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Sharing R&D investments in cleaner technologies to mitigate climate change☆

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ABSTRACT

This paper examines international cooperation on technological development as an alternative to international cooperation on GHG emission reductions. It is assumed that when countries cooperate they coordinate their investments so as to minimize the agreement costs of controlling emissions. Further it is assumed that in such cases they also pool their R&D efforts so as to fully internalize the spillover effects of their investments in R&D. In order to analyze the scope of cooperation, an agreement formation game is solved in three stages. First, countries decide whether or not to sign the agreement. Then, in the second stage, signatories (playing together) and non-signatories (playing individually) select their investment in R&D. Finally, in the third stage, each country decides on its level of emissions non-cooperatively. For linear environmental damages and quadratic investment costs, our findings show that the maximum participation in a R&D agreement consists of six countries and that participation decreases as spillover effects increase until a minimum participation consisting of three countries is reached.

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1. Introduction

Because of the doubts about the effectiveness of an emissions agreement such as the Kyoto Protocol, several scholars have asked whether other types of agreements could be designed to achieve significant reductions of GHG emissions. One idea would be to focus on technological improvements in order to reduce abatement costs, as this might increase a country's willingness to undertake significant emission reductions. For example, it could be beneficial to supplement a Kyoto-type agreement with technology elements if technological development is dependant not only on a country's own R&D investment but also on R&D by other countries through cross-country technology spillovers, see for instance, Carraro and Siniscalco (1997) and, more recently, Lessmann and Edenhofer (2011). Even with no explicit agreement on emissions, a technology agreement leading to increased R&D in clean technologies, and thus lower abatement costs, might yield a reduction in emissions. This is the argument behind the proposals of a climate agreement based on technological development; see for instance, Buchner and Carraro (2004) and Barrett (2006).[1]

The aim of this paper is to examine international cooperation on technological development as an *alternative* to international cooperation on GHG emission reductions. Cooperation on technological development may be designed in several ways. This paper follows the approach adopted by Kamien et al. (1992) in their analysis of the effects of R&D cartelization and research joint ventures on oligopolistic competition. We assume that when countries cooperate they coordinate their R&D activities so as to minimize the agreement costs of controlling emissions. They also share R&D investments and avoid duplication of R&D activities. In other words, when countries cooperate they pool their R&D efforts so as to fully internalize the spillover effects of their investment in R&D. The idea that the degree of spillover effects is different among countries which cooperate than among countries which do not cooperate can also be found in Xepapadeas (1995) and Carraro and Siniscalco (1997).[2]

In order to analyze these issues, a parametric version of the model proposed by Heal and Tarui (2010) to study investment and emission control under technology and pollution externalities is employed. We analyze the formation of an IEA as a three-stage game. In the first stage, countries decide on their participation. Then, in the second stage, signatories select investment in R&D to minimize the total costs to the parties of the agreement and fully internalize the spillover effects of their investments, whereas non-signatories act unilaterally. Finally, in the third stage, each country decides on its level of emissions non-cooperatively.

Our analysis shows that participation in an IEA increases as the spillover effects decrease. Notice that when spillover effects decrease the excludability of R&D investment for non-signatories increases and signatories' investment approaches to a club good which encourages participation. Nevertheless, the scope of this effect is limited since we find that when the spillover effects tend to zero, the level of participation approaches six countries regardless of the number of countries involved in the externality. Thus, even when spillovers are zero for non-signatories and the investment of signatories becomes excludable, it cannot be expected a large level of participation in a technology agreement. On the other hand, when spillover effects reach a maximum and the investment becomes a public good, the stable agreement converges to the result of the standard model with quadratic abatement costs and linear environmental damages: only three countries participate in the IEA. The conclusion is that sharing information promotes cooperation but it is not a sufficient condition to achieve a large membership in a technology agreement. The problem is that the *asymmetry* created by the exchange of information between signatories and non-signatories is not sufficient to eliminate the incentive the countries have to act as free riders when they cooperate in the provision of an (impure) public good as the R&D investment.

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[1] An overview of technology-oriented agreements stressing their potential role in addressing the free-riding incentives in climate negotiations can be found in de Coninck et al. (2008).

[2] In Xepapadeas (1995), it is assumed that when all countries enter into an international agreement, the level of technology is common to all countries (it is a pure public good). Carraro and Siniscalco (1997) normalize to zero the spillover effects for non-signatories so that signatories' investment becomes a club good. A *club good* is a public good that becomes excludable. See Cornes and Sandler (1996) for an excellent presentation of the theory of club goods.

Although the literature on IEAs is extensive, only a few theoretical contributions have addressed the issue studied in the present paper. Barrett (2006) shows that breakthrough technologies cannot improve the performance of IEAs with the exception of breakthrough technologies that exhibit increasing returns to scale.[3] He studies a system of two treaties, one promoting R&D and the other encouraging cooperative adoption. His analysis yields a standard result of the *linear* models: membership can be large but only when the treaty does not make all countries substantially better off.[4] More recently, Hoel and de Zeeuw (2010, 2014) assuming that the cost of adoption decreases with respect to the level of R&D, find that even without increasing returns to scale, a technology agreement can yield better results than those obtained by focusing on abatement targets. This result is obtained for a different timing of the game. They assume that the agreement chooses R&D expenditures after the participation stage. Hong and Karp (2012) assume, as in Barrett (2006), that countries individually decide whether to invest in a public good that reduces abatement costs before the participation stage. Their findings show that when using mixed strategies at the participation stage, the standard result mentioned above reverses: membership can be large but only when the treaty does make all countries substantially better off. Mixed strategies create endogenous risk so that risk aversion increases the equilibrium probability of participation. In this paper, we extend this research to the case of quadratic abatement and investment costs but we assume the timing proposed by Hoel and de Zeeuw (2010, 2014) and focus on pure strategies at the participation stage. Battaglini and Harstad (2012) derive optimistic results about the participation from a dynamic game (stock pollutant) with investment in green technologies. Their findings show that if an incomplete agreement on emissions is signed, countries face a hold-up problem every time they negotiate, however the free-rider problem can be mitigated and significant participation is feasible. In their dynamic game participation becomes attractive because only large coalitions commit to long-term agreements that avoid the hold-up problem.[5] Goeschl and Perino (2012) study the interaction between intellectual property rights (IPRs) for green technologies and the participation in an IEA with a flow pollutant. They find that the presence of IPRs leads to fewer signatories and a strategic reduction of their abatement commitment in anticipation of rent extraction by the firm that holds a global patent to the new abatement technology. The reason is the presence of a hold-up problem in abatement commitment. In this paper, this type of problem does not appear because we assume as in Hoel and de Zeeuw (2010, 2014) that the agreement chooses R&D expenditures after the participation stage.

Finally, we would like to point out that the results obtained from the empirical papers are not conclusive. On the one hand, Buchner and Carraro (2004), Kemfert (2004) and Lessmann and Edenhofer (2011) give support to the idea that supplementing an emission agreement with technology elements or replacing an emission agreement with a technology agreement can have positive effects on the participation level. However, Nagashima and Dellink (2008) and Nagashima et al. (2011) obtain more pessimistic results. To conclude we would like to point out a similarity of our results with a recent paper by van der Pol et al. (2012) who examine effects of altruism on coalition stability. They distinguish between community and impartial altruism and find that community altruism (i.e. the exclusion of non-signatories from the concerns of signatories) can be quite effective to promote participation in an IEA.

[3] A breakthrough technology opens the possibility of GHG emissions being completely eliminated, i.e., fossil fuels could be completely replaced by other non-polluting energies. See Barrett (2009) for a survey of the possibilities of developing these kinds of technologies and Strand (2007) for a study of the effects of a breakthrough technology treaty on the extraction path of fossil fuels.

[4] Ruis and de Zeeuw (2010) give support to this result in the framework of a model with quadratic investment costs. Urpelainen (2012) studies the strategic design of technology funds for climate cooperation between industrialized and developing countries when the success of innovation is uncertain. However, he does not address the issue of participation. Hübler and Finus (2013) consider the possibility of a risky investment as well but their analysis focuses on North-South technology transfers.

[5] Using a similar dynamic game Harstad (2012) analyzes different type of agreements with full participation. Harstad (2012) considers agreements that can be complete or incomplete within different durations and also take into account the possibility of renegotiations. Another contribution using dynamic games is Urpelainen (2010) although this author focuses on the compliance with an IEA. In particular, he studies whether technological standards can help to enforce an IEA.

The paper is organized as follows. The next section specifies the model. In Section 3, the efficient outcome is calculated. Section 4 presents the analysis of a R&D agreement. The conclusions drawn from this research are detailed in Section 5.

2. The model

We develop a static model with N countries that pollute the atmosphere and negotiate the control of greenhouse gas (GHG) emissions, taking into account the effects of spillovers in R&D from one country to another. It is assumed that the effective investment in a country i, y_i, $i = 1, \ldots, N$, depends on the amount invested in R&D in that country, x_i, to develop clean technologies, in addition to the investments in R&D undertaken in all other countries. However, technological diffusion is not perfect; only part of the R&D investments undertaken in other countries is beneficial for country i. Hence, the effective investment of country i is given by

$$y_i = x_i + \gamma_i X_{-i}, \quad \gamma \in [0, 1], \tag{1}$$

where $X_{-i} = \sum_{j \neq i} x_j$. Moreover, countries can achieve larger technological spillovers by means of appropriate instruments such as technological cooperation. Cooperating countries can allow for patent agreements that provide the other countries in the coalition with a large share of their own innovative technology or they can sign agreements on technology transfers and/or joint R&D projects that increase the degree of innovation spillovers inside the coalition. Following the approach adopted by Kamien et al. (1992), it is assumed that when countries cooperate they pool their R&D efforts so as to fully internalize spillover effects, which implies that in this case we will assume that $\gamma_i = 1$ for signatories' investments and $\gamma_i = \gamma \in (0, 1)$ for non-signatories' investments. Thus, if n stands for the number of signatories, s for a signatory country and f for a non-signatory, the effective investment of signatories is

$$y_j^s = X^s + \gamma X^f = \sum_{k=1}^{n} x_k^s + \gamma \left(\sum_{l=1}^{N-n} x_l^f \right), \quad j = 1, \ldots, n, \tag{2}$$

whereas the effective investment for non-signatories is given by (1). If all of the countries sign the technology agreement, the effective investment for signatories is given by

$$y_i = X = \sum_{j=1}^{N} x_j, \quad i = 1, \ldots, N,$$

as in Kamien et al. (1992) when a RJV is formed or in Xepapadeas (1995) when an international agreement with full participation is signed to control GHG emissions. Our specification of the spillovers is placed between two well-known specifications that can be addressed as particular cases: the (pure) *public good* and the *club good*. With $\gamma = 1$, the effective investment is a public good whereas with $\gamma = 0$ the effective investment becomes a club good. Our approach allows to address these two types of goods as particular cases.

In the absence of any explicit abatement activities, emissions in each country depend only on the technology level of the country. We define technology dependent BAU emissions as $\bar{E}(y_i) = \delta - \alpha y_i$, with $\delta, \alpha > 0$, δ standing for the emissions associated with the dirtiest technology and α representing emission abatement per unit invested in clean technologies. According to that, we can define the abatement of country i as $A_i = \bar{E}(y_i) - E_i = \delta - \alpha y_i - E_i$ where E_i stands for the current emissions generated by country i. Thus, abatement costs depend both on the level of abatement and the level of effective investment. Effective R&D investment reduces abatement costs because it reduces the intensity of emissions in the production of goods and services for a country. The greater the effective R&D investment, the lower the ratio of GHG emissions to GDP of the country and, consequently, the lower the abatement costs. It is assumed that abatement costs are quadratic

$$C(A_i) = \frac{c}{2} A_i^2 = \frac{c}{2} (\delta - \alpha y_i - E_i)^2, \quad c > 0, \tag{3}$$

and that the cost of investing in R&D is also quadratic and given by $R(x_i) = rx_i^2/2$, $r > 0$.[6]

Finally, in each country environmental damage depends on global emissions, $E = \sum_{i=1}^{N} E_i$. Environmental damages are assumed to be linear: $D(E) = dE$, $d > 0$. Thus, the total costs of controlling GHG emissions for the representative country can be written as follows:

$$TC_i = \frac{c}{2}(\delta - \alpha y_i - E_i)^2 + dE + \frac{r}{2}x_i^2. \tag{4}$$

3. The efficient solution

First of all we characterize the efficient solution. We assume that when countries cooperate they pool their R&D investment so as to fully internalize spillover effects so that in the efficient benchmark each country can benefit from total investment X. Then countries select emissions and investments to minimize the global total costs given by

$$\min_{\{E_1,\ldots,E_N,x_1,\ldots,x_N\}} GTC = \sum_{i=1}^{N} TC_i = \sum_{i=1}^{N} \left(\frac{c}{2}(\delta - \alpha X - E_i)^2 + dE + \frac{r}{2}x_i^2 \right).$$

The *interior solutions* to the optimization problem for the representative country are given by the following conditions

$$c(\delta - \alpha X - E_i) = Nd, \tag{5}$$

$$\sum_{j=1}^{N} \alpha c(\delta - \alpha X - E_j) = rx_i, \tag{6}$$

where the left-hand side of (5) represents marginal abatement costs and the right-hand side *global* marginal damages. Observe that for the efficient solution, each country has to balance its marginal abatement costs with the marginal benefits its action has on all countries that are given by the reduction in damages caused by the abatement. On the other hand, the left-hand side of (6) stands for the *global* marginal revenue of investment while the right-hand side represents the marginal cost. Notice that the marginal revenue of investment is given by the reduction in abatement cost achieved by the investment taking into account the external effects of investment, i.e. adding this reduction for all the countries.

Thus, the emissions and investment levels of the symmetric efficient solution are

$$E_i^e = \delta - \frac{d}{c}N - \frac{\alpha^2 d}{r}N^3, \tag{7}$$

$$x_i^e = \frac{\alpha d}{r}N^2. \tag{8}$$

These expressions say that emissions decrease with respect to marginal damages whereas investments increase. In this case, to guarantee an interior solution, marginal damages must be lower than the upper bound defined implicitly by condition $E_i^e = 0$.

4. A R&D agreement formation game

We say that a technology agreement is formed if the countries pool their R&D investments so as to fully internalize the spillover effects. The formation of an IEA is modeled as a three-stage game. Each stage will be described briefly in reverse order as the subgame-perfect equilibrium of this three stage game is computed by backward induction.

[6] The assumption that investment costs are quadratic is also used by Carraro and Siniscalco (1997) and is based on the approach adopted by d'Aspremont and Jacquemin (1988, 1990) in their study on the cooperation in R&D with spillovers in the context on an oligopoly with cost-reducing R&D opportunities.

Given the level of participation in the agreement and the investment in R&D of all countries, at the third stage, the emission game, each country simultaneously selects its own emissions acting non-cooperatively and taking the emissions of all other countries as given. At the second stage, the R&D investment game, signatory countries coordinate their R&D activities so as to minimize the sum of agreement costs taking as given the R&D investments of non-signatories. In this case the effective investment for signatories is given by (2). Non-signatories choose their investment in R&D acting non-cooperatively and taking the investments of all other countries as given in order to minimize their own costs of controlling emissions. Signatories and non-signatories choose their R&D investment simultaneously. Thus, R&D investments are provided by the *partial agreement Nash equilibrium* (PANE) with respect to a coalition defined by Chander and Tulkens (1995). Finally, it is assumed that at the first stage countries play a *simultaneous open membership game with a single binding agreement.* In a single agreement formation game, the strategies for each country are to sign or not to sign and the agreement is formed by all players who have chosen to sign. Under open membership, any country is free to join the agreement if it is interested. Finally, we assume that the signing of the agreement is binding on signatories. The game finishes when the emissions subgame is over.

4.1. The third stage: an equilibrium in dominant strategies

As we have supposed that there is no cooperation in the third stage, optimal emissions can be calculated by minimizing the following total cost function

$$\min_{\{E_i\}} \; TC_i = \frac{c}{2}(\delta - \alpha y_i - E_i)^2 + dE, \quad i = 1, \ldots, N$$

given that participation is decided in the first stage and investments in the second stage.

The first-order condition for an *interior solution* of the representative country is

$$c(\delta - \alpha y_i - E_i) = d, \tag{9}$$

where the left-hand side represents marginal abatement costs and the right-hand side *national* marginal damages. As there is no cooperation at this stage, each country only takes into account the benefits its action has on its own environmental damages.

Thus, emissions are given by

$$E_i = \delta - \frac{d}{c} - \alpha y_i. \tag{10}$$

As environmental damages are linear, the reaction functions of the countries are orthogonal and the optimal emissions are given by an equilibrium in dominant strategies.

Adding for the different countries, global emissions are obtained

$$E = \sum_{i=1}^{N} E_i = N\bar{\delta} - \alpha Y, \tag{11}$$

where $\bar{\delta} = \delta - (d/c)$ and $Y = \sum_{i=1}^{N} y_i$ is the global effective investment in R&D.

Next, using (10), total costs can be written as

$$TC_i = \frac{d^2}{2c} + dE + \frac{r}{2}x_i^2, \tag{12}$$

where global emissions are given by (11) and the first term represents abatement costs.

4.2. The second stage: the PANE of the investment game

In this section, we solve stage two assuming that in the first stage n countries, with $n \geq 2$, have signed the agreement. As we have supposed that there is no cooperation in the emissions game, the total costs supported by all countries, signatories and non-signatories, are given by (12). Observe that global effective investment in R&D becomes a public good. Any investment made by a country reduces the total costs of all countries because of the reduction in global emissions. Thus, in the third stage, countries have to decide on the provision of a *pure public bad* whereas in the second stage they have to decide on the provision of an *impure public good* because of the spillovers.

If n countries cooperate in the second stage, the first-order conditions are

$$nd\frac{\partial E}{\partial x_i} + rx_i = 0, \quad i = 1, \ldots, n,$$
$$d\frac{\partial E}{\partial x_i} + rx_i = 0, \quad i = n+1, \ldots, N,$$

so that investment is given by the following expressions

$$x_i = \frac{\alpha dn}{r}\sum_{j=1}^{N}\frac{\partial y_j}{\partial x_i}, \quad i = 1, \ldots, n, \tag{13}$$

$$x_i = \frac{\alpha d}{r}\sum_{j=1}^{N}\frac{\partial y_j}{\partial x_i}, \quad i = n+1, \ldots, N, \tag{14}$$

where (13) is the investment for signatories and (14) is the investment for non-signatories.

As the signature of the technology agreement implies that countries share their R&D investments so as to fully internalize the spillover effects, the effective investment for signatories is given by

$$y_j^s = X^s + \gamma X^f = \sum_{k=1}^{n} x_k^s + \sum_{l=1}^{N-n} x_l^f,$$

and for non-signatories by

$$y_i^f = x_i^f + \gamma(X_{-i}^f + X^s) = x_i^f + \gamma\left(\sum_{l=1}^{N-n-1} x_l^f + \sum_{k=1}^{n} x_k^s\right),$$

so that

$$\sum_{j=1}^{N}\frac{\partial y_j}{\partial x_i} = n + \gamma(N-n),$$

for signatories and

$$\sum_{j=1}^{N}\frac{\partial y_j}{\partial x_i} = 1 + \gamma(N-1)$$

for non-signatories.

Then (13) and (14) yield

$$x_i^f = \frac{\alpha d}{r}(1 + \gamma(N-1)), \tag{15}$$

for non-signatories' investment and

$$x_j^s = \frac{\alpha dn}{r}(n + \gamma(N-n)), \tag{16}$$

for signatories' investment. For $n = N$, (16) gives the level of investment corresponding to the efficient solution and for $n = 1$ coincides with (15) and yields the level of investment corresponding to the fully non-cooperative equilibrium. Again, given the linearity of the environmental damages and effective investment, the PANE is also an equilibrium in dominant strategies.

Cooperation does not affect non-signatories' investment but increases the investment of signatories. Moreover, it is easy to check that signatories devote more resources to R&D than non-signatories and that the signatories' effective investment is larger than the non-signatories' effective investment for any level of participation and spillovers. Then, according to (10), signatories' emissions are lower than non-signatories' emissions. Moreover, as signatories invest more they support a larger cost for controlling pollution given that the abatement costs and environmental damages are the same for both signatories and non-signatories.

On the other hand, it is also easy to verify that global effective investment increases with the number of signatories and that global emissions decrease because global emissions are inversely related with global effective investment. Moreover, there are *positive spillovers* for non-signatories stemming from cooperation, i.e. cooperation decreases the total costs for non-signatories. The incorporation of one country to the agreement reduces global emissions and has no effect on the non-signatories' investment. The result is a reduction in the cost of the countries that stay outside the agreement. This positive effect of cooperation on costs also applies for signatories.

Finally, it is easy to check that the game is *superadditive* that means that the total costs of an agreement joined by an additional country *i* are lower or at maximum equal to the total costs of the agreement plus the total cost of the country *i* acceding to the agreement. Superadditivity is a natural feature as all options open to a set of individual countries should be open to an a coalition of countries.

4.3. *The first stage: the Nash equilibrium of the membership game*

In this section, we investigate which is the level of participation a technology agreement can achieve. First, we present the definition of coalition stability from d'Aspremont et al. (1983), which has been extensively used in the literature on international environmental agreements.

Definition 1. An agreement consisting of n signatories is stable if $TC_j^s(n) \leq TC_i^f(n-1)$ for $j = 1, \ldots, n$ and $TC_i^f(n) \leq TC_j^s(n+1)$ for $i = 1, \ldots, N-n$.

The first inequality, which is also known as the *internal stability condition*, simply means that any signatory country is at least as well-off staying in the agreement as withdrawing from it, assuming that all other countries do not change their membership status. The second inequality, which is also known as the *external stability condition*, similarly requires any non-signatory to be at least as well-off remaining a non-signatory as joining the agreement, assuming once again, that all other countries do not change their membership status. To check the stability conditions the auxiliary function $\Omega(n) = TC_j^s(n) - TC_i^f(n-1)$ is used. If $\Omega(n) = 0$ has a unique positive solution and $\Omega(n)$ is increasing around this positive solution, then there is a *stable* agreement given by the greatest natural number on the left of the positive solution to equation $\Omega(n) = 0$ provided that this number is equal to or lower than N. If we represent this number by $\tilde{n}$, we have that $\Omega(\tilde{n})$ is negative and the internal stability condition is satisfied. Moreover, as $\Omega(n)$ is an increasing function, $\Omega(\tilde{n}+1)$, where $\tilde{n}+1$ is the lowest natural number on the right of the positive solution to equation $\Omega(n) = 0$, must be positive which means that $TC_j^s(\tilde{n}+1)$ is greater than $TC_i^f(\tilde{n})$ which according to Definition 1 means that an agreement consisting of $\tilde{n}$ countries is also externally stable. If the positive solution to $\Omega(n) = 0$ is a natural number, the self-enforcing agreement consists of a number of signatories equal to the solution to the equation and the internal stability condition is satisfied as an equality. If N is lower than $\tilde{n}$, the grand coalition could be stable provided that$\Omega(N)$ is negative. If $\Omega(n) = 0$ has more than one positive solutions, we could have more than one self-enforcing agreement.

Next, the stability analysis is performed to investigate whether a self-enforcing technology a agreement exists. The result is

Proposition 1. *If $\gamma \in (0.7, 1)$ the only stable agreement consists of three countries regardless of the number of countries involved in the environmental problem. If $\gamma \in (0, 0.7]$ the participation in an IEA increases as the degree of spillovers goes down and decreases with the number of countries involved in the environmental problem although the membership cannot be either larger than six countries or lower than three countries.*

Proof. In order to prove this result, we write the auxiliary function $\Omega(n)$ using the expressions of the total costs that can be obtained from (15) and (16)

$$\Omega(n) = \frac{\alpha^2 d^2}{2r}((2(N-n+1)-1)(1+\gamma(N-1))^2 + 2(n-1)^2(n-1+\gamma(N-n+1))^2 \\ -2(N-n)(1+\gamma(N-1))^2 - n^2(n+\gamma(N-n))^2),$$

which after some manipulation can be written as

$$\Omega(n) = \frac{\alpha^2 d^2}{2r}((1-\gamma)(n^3-8n^2+10n-4)(n+\gamma(N-n)) + \gamma N(n^2-4n+2)(n+\gamma(N-n)) \\ +2(n-1)^2(1-\gamma)^2 + (1+\gamma(N-1))^2). \tag{17}$$

It is immediate that $\Omega(n)$ is positive for $n \geq 7$ since $n^3 - 8n^2 + 10n - 4$ is positive for $n \geq 7$ and $n^2 - 4n + 2$ is positive for $n \geq 4$ and the other terms are also positive for all n. Thus, no agreement consisting of seven or more signatories is going to satisfy the internal stability condition (ISC). Next, we proceed studying the stability of $n = \{2, 3, 4, 5, 6\}$. For $n = 2$ and $n = 3$, it is easy to show that $\Omega(2)$ and $\Omega(3)$ are negative for all $N \geq 2$ and $\gamma \in (0, 1)$. Thus, as the external stability condition (ESC) for an agreement consisting of two countries requires that $\Omega(3)$ be positive or zero, a bilateral agreement can only be stable if $N = 2$. For an agreement with three countries, the ISC is fulfilled for all γ and $N \geq 2$ according to Lemma 1 in Weikard (2009) because $\Omega(3)$ is negative.[7] On the other hand, the ESC requires that

$$\Omega(4) = \frac{3\alpha^2 d^2}{2r}((N^2+6N-31)\gamma^2 - (6N-62)\gamma - 31)$$

be positive or zero. Performing $\Omega(4) = 0$, we obtain a contour of values for γ and N defined in an explicit way by the positive root of this equation

$$\bar{\gamma}(N; 4) = \frac{9.325N - 31}{N^2 + 6N - 31}$$

such that if (N, γ) is above the contour $\Omega(4) = 0$, $\Omega(4)$ is positive. The contour is decreasing with respect to N and the maximum value for γ is equal to 0.70 for $N = 4$.[8] The contour is represented in black in Fig. 1. Thus, for all the combinations (N, γ) above or on the contour $\Omega(4) = 0$ an agreement consisting of three countries is stable. When (N, γ) is on the contour, the ESC for $n = 3$ is satisfied as an equality. For an agreement consisting of four countries, the ISC is fulfilled for all the combinations below or on $\bar{\gamma}(N; 4)$ because then $\Omega(4)$ is negative or zero. Moreover, the ESC requires that

$$\Omega(5) = \frac{4\alpha^2 d^2}{r}((N^2 - N - 14)\gamma^2 + (N+28)\gamma - 14)$$

be positive or zero. Calculating $\Omega(5) = 0$, we obtain a contour of values for γ and N defined in an explicit way by the positive root of this equation

$$\bar{\gamma}(N; 5) = \frac{3.275N - 14}{N^2 - N - 14},$$

such that if (N, γ) is above the contour $\Omega(5) = 0$, $\Omega(5)$ is positive. The contour is decreasing with respect to N and the maximum value for γ is equal to 0.45 for $N = 4$. The contour is represented in red in Fig. 1. Therefore we can conclude that an agreement consisting of four countries is stable for all the combinations of (N, γ) in the region of Fig. 1 defined by the contours $\Omega(4) = 0$ in black and $\Omega(5) = 0$ in red, including the contours. Moreover, on $\Omega(4) = 0$, both $n = 3$ and $n = 4$ are stable. For $n = 3$ the ESC is satisfied as an equality whereas for $n = 4$ the ISC is satisfied as an equality. For an agreement consisting

[7] Weikard (2009) shows that if a coalition formation game is superadditive, has positive spillovers and the players are symmetric, external instability of an n-player coalition implies the internal stability of an $n + 1$-player coalition.

[8] Notice that the grand coalition is stable for $N = 3$ for any value of γ in the interval (0, 1) since $\Omega(3)$ is negative.

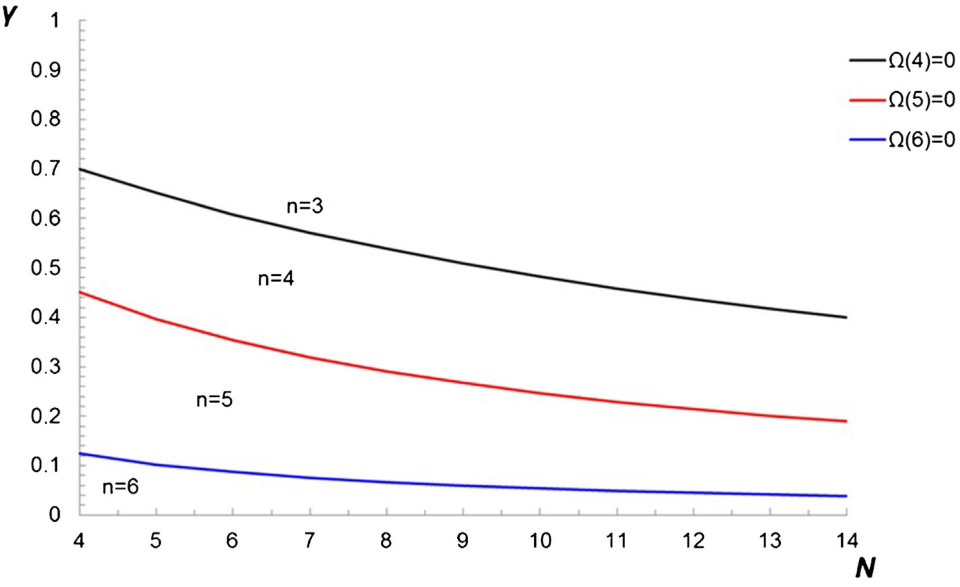

Fig. 1. Stable agreements as a function of N and γ.

of five countries the ISC is satisfied for all the combinations (N, γ) below or on $\bar{\gamma}(N; 5)$ because then $\Omega(5)$ is negative or zero. However, the ESC requires that

$$\Omega(6) = \frac{\alpha^2 d^2}{2r}((15N^2 - 70N - 45)\gamma^2 + (70N + 90)\gamma - 45)$$

be positive or zero. Now performing $\Omega(6) = 0$, we obtain a contour of values for γ and N defined in an explicit way by the positive root of this equation

$$\bar{\gamma}(N; 6) = \frac{8.59N - 45}{15N^2 - 70N - 45},$$

such that if (N, γ) is above the contour $\Omega(6) = 0$, $\Omega(6)$ is positive. The contour is decreasing with respect to N and the maximum value for γ is equal to 0.1252 for $N = 4$. The contour is represented in blue in Fig. 1. Therefore we can conclude that an agreement consisting of five countries is stable for all the combinations of (N, γ) in the region of Fig. 1 defined by the contours $\Omega(5) = 0$ in red and $\Omega(6) = 0$ in blue, including the contours. On the contour $\Omega(5) = 0$, both $n = 4$ and $n = 5$ are stable. For $n = 4$ the ESC is satisfied as an equality whereas for $n = 5$ the ISC is satisfied as an equality. Finally, an agreement consisting of six countries can be stable if (N, γ) is below or on the contour $\Omega(6) = 0$ because the ISC is satisfied for all γ. Remember that $\Omega(n)$ is positive for all $n \geq 7$ regardless of the value of γ. Moreover, on the contour $\Omega(6) = 0$, $n = 5$ is also stable although the ESC is satisfied as an equality. Thus, Fig. 1 says us that for $\gamma \geq 0.7$ no agreement consisting of more than three countries can be stable regardless of the number of countries involved in the environmental problem. Finally, it is clear that for $\gamma < 0.7$ the participation increases as γ decreases and decreases as N increases but it cannot be larger than six countries or smaller than three. □

In order to illustrate the proposition, we have calculated the critical values for γ when $N = 10$. When there are only ten countries involved in the externality the critical values for γ are: $\gamma(N = 10, n = 4) = 0.48$, $\gamma(N = 10, n = 5) = 0.24$, $\gamma(N = 10, n = 6) = 0.05$. Then if $\gamma \in (0, 0.05)$ an agreement consisting of six countries is stable. However, if $\gamma \in (0.05, 0.24)$ the stable agreement is formed by five countries. For values of γ in the interval (0.24, 0.48), the stable agreement consists of four countries. Finally, if $\gamma > 0.48$, only three countries can form a stable agreement.

Table 1
Participation in a R&D agreement with $\gamma = 0.25$.

n	x_i^f	x_j^s	y_i^f	y_j^s	E	TC_i^f	TC_j^s
1	0.065		0.211		997.75	9.979	
2	0.065	0.160	0.259	0.450	996.90	9.970	9.975
3	0.065	0.285	0.376	0.969	994.33	9.944	9.964
▸4	0.065	0.440	0.586	1.857	988.92	9.890	9.938
5	0.065	0.625	0.911	3.206	979.28	9.794	9.891
6	0.065	0.840	1.374	5.105	963.74	9.638	9.814
7	0.065	1.085	1.996	7.644	940.37	9.405	9.698
8	0.065	1.360	2.801	10.913	906.96	9.071	9.532
9	0.065	1.665	3.811	15.001	861.04	8.611	9.303
10		2.000		20.000	798.67		8.987

$\alpha = 1$, $\delta = 100$, $c = 0.75$, $d = 0.01$, $r = 0.5$, $N = 10$.

Table 1 shows the solution of the investment game for different values of participation and $\gamma = 0.25$. The selected set of values for parameters yields an interior solution for emissions for both types of countries. It can be seen that for all n between 1 (the fully non-cooperative equilibrium) and 10 (the grand coalition), the signatories' investment is larger than the non-signatories' investment and that this difference increases with membership. The same occurs with total costs. Moreover, at the aggregate level, total costs and global emissions decrease as the participation in the agreement increases.

In Table 2 we have recalculated the example for $\gamma = 0.025$. According to our results, the participation increases, in this example, from four countries to six. Basically, the increment in participation is explained by the reduction in spillover effects softening the variations in investments caused by the exit of one country from the agreement. With the exception of $n = \{9, 10\}$, when one country leaves the agreement the reduction in investment that is achieved when $\gamma = 0.025$ is lower than when $\gamma = 0.25$. Thus, when spillover effects are lower the incentive to act as a non-signatory is reduced because the saving in investment costs is then smaller. On the other hand, we find that the reduction in spillover effects has the same effect on global emissions. With the exception of $n = \{8, 9, 10\}$, when one country leaves the agreement the increase in global emissions that the exit causes when $\gamma = 0.025$ is lower than when $\gamma = 0.25$. Thus, when spillover effects are lower the incentive to act as a non-signatory is augmented because in this case the increment in environmental damages is smaller. But for an interior solution, marginal damages are low and the first incentive dominates the second yielding a larger level of participation.

From the previous proof, it is straightforward to derive the following result:

Corollary 1. *For $\gamma = 1$, the global effective investment becomes a pure public good and then a bilateral agreement also satisfies the stability conditions.*

Table 2
Participation in a R&D agreement when $\gamma = 0.025$.

n	x_i^f	x_j^s	y_i^f	y_j^s	E	TC_i^f	TC_j^s
1	0.024		0.030		999.57	9.996	
2	0.024	0.088	0.033	0.181	999.24	9.993	9.994
3	0.024	0.190	0.042	0.576	997.84	9.979	9.987
4	0.024	0.332	0.061	1.332	994.18	9.942	9.969
5	0.024	0.512	0.091	2.566	986.58	9.866	9.931
▸6	0.024	0.732	0.136	4.394	972.96	9.730	9.864
7	0.024	0.990	0.199	6.935	950.72	9.507	9.752
8	0.024	1.288	0.283	10.305	916.86	9.169	9.583
9	0.024	1.624	0.390	14.621	867.89	8.680	9.339
10		2.000		20.000	798.67		8.987

$\alpha = 1$, $\delta = 100$, $c = 0.75$, $d = 0.01$, $r = 0.5$, $N = 10$.

Proof. For $\gamma = 1$, $\Omega(2)$ is negative, $\Omega(3) = 0$ and $\Omega(n) > 0$ for $n \geq 4$. Then the ESC of an agreement consisting of two countries is satisfied as an equality and consequently conditions of Definition 1 are satisfied. Consequently, the ISC of an agreement consisting in three countries is also satisfied as an equality. □

This result is consistent with that obtained by Barrett (1994) with linear emission damages and quadratic specification of abatement costs and shows that adding a new public good, the effective investment, to Barrett's model does not have effects on the scope of international cooperation to control pollution.

On the other hand, it is also easy to obtain that

Corollary 2. *For $\gamma = 0$, the global effective investment becomes a club good and the only stable agreement consists of six countries regardless of the number of countries involved in the environmental problem.*

Proof. For $\gamma = 0$, (17) yields

$$\Omega(n) = \frac{\alpha^2 d^2}{2r}((n^3 - 8n^2 + 10n - 4)n + 2(n-1)^2 + 1),$$

that it is positive for $n \geq 7$ and negative for $n \leq 6$. Thus, the unique agreement that satisfies both stability conditions consists of six countries. □

When the signatories can exclude the non-signatories from the spillovers coming from investment cooperation increases but it is not sufficient to yield high degrees of participation. Thus, only when the environmental problem affects a reduced number of countries, the exclusion of non-signatories from the club could have a relevant effect on participation.

5. Conclusions

This paper aims to study the effects of R&D spillovers on the formation of IEAs by solving a three-stage game where the membership decision is taken in the first stage, the investment game is played in the second stage and the emission game is played in the last stage. It is assumed that the marginal abatement costs of signatory countries are decreased by the sum of signatories' R&D efforts in addition to some spillovers from non-signatories' R&D whereas the marginal abatement costs of a non-signatory is only affected by its own investment and the spillover effects of the rest of countries. We find that for a R&D agreement the maximum participation consists of six countries and that participation decreases as the degree of spillovers increases until that a minimum participation consisting of three countries is reached. Thus, sharing information promotes cooperation but the effects on participation are modest; the incentive the countries have to act as free riders in the provision of an (impure) public good practically eliminates the positive effects of the internalization of the spillovers effects between signatories on participation. Summarizing, our analysis does not give reasons to think that technology agreements, such as those studied in this paper, are a good alternative to international cooperation on climate change mitigation.

Some extensions of the model are on the agenda for future research. Primarily, the corner solution of the game could be investigated. In this paper, we have obtained the solution of the game with positive emissions, which means that the focus has been on mitigation. However, the model can present corner solutions or in other words, it admits the possibility that GHG emissions could be completely eliminated, that is, the use of fossil fuels could be eradicated through the adoption of a breakthrough technology. In our model emissions can become zero if a certain level of investment is reached. Through this research, we would have a more complete view of the possibilities that a R&D agreement would have to promote greater participation in an IEA. On the other hand, it is also clear that investment in R&D is a risky activity. Thus, a natural extension of our analysis would be to consider some kind of probabilistic model that implies that the investment in R&D could fail to deliver a cleaner technology. Finally, it would be also interesting to incorporate cooperation in controlling emissions and study whether it may lead to hold-up problems.

References

Barrett, S., 1994. Self-enforcing international environmental agreements. Oxford Econ. Pap. 46, 878–894.
Barrett, S., 2006. Climate treaties and “breakthrough” technologies. Am. Econ. Rev. 96, 22–25.
Barrett, S., 2009. The coming global climate – technology revolution. J. Econ. Perspect. 23, 53–75.
Battaglini, M., Harstad, B., 2012. Participation and duration of environmental agreements. NBER Working Paper 18585.
Buchner, B., Carraro, C., 2004. Economic and environmental effectiveness of a technology-based climate protocol. Clim. Policy 4, 229–248.
Carraro, C., Siniscalco, D., 1997. R&D cooperation and the stability of international environmental agreements. In: Carraro, C. (Ed.), International Environmental Negotiations: Strategic Policy Issues. Edward Elgar Publishing, Cheltenham, UK.
Chander, P., Tulkens, H., 1995. A core-theoretic solution for the design of cooperative agreements on transfrontier pollution. Int. Tax Public Finance 2, 279–294.
Cornes, R., Sandler, T., 1996. The Theory of Externalities, Public Goods and Club Goods, 2nd ed. Cambridge University Press, Cambridge, UK.
d’Aspremont, C., Jacquemin, A., 1988. Cooperative and noncooperative R&D in duopoly with spillovers. Am. Econ. Rev. 78, 1133–1137.
d’Aspremont, C., Jacquemin, A., 1990. Cooperative and noncooperative R&D in duopoly with spillovers: erratum. Am. Econ. Rev. 80, 641–642.
d’Aspremont, C., Jacqemin, J., Gadszeweiz, J., Weymark, J.A., 1983. On the stability of collusive price leadership. Can. J. Econ. 16, 17–25.
de Coninck, H., Fischer, C., Newell, R.G., Ueno, T., 2008. International technology-oriented agreements to address climate change. Energy Policy 36, 335–356.
Goeschl, T., Perino, G., 2012. The climate policy hold-up: how intellectual property rights turn international environmental agreements into buyer cartels for abatement technologies. Working Paper. University of East Anglia.
Harstad, B., 2012. Climate contracts: a game of emissions, investments, negotiations, and renegotiations. Rev. Econ. Stud. 79, 1527–1557.
Heal, G., Tarui, N., 2010. Investment and emission control under technology and pollution externalities. Resour. Energy Econ. 32, 1–14.
Hoel, M., de Zeeuw, A., 2010. Can a focus on breakthrough technologies improve the performance of international environmental agreements? Environ. Resour. Econ. 47, 395–406.
Hoel, M., de Zeeuw, A., 2014. Technology agreements with heterogeneous countries. In: Cherry, T.L., Hovi, J., McEvoy, D.M. (Eds.), Toward a New Climate Agreement. Conflict, Resolution and Governance. Routledge, New York, USA.
Hong, F., Karp, L., 2012. International environmental agreements with mixed strategies and investment. J. Public Econ. 96, 685–697.
Hübler, M., Finus, M., 2013. Is the risk of north–south technology transfer failure an obstacle to a cooperative climate change agreement? Int. Environ. Agreem.: Politics Law Econ., http://dx.doi.org/10.1007/s10784-013-9208-3 (forthcoming).
Kamien, M.I., Muller, E., Zang, I., 1992. Research joint ventures and R&D cartels. Am. Econ. Rev. 82, 1293–1306.
Kemfert, C., 2004. Climate coalitions and international trade: assessment of cooperation incentives by issue linkage. Energy Policy 32, 455–465.
Lessmann, K., Edenhofer, O., 2011. Research cooperation and international standards in a model of coalition stability. Resour. Energy Econ. 33, 36–54.
Nagashima, M., Dellink, R., 2008. Technology spillovers and stability of international climate coalitions. Int. Environ. Agreem.: Politics Law Econ. 8, 343–365.
Nagashima, M., Weikard, H.-P., de Bruin, K., Dellink, R., 2011. International climate agreements under induced technological change. Metroeconomica 62, 612–634.
Ruis, A., de Zeeuw, A., 2010. International cooperation to combat climate change. Public Finance Manage. 10, 379–404.
Strand, J., 2007. Technology treaties and fossil-fuels extraction. Energy J. 28, 129–141.
Urpelainen, J., 2010. Enforcing international environmental cooperation: technological standards can help. Rev. Int. Organ. 5, 475–496.
Urpelainen, J., 2012. The strategic design of technology funds for climate cooperation: generating joint gains. Environ. Sci. Policy 15, 92–105.
van der Pol, T., Weikard, H.-P., van Ireland, E., 2012. Can altruism stabilise international climate agreements? Ecol. Econ. 81, 112–120.
Weikard, H-P., 2009. Cartel stability under an optimal sharing rule. Manch. School 77, 575–593.
Xepapadeas, A., 1995. Induced technical change and international agreements under greenhouse warming. Resour. Energy Econ. 17, 1–23.