coalitions, we present the two benchmark cases: pure non-cooperation and full cooperation. That is, the choice in the first stage is assumed exogenous and we solve for countries' second stage choices. In the next Section we endogenize the first stage choice and define the size of stable coalitions.

2.1 The pure non-cooperative case

In the pure non-cooperative case, we assume that all countries act individually and no coalition is formed. In the second stage, each country i, $i \in N$, chooses $e_i$and x_i in order to maximize its own welfare W_i, given in (1), taking the other countries' emission and abatement levels as given. When choosing $e_i$and x_i country i takes into account its choice of adaptation level, which will be made in the third stage of the game after observing global net emissions, and is given by (2).

Substituting v_i from (2) into country i's welfare function (1), reduces the choice variables to $e_i$and x_i. The first order conditions, $\frac{\partial W_i}{\partial e_i} = 0 \Longrightarrow ba - be_i -$

$\left(c - \frac{2\theta^2}{\omega}\right) NE = 0$, and $\frac{\partial W_i}{\partial x_i} = 0 \Longrightarrow \left(c - \frac{2\theta^2}{\omega}\right) NE - dx_i = 0$, yield country i's emission and abatement as functions of the rest of the countries' net emissions, $NE_{-i} = \sum_{j \neq i}(e_j - x_j)$,

$$e_i(NE_{-i}) = \frac{(1+\delta)\,a}{1+\delta+\gamma\delta} - \frac{\gamma\delta NE_{-i}}{1+\delta+\gamma\delta}, \tag{3}$$

and

$$x_i(NE_{-i}) = \frac{a}{1+\delta+\gamma\delta} + \frac{NE_{-i}}{1+\delta+\gamma\delta}, \tag{4}$$

respectively, where $\mu = c - \frac{2\theta^2}{\omega}$, $\gamma = \frac{\mu}{b}$ and $\delta = \frac{d}{\mu}$. The parameter γ is the ratio between net damages and benefits from emissions and δ is the ratio between of abatement costs to net damages from emissions. The parameter $\mu = \frac{\partial^2 D(NE)}{\partial NE^2}|_{v_i = \frac{\theta}{\omega} NE}$, denotes the slope of marginal damages after substituting the optimal choice of adaptation from (2). We assume that $c > \frac{2\theta^2}{\omega}$, so that $\mu > 0$. This restriction on μ excludes not interesting cases of either very low adaptation cost or very high effectiveness of adaptation relative to damages.

Country i's best reaction to an increase in the rest of the countries' net emissions is to decrease its own net emissions both by decreasing its emissions, the slope of the emission reaction function is $re_i = -\frac{\gamma\delta}{1+\delta+\gamma\delta}$, and by increasing its abatement effort, the slope of the abatement reaction function is $rx_i = \frac{1}{1+\delta+\gamma\delta}$. It is interesting to note that the speed of reaction of emission exceeds that of abatement if $\gamma\delta > 1 \Longrightarrow d > b$, that is when the cost of abatement exceeds the benefits from emission: If benefits from emissions are high, country i adjusts mostly by increasing abatement, while when abatement costs are high, it adjusts by primarily reducing emission.

Since all countries are symmetric, at the equilibrium, they all choose the same level of emissions, denoted by e_{nc}, and abatement, denoted by x_{nc}. The system of reaction functions (3) and (4) yields the Nash level of emission and abatement,

$$e_{nc} = \frac{(n+\delta)a}{\delta + (1+\gamma\delta)\,n}, \; x_{nc} = \frac{na}{\delta + (1+\gamma\delta)\,n}. \tag{5}$$

Therefore, each country's net emissions Ne_{nc} are,

$$Ne_{nc} = e_{nc} - x_{nc} = \frac{\delta a}{\delta + (1+\gamma\delta)\,n}. \tag{6}$$

In order to verify the above results intuitively, we calculate their values at two extreme cases: First in the absence of net environmental damages, $\mu = 0$, emissions take their highest value, $e_{nc|\mu=0} = a$, and abatement effort approaches zero, $x_{nc|c=0} = 0$; second, if abatement becomes costless, $d = 0$, countries choose the highest level of emissions, $e_{nc|d=0} = a$, since they can costlessly abate the total amount of emissions, $x_{nc|d=0} = a$.

Aggregate emission and abatement levels under the non-cooperative case are, $E_{nc} = ne_{nc} = n\frac{a(n+\delta)}{n+\delta+n\gamma\delta}$ and $X_{nc} = nx_{nc} = n\frac{an}{n+\delta+n\gamma\delta}$, respectively and therefore net emissions are, $NE_{nc} = E_{nc} - X_{nc} = n\frac{a\delta}{n+\delta+n\gamma\delta}$. Following the realization of global net emissions, in the second stage, countries choose, at the last stage, their level of adaptation, $v_{nc} = \frac{\theta a n \delta}{\omega(n+\delta+n\gamma\delta)}$.

2.2 The full cooperation case

In the case of full cooperation, we assume that in the first stage the grand coalition is formed and is stable. In the second stage emission and abatement decisions are taken collectively, that is, countries choose $e_i$and x_i so as to maximize aggregate welfare, $\sum_{i=1}^{n} W_i$, where W_i is given in (1). In the third stage, again each country chooses the level of adaptation v_i, given in (2).

We derive country i's emission and abatement under cooperation from the first order conditions of $\max_{e_i,x_i} \sum_{i=1}^{n} W_i$, after substituting the value of v_i from (2). We use the notation defined above and we denote equilibrium values of emission and abatement levels by a subscript c,

$$e_c = \frac{a(n^2 + \delta)}{n^2 + \delta + n^2\gamma\delta},\ x_c = \frac{an^2}{n^2 + \delta + n^2\gamma\delta}. \tag{7}$$

Thus, each country's net emissions Ne_c are,

$$Ne_c = e_c - x_c = \frac{\delta a}{n^2 + \delta + n^2\gamma\delta}.$$

It is easily verified that in the two extreme cases of $\mu = 0$ and $d = 0$, emissions and abatement take the same values as in the case of no-cooperation. Aggregate emission and abatement levels under the full cooperation case are, $E_c = ne_c = n\frac{a(n^2+\delta)}{n^2+\delta+n^2\gamma\delta}$ and $X_c = nx_c = n\frac{an^2}{n^2+\delta+n^2\gamma\delta}$, respectively and therefore net emissions are, $NE_c = E_c - X_c = n\frac{a\delta}{n^2+\delta+n^2\gamma\delta}$. Following the realization of global net emissions, each country chooses independently its level of adaptation, according to (2), yielding $v_c = \frac{\theta na\delta}{\omega(n^2+\delta+n^2\gamma\delta)}$.

It is easily verifiable that each country i's net emissions are lower in the full cooperation case, i.e. $e_c - x_c < e_{nc} - x_{nc}$. In the full cooperation case, each country emits less ($e_c < e_{nc}$) and abates more ($x_c > x_{nc}$) relative to the non-cooperative case. That is, aggregate net emissions are lower when all countries cooperate. It can also be shown that aggregate welfare is higher under full cooperation.

3 Coalition formation

The ratification of the IEA is depicted by the formation of a coalition and is modelled as a three-stage game. In particular, a set of countries $S \subset N$ sign an agreement over emissions and abatement levels and $N \backslash S$ do not. In the last stage of the game, countries observe the coalition size and global net emissions and simultaneously choose their adaptation level independently, according to (2). In the second stage, the mitigation game, signatories choose their emission and abatement levels in order to maximize the coalition's welfare taking taking into account nonsignatories' reactions to their choices. That is, we assume that the coalition acts as a leader. The nonsignatories act noncooperatively as singletons, taking the signatories' choices as given. In the first stage of the game, countries choose whether to sign or not the one and only agreement. The game is solved by backward induction, starting from stage two, to which the solution is given in (2) and thus, we move to the mitigation stage of the game.

3.1 Mitigation strategies

We assume that a set of countries $S \subset N$ sign an agreement over emission and abatement levels and $N \backslash S$ do not. Denote the size of coalition by $|S| = s$; the coalition's total emissions by $E_s = se_s$, with e_s each member's emissions, and the coalition's total abatement by $X_s = sx_s$, with x_s each member's abatement. In a similar manner, each non-signatory emits e_{ns} and abates x_{ns}, giving rise to total nonsignatories' emission and abatement levels $E_{ns} = (n-s)e_{ns}$ and $X_{ns} = (n-s)x_{ns}$ respectively. The aggregate emission and abatement levels are, $E = E_s + E_{ns} = se_s + (n-s)e_{ns}$ and $X = X_s + X_{ns} = sx_s + (n-s)x_{ns}$ respectively. Thus, aggregate net emissions are,

$$NE = E - X = s\left(e_s - x_s\right) + (n-s)\left(e_{ns} - x_{ns}\right)$$

We calculate nonsignatories' reaction functions, $e_{ns}(e_s)$ and $x_{ns}(x_s)$, using equations (3) and (4). Substituting total net emissions of the rest of the countries, $\sum_{j \neq i}(e_j - x_j) = NE_s + (n-s-1)\left(e_{ns} - x_{ns}\right)$, where $NE_s = s\left(e_s - x_s\right)$, into the reaction function (3) yields each nonsignatory's emissions $e_{ns}\left(e_s, x_s\right)$ as a function of the signatories' emission e_s and abatement x_s choices. Similarly, substituting $\sum_{j \neq i}(e_j - x_j)$ into the reaction function (4) yields each non-signatory country's abatement $x_{ns}\left(e_s, x_s\right)$ as a function of the signatory countries' emission e_s and abatement x_s. For brevity, we only report nonsignatories net emissions' reaction function,[3]

$$Ne_{ns}(NE_s) = \frac{\delta a}{\delta + (1+\gamma\delta)(n-s)} - \frac{(1+\gamma\delta)\, NE_s}{\delta + (1+\gamma\delta)(n-s)}. \tag{8}$$

It is clear that when all countries act as singletons, $s = 0$, the above collapses to the Nash equilibrium, $Ne_{ns|s=0} = Ne_{nc}$, defined in equation (6). Furthermore, it can be verified that in the absence of net damages, $\mu = c - \frac{\theta^2}{\omega} = 0$, $Ne_{ns|c=0} = a$, while when abatement is costless, $d = 0$, $Ne_{ns|d=0} = 0$.

Finally, if abatement was not an option, which is the same as if it was extremely expensive, that is, $d \to \infty$, then $x_{ns} = x_s \to 0$ and $Ne_{ns} = \frac{a}{1+\gamma(n-s)} - \frac{\gamma}{1+\gamma(n-s)} se_s = e_{ns}$, which is exactly the same reaction function as the one in Diamantoudi and Sartzetakis (2006). We can compare the slopes of the net emission reaction functions with and without the option of abatement. It is clear that when technological advancements reduce the cost of abatement substantially, non-signatory countries adjust their net emissions, responding to an change in the coalition's emissions, faster relative to when abatement is not an option. Denote the slope of the reaction function in (6) by $r_{Ne_{ns}} = \frac{\partial Ne_{ns}}{\partial NE_s} = -\frac{(1+\gamma\delta)}{\delta+(1+\gamma\delta)(n-s)}$ and the slope in the absence of abatement option by $r_{e_{ns}} = \frac{\partial e_{ns}}{\partial NE_s} = -\frac{\gamma}{1+\gamma(n-s)}$. Then, $r_{Ne_{ns}} - r_{e_{ns}} = \frac{1}{[1+\gamma(n-s)][\delta+(1+\gamma\delta)(n-s)]} > 0$, which goes to zero as $d \to \infty$ and becomes larger the smaller is the cost of abatement.

Signatories maximize the coalition's welfare, sW_s, taking explicitly into account nonsignatories' behavior $e_{ns}\left(e_s, x_s\right)$ and $x_{ns}\left(e_s, x_s\right)$. Given these, aggregate net emissions depend only on signatories' choices, $NE(e_s, x_s) = s\left(e_s - x_s\right) +$

[3] The emission and abatement reaction functions will have the same numeratiors as (3) and (4) respectivelly anf the denominator in the following expression.

$(n-s)\left(e_{ns}\left(e_s,x_s\right)-x_{ns}\left(e_s,x_s\right)\right)$. That is, signatories choose e_s and x_s in order to maximize collective welfare,

$$\max_{e_s,x_s}\sum W_s=s\left[B_s(e_s)-D_s(NE,v_s(NE))-CA_s(x_s)-CV_s(v_s(NE))\right].$$

The first-order conditions of the above maximization problem yield signatories emission and abatement effort levels,

$$e_s = a\left(1-ns\frac{\gamma\delta^2}{\Psi}\right), \tag{9}$$

$$x_s = ans\frac{\delta}{\Psi}, \tag{10}$$

where $\Psi=\Omega^2+s^2\delta\left(1+\gamma\delta\right)>0$ and $\Omega=\delta+\left(n-s\right)\left(1+\gamma\delta\right)>0$. Therefore, the signatories' net emissions are,

$$Ne_s=e_s-x_s=a\left(1-ns\frac{\delta(1+\gamma\delta)}{\Psi}\right). \tag{11}$$

Aggregate emission and abatement levels by the signatories are, $E_s=a\left(1-ns\frac{\gamma\delta^2}{\Psi}\right)s$ and $X_s=ans\frac{\delta}{\Psi}s$ respectively and thus, aggregate net emissions are,

$$NE_s=E_s-X_s=a\left(1-ns\frac{\delta(1+\gamma\delta)}{\Psi}\right)s. \tag{12}$$

It should be noted that, in the absence of environmental net damages, $\mu=0$, emissions take their highest value $e_{s|c=0}=a$, and abatement effort is zero, $x_{s|c=0}=0$.

Substituting e_s and x_s into the non-signatories' reaction functions, we derive the non-signatories' emission and abatement level,

$$e_{ns}=a\left(1-n\frac{\gamma\delta\Omega}{\Psi}\right)=e_s+\frac{an\gamma\delta\left(\delta s-\Omega\right)}{\Psi}, \tag{13}$$

$$x_{ns}=\frac{an\Omega}{\Psi}=x_s-\frac{an\left(\delta s-\Omega\right)}{\Psi}. \tag{14}$$

The above imply that $e_{ns}\lesseqgtr e_s\Leftrightarrow\delta s\lesseqgtr\Omega$, and $x_{ns}\lesseqgtr x_s\Leftrightarrow\Omega\lesseqgtr\delta s$. We will explore this condition when we compare the welfare of signatories and non-signatories. At this point note that since for small coalition sizes $\Omega>\delta s$ regardless of the value of the parameters, for these coalition sizes non-signatories emit less and abate more than the signatories. at some coalition size

Therefore, the net emission level of the non-signatories is,

$$Ne_{ns}=e_{ns}-x_{ns}=a\left(1-n\frac{\Omega(1+\gamma\delta)}{\Psi}\right)=Ne_s+\frac{an(1+\gamma\delta)\left(\delta s-\Omega\right)}{\Psi}. \tag{15}$$

which implies that $Ne_{ns}\lesseqgtr Ne_s\Leftrightarrow\delta s\lesseqgtr\Omega$.

Aggregate emission and abatement levels by non-signatories are, $E_{ns}=\left[\frac{a(n-s+\delta)}{\Omega}-\frac{\alpha\gamma s\delta}{\Omega}(1-\frac{ns\delta(1+\gamma\delta)}{\Psi})\right](n-s)$ and $X_{ns}=\left[\frac{a(n-s)}{\Psi}+\frac{\alpha s}{\Omega}(1-\frac{ns\delta(1+\gamma\delta)}{\Psi})\right](n-s)$ respectively. The aggregate net emission level is,

$$NE_{ns}=E_{ns}-X_{ns}=\left[Ne_s+\frac{an(1+\gamma\delta)\left(\delta s-\Omega\right)}{\Psi}\right](n-s). \tag{16}$$

From (12) and (16), global net emission level $E - X = (E_{ns} - X_{ns}) + (E_s - X_s)$ is,

$$NE = E - X = \sum_{i=1}^{n}(e_i - x_i) = an\frac{\delta\Omega}{\Psi}. \tag{17}$$

Following the realization of global net emissions, at the adaptation stage of the game, signatories and non-signatories choose their adaptation level simultaneously, acting unilaterally, according to (2). Given the assumption of symmetry, signatories and no-signatories choose the same level of adaptation,

$$v_s = v_{ns} = \frac{\theta\delta\Omega}{\omega\Psi}na.$$

Unlike the previous two cases, the non-cooperative and the full cooperation case, in which the level of emission are strictly positive, $e_{nc} > 0$ and $e_c > 0$, in the coalition formation case we have to restrict the parameters of the model in order to guarantee interior solutions. Therefore, we need to restrict the parameters so that both are positive, given that emissions correspond to production and consumption which cannot be negative. The following Lema establishes the necessary conditions for interior solutions.

Lemma 1 *In the case that abatement is not available, that is,$\delta \to \infty$, $e_s > 0$ and $e_{ns} > 0$ if and only if $0 < \gamma < \frac{4}{n(n-4)}$ and $n > 4$. As abatement becomes relatively inexpensive, $e_s > 0$ and $e_{ns} > 0$ hold for higher values of γ, which are increasing as δ decreases.*

The proof is relegated to the Appendix. The intuition of the above result is clear: as abatement becomes available at low cost, countries both in and outside the coalition are able to decrease their net emissions by engaging in abatement keeping their emissions and thus their production positive, even when damages from emissions are relatively high. This will prove very important for the determination of the maximum size of the stable coalition as will be discussed in what follows.

Substituting the equilibrium values of the choice variables from (9), (10), (13) and (14) we derive the indirect welfare function of signatories (w_s) and non-signatories (w_{ns}),

$$w_s = ba^2\frac{1}{2}\left(1 - \frac{\gamma n^2\delta^2}{\Psi}\right), \tag{18}$$

$$w_{ns} = ba^2\frac{1}{2}\left[1 - \frac{\gamma\delta n^2\Omega^2\left(1 + \delta(1+\gamma)\right)}{\Psi^2}\right]. \tag{19}$$

Proposition 1 establishes the properties of these indirect welfare functions, in a way similar to Diamantoudi and Sartzetakis (2006).

Proposition 2 *We consider the indirect welfare function of signatories and non-signatories, (w_s) and (w_{ns}) respectively. If we define $s^{\min} = \frac{\delta+(1+\delta\gamma)n}{(1+\delta+\delta\gamma)}$, then,*

(i) $s^{\min} = \arg\min_{s\in\Re\cap[0,n]} w_s(s)$, that is, $s^{\min}$ is the s at which w_s is minimized,

(ii) $w_s(s)$ increases in s if $s > s^{\min}$ and it decreases in s if $s < s^{\min}$,

(iii) $w_{ns}(s) \lesseqgtr w_s(s)$ for all $s \lesseqgtr s^{\min}$.

The proof of the above Proposition follows exactly the same steps as the proof in Diamantoudi and Sartzetakis (2006).[4] The above defined properties of the indirect welfare function imply that the indirect welfare function of the non-signatories cuts the indirect welfare function of the signatories from below at its minimum. which is defined by $s^{\min}$. Note that $s^{\min}$ solves $\Omega = \delta s$, that is, the welfare of the signatories takes its minimum value at the coalition size that sets equal the emission and abatement of signatories and non-signatories.

In the case that countries choose only their emission level, Diamantoudi and Sartzetakis (2006) find that the critical coalition size at which $w_{ns}(s) = w_s(s)$, is $s^{\min}_{x=v=0} = \frac{1+\gamma n}{1+\gamma}$, which is clearly increasing in γ, for $n > 1$. They associate the size of the stable coalition to the integer closer to $s^{\min}_{x=v=0}$ and after restricting the admissible values of γ so as to have positive emission level, the size of stable coalitions is limited to $s^*_{x=v=0} \in \{2, 3, 4\}$. Specifying analytically, as Diamantoudi and Sartzetakis (2006) do in Proposition 3, the set of admissible stable coalition sizes when abatement is a separate choice variable and adaptation is also available, is cumbersome and does not add much to the analysis. The following Corollary presents the results of the comparison between the case that emission is the only choice variable and the case we develop in the present paper.

Corollary 3 *Allowing countries to choose abatement separately from emission level increases the size of the stable coalition for any admissible values of benefits and damages parameters. This potential enlargement of the coalition size is increasing as the cost of abatement decreases. Improving the efficiency, or reducing the cost, of adaptation has a negative effect on the stable size of the coalition.*

Direct comparison of the two cases reveals that $s^{\min} > s^{\min}_{x=v=0}$. Furthermore, $\frac{\partial s^{\min}}{\partial \delta} = \frac{1-n}{(1+\delta+\delta\gamma)^2} < 0$, that is, recalling that $\delta = \frac{d}{\mu}$, as either the cost of abatement decreases or environmental damages increase, the higher is the size of stable coalition. Finally, improved efficiency of adaptation or decreased cost of adaptation implies that $\mu = c - \frac{2\theta^2}{\omega}$ becomes smaller. In such case δ becomes bigger and γ smaller, both of which lead to smaller stable coalition sizes. In what follows we illustrate the above results by considering numerical examples.

4 The size of a Stable IEA

In the first stage of the game, countries choose whether to join or not the coalition. The equilibrium number of countries participating in an IEA, is derived by applying the notions of internal and external stability of a coalition as was originally developed by D'Aspremont et. al (1983) and extended to IEAs by Carraro & Siniscalco (1993) and Barrett (1994). The internal stability implies that no country in the coalition has an incentive to leave the coalition, while external stability implies that no country outside the coalition has an incentive to join the coalition. Formally, the internal and external stability conditions take the following form,

$$w_s(s^*) \geq w_{ns}(s^* - 1) \text{and } w_s(s^* + 1) \leq w_{ns}(s^*),$$

[4]The proof is available to the interested reader upon request.

respectively, where s^* denotes the size of a stable IEA.

To determine the size of a stable coalition we choose to resort to numerical simulations.

4.1 The abatement effect

We start by isolating and examining the effect of the introduction of abatement effort on the size of the coalition. In order to do this we assume that the effectiveness of adaptation is zero, $\theta = 0$, which implies, $\mu = c$ and $\delta = \frac{d}{c}$. In order to make the comparison easy, we choose the same parameter values used in Diamantoudi and Sartzetakis (2006). That is, we assume the following values for the parameters: $n = 10$, $a = 10$, $b = 6$, and $c = 0.39999$, which results in $\gamma = 0.066665$. These values satisfy the restrictions set in *Proposition 2*, since the parameter γ is less than $\gamma < \frac{4}{n(n-4)} < 0.066667$.

In our model we have to restrict the value of the parameter δ according to the condition in *Proposition 2.* This condition yields, $0 \leq \delta < 1.63704$ and we choose $\delta = 0.6$. We take a small value for the parameter δ (this means a large value for the parameter c and a small value for the parameter d) in order to be sure that the signatories will be better off under the coalition formation than under the Cournot game (acting non-cooperatively). With $\delta = 0.6$, and given $c = 0.39999$ we have $d = 0.239994$. Therefore, the environmental damage is greater than the abatement cost parameter.

Using all the above specifications, we confirm that the size of the stable IEA is $s^* = 7$. This size satisfies all the constraints for $e_s - x_s > 0$ and $e_{ns} - x_{ns} > 0$ and also the internal and external stability conditions. Note that for the same parameter values, the optimal size of the coalition in Diamantoudi and Sartzetakis (2006) is $s^* = 3$.

In Figure 1, we plot the indirect welfare functions against different coalition sizes s. The red curve depicts $w_s(s)$, the purple curve $w_{ns}(s)$ and the orange curve $w_{ns}(\ s-1)$. Notice that $w_{ns}(s-1)$ is a horizontal shift of $w_{ns}(s)$.

Figure 1 plots the functions for all possible values of $s = 0, \ldots, 10$. According to Figure 1 for coalition $s^* = 7$, the internal condition is satisfied i.e. $w_s(s^*) \geq w_{ns}(s^*-1)$ since $w_s(7) > w_{ns}(6)$, that is, the $w_s(s)$ curve is above the $w_{ns}(s-1)$ curve. Moreover, coalition $s^* = 7$ is externally stable i.e. $w_s(s^*+1) \leq w_{ns}(s^*)$ since at $s = s^*+1 = 8$ the $w_{ns}(s-1)$ curve is above the $w_s(s)$ curve. Therefore, the coalition of size $s^* = 7$ is stable.

Remark 1 *When the option of abating emissions is considered, the optimal size of the coalition is significantly greater relative to the case that abatement is not a choice.*

Similar to the analysis in Diamantoudi and Sartzetakis (2006) the stable coalition size is the higher integer following the size of the coalition for which the welfare of the signatories is at its minimum, $s^{\min}$ and for which $w_s = w_{ns}$. This point is $s^{\min} = 1 + \frac{(1+\delta\gamma)}{(1+\delta+\delta\gamma)}(n-1) = 6.70732$.

The results of the simulation of the coalition formation game using the parameter values $n = 10$, $a = 10$, $b = 6$, and $c = 0.39999$, $d = 0.239994$ and $\theta = 0$, are summarized in the following Table.[5]

[5]Table 1 does not report adaptation choices, since it is clear that under the assumption that adaptation is not effective, $\theta = 0$, signatory and non-signatory countries choose $v = 0$.

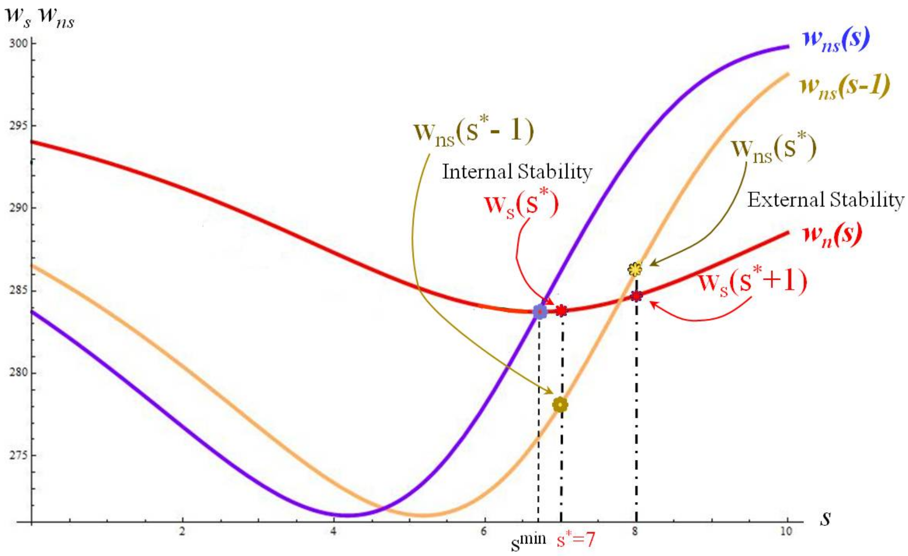

Figure 1: Defining the size of a stable IEA

Non-signatories	
Variable	Value
e_{ns}	9.66498
x_{ns}	8.37566
$e_{ns} - x_{ns}$	1.28932
w_{ns}	286.194
Signatories	
e_s	9.62175
x_s	9.4564
$e_s - x_s$	0.16535
w_s	283.789
Total net emissions	
E	96.3472
X	91.3218
$\sum_{i=1}^{n}(e_i - x_i)$	5.0254

Table 1. Coalition Formation with abatement and without adaptation

These values confirm that signatories emit less and abate more than non-signatories, i.e. $e_s < e_{ns}$ and $x_s > x_{ns}$. Moreover, the net emissions are significantly smaller for the signatories, $e_s - x_s$, than for the non-signatories, $e_{ns} - x_{ns}$. The total net emissions, $\sum_{i=1}^{n}(e_i - x_i)$, include the activities from both signatories, which are $s = 7$, and non-signatories, which are $(n - s) = 3$. Furthermore, total net emissions are smaller relative to the non-cooperative case, which are $NE_c = 5.4545$, but larger than the full cooperation case, which are $NE_c = 0.5736$.

4.1.1 Comparative static analysis of the abatement effect

In the simulations presented above we used a value for the parameter δ that is below 1, indicating that the abatement cost parameter d is smaller than the emission damage parameter c. In particular we have used the value $\delta = 0.6$. However, the constraint derived from Proposition 1 for the values of all other parameters is $0 \leq \delta < 1.63704$. In order to ensure that the main result of the paper holds for any of the permitted values of the parameters, we simulate the model for two extreme values of δ, namely, $\delta = 0.0000001$ and $\delta = 1.637$. The first case indicates that abatement cost is negligible relative to environmental damages, while the second we assume that abatement costs exceed environmental damages. Table 2 presents the results of the simulations, including in the first column the case presented in the previous Sections.

Case study [6]	**1**	**2**	**3**
δ	0.6	$1 * 10^{-7}$	1.637
c	0.399	0.399	0.399
d	0.239	$3.99 * 10^{-8}$	0.655
$s^{\min}$	6.707	10	4.635
s^*	7	10	5
	Non-signatories		
e_{ns}	9.665	10	9.192
x_{ns}	8.375	9	7.406
$e_{ns} - x_{ns}$	1.289	1	1.785
w_{ns}	286.2	300	250.7
	Signatories		
e_s	9.622	10	9.079
x_s	9.456	10	8.439
$e_s - x_s$	0.165	$1 * 10^{-8}$	0.639
w_s	283.8	300	244.7
	Total net emissions		
E	96.347	100	91.354
X	91.322	100	79.229
$\sum_{i=1}^{n}(e_i - x_i)$	5.025	$1 * 10^{-7}$	12.124

Table 2. Coalition formation with abatement and without adaptation under different values of δ

The results of the simulations presented in Table 2 reveal that the value of the parameter δ is crucial in determining the size of the stable IEA. As we show above, when $\delta = 0.6$, the size of the stable coalition is $s^* = 7$. When δ takes a very low value, i.e. $\delta = 0.0000001$, the number of signatory countries increases, reaching the size of the grand coalition, $s^* = 10$. On the contrary, when δ takes a very high value, i.e. $\delta = 1.637$, the number of signatory countries decreases to $s^* = 5$. Notice though that even when the abatement cost parameter takes the highest value allowed by the model's constraints, the size of the stable coalition is higher than the case in which countries have only one choice variable (either emission or abatement).

[6]The values in the table are rounded to the nearest ten, hundred, and/or thousand according to the needs of calculations.

In the case in which δ approaches zero and the the grand coalition emerges, countries' emissions are the lowest possible receiving the highest welfare. This is because the slope of the marginal abatement cost is lower than the slope of the marginal environmental cost. In this case it is individually rational for the countries to abate.

4.2 The adaptation effect

We can now turn to consider the effect of adaptation on the size of the stable coalition. We shown above that in the absence of adaptation option, allowing countries to choose both emission and abatement levels, increases the size of the stable coalition. In order to examine the effect of adaptation we run simulations of the model for different values of θ and ω that satisfy all conditions set above. We will use the same as above parameter values $n = 10$, $a = 10$, $b = 6$, and $c = 0.39999$, $d = 0.239994$ and we will assume $\omega = 0.3$ and we will examine two different levels of adaptation effectiveness, a relatively very low $\theta = 0.03$ and a significantly high one, $\theta = 0.34$. Both these values satisfy the restriction of positive net damages from emissions, that is, $\mu > 0$, which implies that $\theta < \sqrt{c\omega}$. Table 3 presents the results of the simulations.

Case study	**1**	**2**
a	10	10
b	6	6
c	0.399	0.399
d	0.239994	0.239994
ω	0.3	0.3
θ	0.03	0.34
s	7	3
Non-signatories		
e_{ns}	9.66708	9.87285
x_{ns}	8.32311	3.1789
v_{ns}	0.504418	63.2663
$e_{ns} - x_{ns}$	1.34398	6.69394
w_{ns}	286.317	277.445
Signatories		
e_s	9.62096	9.73034
x_s	9.47635	6.74179
v_s	0.504418	63.2663
$e_s - x_s$	0.144608	2.98854
w_s	283.755	273.034
Total net emissions		
$E - M$	5.04418	55.8232

Table 3. Coalition formation with abatement and adaptation, under different values of θ

From the results of the simulations presented in Table 3 we conclude that as adaptation becomes more effective, the size of the coalition drops. For very low effectiveness of adaptation, $\theta = 0.03$, the effect is negligible as it is clear from the values depicted in the first column of Table 3. However, as adaptation becomes more effective, the net damage from emission, indicated by the parameter μ, decreases and incentives to join the coalition decrease. For, $\theta = 0.34$, which implies a very low net damage $\mu = 0,137$, the size of the coalition drops to $s^* = 3$, as in the case that abatement was not an option. Both signatory and non-signatory countries increase their emission and decrease their abatement effort, since adaptation can reduce effectively damages from net emissions.

5 Conclusions

The present paper examines the size of stable IEAs employing a non-cooperative leadership framework and assuming that countries choose emission and abatement levels separately and they also choose adaptation. We assume the following specific functions: benefits are assumed concave in the country's own emissions; environmental damages are convex in aggregate net emissions and linear in the country's adaptation effort; abatement and adaptation cost functions are convex. Coalition formation is modelled as a three stage game: in the last stage countries choose independently their level of adaptation activities, after observing global net emissions. In the second stage, countries choose their levels of emission and abatement and in the first stage counties choose whether or not to join a coalition that aims at controlling emissions. Within this framework we find that first, assuming adaptation is not very effective, the size of the stable coalition is always larger than in the case in which countries can choose only their emissions level. Second, the difference in the size of stable coalitions increases the less costly abatement becomes. Finally, as the effectiveness of adaptation effort increases, the incentives to join the coalition decrease and for highly effective adaptation the size of the stable coalition returns to levels commonly reported in the literature without the abatement option.

There are a number of directions in which this research project can be extended. First a full analytical solution of the model should be provided. Second the introduction of abatement technology in the emission model allows us to explore possible spillover effects. It would be interesting to examine whether the positive externalities resulting from spillovers could offset the existing free-riding incentives. Finally, it is worth examining the effect of assuming that adaptation has a multiplicative effect on damages from net emissions.

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7 Appendix: Proof of Lemma 1

From (9) we have that $e_s > 0 \Leftrightarrow \Omega^2 + \delta s^2 > (n-s)s\gamma\delta^2 \Longrightarrow \delta^2 + \delta s^2 + 2\delta(n-s) + (n-s)\left[\left(1+\gamma^2\delta^2+2\gamma\delta\right)(n-s) - \gamma\delta^2(s-2)\right] > 0$. We derive the size of the coalition that minimizes this expression $A(s) = \delta^2 + \delta s^2 + 2\delta(n-s) + (n-s)\left[\left(1+\gamma^2\delta^2+2\gamma\delta\right)(n-s) - \gamma\delta^2(s-2)\right]$, which is $\underline{s} = \frac{2\delta(1+\gamma\delta)+n(2+\gamma\delta(4+\delta+2\gamma\delta))}{2(1+\gamma\delta)(1+\delta+\gamma\delta)}$. Substituting the value $\underline{s}$ into the $A(s)$, we get $A(\underline{s}) = \frac{a\left(4\delta^2(1+\gamma\delta)+4n\delta(1+\gamma\delta)(2+\gamma\delta)+n^2(4+\gamma\delta(8+\gamma(4-\delta)\delta))\right)}{4\delta^2(1+\gamma\delta)+8n\delta(1+\gamma\delta)^2+n^2(4+\gamma\delta(12+\gamma\delta(12+\delta+4\gamma\delta)))}$. Then $A(\underline{s}) > 0$, if $4\delta^2(1+\gamma\delta)+4n\delta(1+\gamma\delta)(2+\gamma\delta)+n^2(4+\gamma\delta(8+\gamma(4-\delta)\delta)) > 0$, which is definitely true for $\delta < 4$. Clearly this is a sufficient but not necessary condition. Notice that if we divide the last expression with δ^3 and let $\delta \to \infty$, the expression reduces to the condition presented in Proposition 1, in D&S (2006). That is, if abatement is not available (extremely expensive) then the only option is to decrease the economic activity and thus emissions, which restricts the size of the coalition to maximum four countries as shown in D&S (2006). However, as the cost of abatement decreases substantially, a large part of the necessary emission reduction is achieved through abatement which eases the restriction on γ. That is, you can have a situation with substantial damages relative to benefits from emissions so that countries want to take strong action and in the same time you have available abatement technologies that can achieve the necessary emission reductions at a reasonable cost.

From (13) we have that $e_{ns} > 0 \Longleftrightarrow (\Omega - n\gamma\delta)\,\Omega + s^2\delta(1+\gamma\delta) > 0$. Dividing the expression by δ^2 and denoting by $\phi = \frac{1}{\delta}$, yields, $(n-s)^2(\phi+\gamma)^2 + \left[s^2 - (n-s)(\gamma n - 2)\right](\phi+\gamma) - (\gamma n - 1) > 0$. If abatement is not available, that is $\delta \to \infty$, which implies $\phi \to 0$, the expression reduces to the condition presented in Proposition 1, in D&S (2006). However, as the cost of abatement decreases and ϕ emission of nonsignatories are positive for higher values of γ. Although the necessary condition can be derived using the above technique, it is very complicated and we omit it. It is important to notice that the condition constraints the values of γ and δ.