NOTA DI LAVORO

41.2014

Sharing R&D Investments in Cleaner Technologies to Mitigate Climate Change

By **Abeer El-Sayed** and **Santiago J. Rubio**, Department of Economic Analysis and ERICES, University of Valencia, Spain

Climate Change and Sustainable Development
Series Editor: Carlo Carraro

Sharing R&D Investments in Cleaner Technologies to Mitigate Climate Change

By Abeer El-Sayed and Santiago J. Rubio, Department of Economic Analysis and ERICES, University of Valencia, Spain

Summary

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 and that 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 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 the coalition information exchange decreases until a minimum participation consisting of three countries is reached. We also find that the grand coalition is stable if the countries sign an international research joint venture but in this case the effectiveness of the agreement is very low.

Keywords: International Environmental Agreements, R&D Investment, Technology Spillovers, Coalition Information Exchange, Research Joint Ventures

JEL Classification: D74, F53, H41, Q54, Q55

We are grateful to Rafael Moner for his very useful comments. The authors acknowledge funding from the Ministerio de Ciencia e Innovación under grant ECO2010-21539.

Address for correspondence:

Santiago J. Rubio
Department of Economic Analysis
University of Valencia
Edificio Departamental Oriental
Avda. de los Naranjos s/n
46022 Valencia
Spain
E-mail: santiago.rubio@uv.es

Sharing R&D Investments in Cleaner Technologies to Mitigate Climate Change*

Abeer El-Sayed and Santiago J. Rubio†

Department of Economic Analysis and ERICES

University of Valencia, Spain

24 August 2013

*We are grateful to Rafael Moner for his very useful comments. The authors acknowledge funding from the *Ministerio de Ciencia e Innovación* under grant ECO2010-21539.

†Corresponding author: Department of Economic Analysis, University of Valencia, Edificio Departamental Oriental, Avda. de los Naranjos s/n, 46022 Valencia, Spain. E-mail address: santiago.rubio@uv.es

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 and that 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 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 the coalition information exchange decreases until that a minimum participation consisting of three countries is reached. We also find that the grand coalition is stable if the countries sign an international research joint venture but in this case the effectiveness of the agreement is very low.

Keywords: International environmental agreements; R&D investment; Technology spillovers; Coalition information exchange; Research joint ventures

JEL Classification System: D74, F53, H41, Q54, Q55

1 Introduction

Climate change is becoming an important issue in human lives. Due to the absence of a supra-national authority that can enforce environmental policies to control greenhouse gas (GHG) emissions on a global scale, countries have had to negotiate an international environmental agreement (IEA), the Kyoto Protocol, to address this problem. The aim of the Kyoto Protocol is to achieve a reduction in GHG emissions of 5% taking as reference the level of 1990 for countries of Annex B in the commitment period 2008-2012. However, there are many doubts about the possibilities of reaching the target of abating GHG emissions for that period. Limited coverage and moderate emission reductions requirements are two limitations that can reduce the effectiveness of the agreement. Moreover, there is increasing uncertainty about whether there will be any follow-up after 2012.

Because of the doubts about the effectiveness of an emission agreement as the Kyoto Protocol, several scholars have asked whether other types of agreements can be designed to achieve large reductions of GHG emissions. One idea would be to focus on technology 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 depends 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 to lower abatement costs, might yield a reduction in emissions. This is the argument behind the proposals of a climate agreement on technology development, see for instance, Buchner and Carraro (2004) and Barrett (2006).[1]

[1] There are several international proposals to promote climate-technology R&D, such as the Carbon Sequestration Leadership Forum (with 21 member countries plus the European Commission), the International Partnership for the Hydrogen Economy (17 countries plus the European Commission) and the ITER (International Thermonuclear Experimental Reactor) project, although the ITER project cannot see exclusively as a climate-technology R&D project. An overview of technology-oriented agreements stressing their potential role in addressing the free-riding incentives in climate negotiations can be found

The aim of the present 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 and assumes that when countries cooperate they coordinate their R&D activities so as to minimize the agreement costs of controlling emissions and 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.[2]

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

Our findings show that for the interior solution of the game, signatories invest more in R&D than non-signatories even if signatories fully internalize the spillover effects of their investments in R&D. The consequence is that the signatories' investment costs are larger than the non-signatories' investment costs and hence the total costs are also larger for

in de Coninck et al. (2008).

[2]The idea that the degree of spillovers is different among countries which cooperate than among countries which do not cooperate can be also found in Xepapadeas (1995) and Carraro and Siniscalco (1997). 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 perfect public good). Carraro and Siniscalco (1997) normalize to zero the spillover effects for non-signatories. The present paper assumes that spillover effects are positive for non-signatories and are fully internalized for signatories so that the level of technology becomes imperfect public good.

signatories. Moreover, there are *positive* externalities for non-signatories stemming from cooperation, i.e. cooperation decreases the total costs of non-signatories. Then, if one country abandons the grand coalition, its total costs decrease because the reduction in investment costs more than compensates the increment in environmental damages caused by the increase in global emissions, which makes the grand coalition unstable. Nevertheless, our analysis shows that the participation in an IEA increases as the spillover effects decrease although the membership upper bound is of six countries regardless of the number of countries involved in the environmental problem. Thus, spillover effects play against cooperation, but even with low spillover effects is not possible to achieve a stable agreement consisting of more than six countries. Notice that the lower the spillover effects the larger the asymmetry in terms of information exchange between signatories and non-signatories. In fact, when spillover effects increase 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 is not a sufficient condition to achieve a large membership in a technology agreement so that this type of agreement does not appear as a good alternative to international cooperation on GHG emission reductions. The problem is that the asymmetry 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 (imperfect) public good, the effective investment. To check this hypothesis we have studied an international research joint venture (IRJV) that only obliges signatories to share information. The result of our research is that the grand coalition is the unique IRJV regardless of the degree of spillovers and the number of countries involved in the environmental problem. Thus, sharing information plays for participation but cooperating in deciding the level of investment plays against participation and, in fact, practically eliminates all the positive effects of the coalition information exchange. Unfortunately, we can not neither to present an IRJV as an alternative to an emission agreement because its effectiveness is low. Sharing information stimulates participation but at the cost of getting a low percentage of the potential gains coming from cooperation.

Although the literature on IEAs is very extensive, only a few theoretical contributions have addressed the issue studied in the present paper. The first paper worth commenting on is Carraro and Siniscalco (1997). They employ a numerical example to show that one possible way of overcoming the free-rider incentive is to link the unstable emission agreement with information exchange on technology development. The timing of their model is as follows: first, the government decides whether or not to cooperate; then, given this decision, signatories impose cooperatively the emission target and an exogenously given degree of spillovers on firms, and non-signatories act in a non-cooperative way; finally, polluting firms decide simultaneously and non-cooperatively R&D investment and production. Each firm is assumed to be located in a different country and all firms are supposed to sell to in a non-competitive, single global market. An important feature of the model is that the firm's innovation effort affects both the economic and environmental technology. Thus, the technology agreement involves to share information about R&D investment that reduce emissions and production costs.

A second interesting paper to comment is Barrett (2006) that shows that breakthrough technologies cannot improve the performance of international environmental agreements with the exception of breakthrough technologies that exhibit increasing returns to scale.[3] Barrett (2006) studies a system of two treaties, one promoting R&D and the other encouraging cooperative adoption.[4] First, countries participate in a R&D investment treaty. In this first stage, each country decide to invest in R&D to develop new technology. In a second stage, countries decide whether or not to participate in a technology adoption agreement which implies the complete elimination of emissions. In a third stage, signatories decide collectively whether to adopt the new technology that is a public good. Finally, non-signatories decide individually whether to adopt the new technology. The

[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] 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.

model 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.[5] Our results also go in the same direction in the sense that our model yields a prediction on participation that converges, for large enough spillovers, to the standard result of the mitigation models with quadratic abatement costs and linear environmental damages: membership consists of three countries. Thus, in both cases a technology agreement does not seem a good alternative for solving the problem of the low participation in an emission agreement that predicts the theoretical models because in both cases the public good feature of investment in R&D yields an incentive to act as a free rider that reduces participation.

More recently, Hoel and de Zeeuw (2010) show that a focus on the R&D phase in the development of breakthrough technologies can change the result obtained by Barrett (2006). Assuming that the cost of adoption decreases with respect to the level of R&D, they find that even without increasing returns to scale, a technology agreement can yield better results than those obtained by focusing on abatement targets, although the first best cannot be achieved. This result is obtained when the non-cooperative equilibrium with full adoption exists and for a different timing of the game. Hoel and de Zeeuw (2010) assume that the agreement chooses R&D expenditures after the participation stage. Hong and Karp (2012) explore a similar idea but in the framework of the standard model of an IEA formation with linear payoff. The authors assume that the cost of abatement decreases with respect to the level of R&D. Moreover, they 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 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 assuming the timing proposed by Hoel and de Zeeuw (2010) and focusing on pure strategies at the participation stage.

[5] Ruis and de Zeeuw (2010) give support to this result in the framework of a model with quadratic investment costs.

The last theoretical paper we would like to comment is Battaglini and Harstad (2012). These authors derive optimistic results about the participation from a dynamic game with investment in green technologies. Their findings show that if a complete agreement on emissions and investments is signed, signatories eliminate the hold-up problem associated with their investments but in this case most countries prefer to free-ride rather than participate. However, if an incomplete agreement on emissions is signed, countries face a hold-up problem every time they negotiate but 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.[6]

Finally, we would like to point out that the results obtained from the empirical papers are not conclusive. On one hand, Buchner and Carraro (2004), Kemfert (2004) and Lesmann 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 into the agreement. However, Nagashima and Dellink (2008, 2011) obtain more pessimistic results. Nagashima and Dellink (2008) address the effects of asymmetric spillovers, that affect the marginal abatement cost curve, on the participation in an emission agreement. Their results show that spillovers do not substantially increase the success of IEAs. In their model the size of the spillovers depend on the state of technology that is exogenously given. More recently, Nagashima et al. (2011) have extended this analysis by relaxing the assumption of exogenous technological change, but do not consider knowledge spillovers. The results continue being pessimistic, stable coalitions are smaller when the gains from cooperation are large.

The paper is organized as follows. The next section specifies the model. In Section 3,

[6] 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 with different durations and taking also into account the possibility of renegotiations. Another contribution using dynamic games is Urpelainen (2010) although this author focuses on the compliance of an IEA. In particular, he studies whether technological standards can help to enforce an IEA.

the fully non-cooperative equilibrium is calculated and in Section 4 the efficient outcome. Section 5 presents the analysis of a R&D agreement and Section 6 the analysis of an international research joint venture. The conclusions drawn from this research are detailed in Section 7.

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, $i = 1,..,N$, depends on the amount invested in R&D in that country, x_i, to develop clean technologies and also 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

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

where $X_{-i} = \sum_{j \neq i} x_j$. Moreover, countries can reach larger technological spillovers by means of appropriate instruments such as technological cooperation. Cooperating countries can allow for patents 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 at 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

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

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

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

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. Following Carraro and Siniscalco (1997), $1 - \gamma$ can be defined as the "differential technological leakage" or the "coalition information exchange."[7]

In the absence of any explicit abatement activities, emissions in each country depend only on the technology level of the country. So, the business as usual emissions (BAU) for a level of effective investment equal to y_i is defined 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 each 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 over the 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 $R(x_i) = r x_i^2/2$, $r > 0$.[8]

[7] Carraro and Siniscalco (1997) also assume that the degree of innovation spillovers is larger among countries which cooperate than among countries which do not cooperate, although they assume that $\gamma_i = \gamma \in (0, 1)$ for signatories' investments and $\gamma_i = 0$ for non-signatories' investments. In this case, the coalition information exchange is given directly by γ, the degree of spillovers.

[8] 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

Finally, in each country environmental damages depend 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 Fully Non-Cooperative Equilibrium

The fully non-cooperative equilibrium can be calculated as the equilibrium of a two-stage game. In the first stage, countries decide the level of investment in R&D. In the second stage they decide about emissions. In both stages, the Nash equilibrium is calculated. Solving by backward induction, we begin analyzing the equilibrium of the second stage.

For a given technology, the optimal emissions can be calculated by minimizing the following total cost function

$$\min_{\{E_i \geq 0\}} TC_i = \frac{c}{2}(\delta - \alpha y_i - E_i)^2 + dE, \quad i = 1, ...N,$$

which yields for the representative country[9]

$$c(\delta - \alpha y_i - E_i) = d,$$

where the left-hand side represents marginal abatement costs and the right-hand side marginal damages. Observe that the marginal abatement costs decrease with the effective investment. Thus, the emissions level of the fully non-cooperative equilibrium is

$$E_i = \bar{\delta} - \alpha y_i. \tag{5}$$

Adding for the different countries, global emissions are obtained

$$E = \sum_{i=1}^{N} E_i = N\bar{\delta} - \alpha Y, \tag{6}$$

cooperation in R&D with spillovers in the context on an oligopoly with cost-reducing R&D opportunities. Golombek and Hoel (2005) in their study of climate policy under technology spillovers assume linear investment costs that corresponds to the alternative approach adopted by Kamien et al. (1992) for the analysis of cooperation in R&D with spillovers. Amir (2000) presents an extensive comparison of these two well-known R&D models.

[9] In order to simplify the notation, $\bar{\delta}$ stands for the difference $\delta - (d/c)$ that it is assumed positive.

where Y is the global effective investment in R&D.

$$Y = \sum_{i=1}^{N} y_i = \sum_{i=1}^{N} (x_i + \gamma X_{-i}). \tag{7}$$

Next, using (5) and (6), total costs can be written as

$$TC_i = \frac{d^2}{2c} + d(N\bar{\delta} - \alpha Y) + \frac{r}{2}x_i^2, \tag{8}$$

where the first term represents abatement costs, the second term stands for environmental damages and the third term for investment costs.

Now we calculate the equilibrium for the first stage of the game as follows

$$\min_{\{x_i \geq 0\}} TC_i = \frac{d^2}{2c} + d(N\bar{\delta} - \alpha Y) + \frac{r}{2}x_i^2, \quad i = 1, ..., N, \tag{9}$$

where Y is given by (7).

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 second stage of the game, countries have to decide which is the provision of a *public bad* whereas in the first stage they have to decide about the provision of a *imperfect public good* because of the spillovers.

The first-order condition for an *interior solution* is

$$\frac{\partial TC_i}{\partial x_i} = -d\alpha \frac{\partial Y}{\partial x_i} + r x_i = 0,$$

where $\partial Y / \partial x_i = 1 + \gamma(N-1)$, so that the following condition must be satisfied

$$d\alpha \left(1 + \gamma(N-1)\right) = r x_i, \tag{10}$$

where the left-hand side represents marginal revenue of investment while the right-hand side represents marginal cost. Notice that marginal revenue is equal to marginal damages, d, multiply by the decrease in global emissions caused by the increase in investment of the country, $\alpha \left(1 + \gamma(N-1)\right)$. This reduction depends positively on the degree of spillovers. Thus, the level of investment of the fully non-cooperative equilibrium is given by[10]

$$x_i^{nc} = \frac{\alpha d}{r}\left(1+\gamma\left(N-1\right)\right). \tag{11}$$

If we focus on the symmetric solution, the effective investment is

$$y_i^{nc} = x_i^{nc} + \gamma X_{-i}^{nc} = x_i^{nc} + \gamma(N-1)x_i^{nc} = x_i^{nc}(1+\gamma(N-1)),$$

that using (11) yields

$$y_i^{nc} = \frac{\alpha d}{r}\left(1+\gamma\left(N-1\right)\right)^2, \tag{12}$$

while global effective investment is given by

$$Y^{nc} = N y_i^{nc} = \frac{\alpha d N}{r}\left(1+\gamma\left(N-1\right)\right)^2. \tag{13}$$

Observe that effective investment increases with marginal damages and spillover effects. Finally, global emissions are now given by[11]

$$E^{nc} = N\bar{\delta} - \alpha Y^{nc} = N\bar{\delta} - \frac{\alpha^2 d N}{r}(1+\gamma(N-1))^2, \tag{14}$$

and the total costs by

$$TC_i^{nc} = \frac{d^2}{2c} + d\left(N\bar{\delta} - \frac{\alpha^2 dN}{r}(1+\gamma(N-1))^2\right) + \frac{\alpha^2 d^2}{2r}\left(1+\gamma\left(N-1\right)\right)^2,$$

where the first term represents abatement costs, the second term the environmental damages and the last term the investment costs. Simplifying this expression total costs can be written as

$$TC_i^{nc} = dN\delta - \frac{d^2\left(2N-1\right)}{2cr}\left(r+\alpha^2 c\left(1+\gamma\left(N-1\right)\right)^2\right). \tag{15}$$

[10]Because of the linearity of environmental damages, there exist for the two stages of the game a dominant strategy, i.e. optimal emissions and investment of one country are independent of the emissions and investment of the rest of countries.

[11]Notice that emissions are decreasing with respect to marginal damages. Thus, to guarantee an interior solution for the game, marginal damages must be lower than the upper bound defined implicitly by condition $E^{nc} = 0$.

4 The Efficient Solution

In order to characterize the efficient solution, the game is solved again in two stages, but on this occasion assuming that countries minimize global total costs in both stages. We begin analyzing the solution of the second stage. Given the technology, countries select emissions to minimize the global total costs

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

The *interior solution* to the optimization problem for the representative country is

$$c(\delta - \alpha y_i - E_i) = Nd,$$

where the left-hand side 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 benefits its action has on the rest of country being the benefit the reduction in damages caused by the abatement. Thus, the emissions level of the efficient solution is

$$E_i = \delta - \frac{Nd}{c} - \alpha y_i, \tag{16}$$

and global emissions are

$$E = \sum_{i=1}^{N} E_i = N\left(\delta - \frac{Nd}{c}\right) - \alpha Y, \tag{17}$$

where Y is global effective investment in R&D which is given by[12]

$$Y = \sum_{i=1}^{N} y_i = \sum_{i=1}^{N} (x_i + X_{-i}). \tag{18}$$

Using (16) and (17), total costs for the representative country can be written as

$$TC_i = \frac{d^2N^2}{2c} + d\left(N\left(\delta - \frac{Nd}{c}\right) - \alpha Y\right) + \frac{r}{2}x_i^2, \tag{19}$$

[12] We assume that when countries cooperate they pool their R&D investment so as to fully internalize spillover effects, i.e. $\gamma = 1$ for the efficient solution.

where the first term represents abatement costs, the second term stands for environmental damages and the third term for investment costs.

Next, in the first stage, countries select the level of investment to minimize the global total costs of controlling emissions that are given by the following expression

$$\begin{aligned} GTC &= \sum_{i=1}^{N} TC_i = \sum_{i=1}^{N} \left(\frac{d^2N^2}{2c} + d\left(N\left(\delta - \frac{Nd}{c}\right) - \alpha Y\right) + \frac{r}{2}x_i^2 \right) \\ &= \frac{d^2N^3}{2c} + Nd\left(N\left(\delta - \frac{Nd}{c}\right) - \alpha Y\right) + \frac{r}{2}\sum_{i=1}^{N} x_i^2. \end{aligned} \tag{20}$$

Now we calculate the equilibrium for the first stage as follows

$$\min_{\{x_1,..,x_N\}} GTC = \frac{d^2N^3}{2c} + Nd\left(N\left(\delta - \frac{Nd}{c}\right) - \alpha Y\right) + \frac{r}{2}\sum_{i=1}^{N} x_i^2, \tag{21}$$

where Y is given by (18).

The first-order condition for an *interior solution* is

$$\frac{\partial GTC}{\partial x_i} = -Nd\alpha\frac{\partial Y}{\partial x_i} + rx_i = 0,$$

where $\partial Y/\partial x_i = N$, because $\gamma = 1$ so that the following condition must be satisfied

$$\alpha dN^2 = rx_i, \tag{22}$$

where the left-hand side represents the marginal revenue of investment while the right-hand side represents the marginal cost. Observe that for the efficient solution, the marginal revenue of investment depends on global marginal damages, Nd, and the reduction in global emissions caused by the increase in investment of one country is given by αN. Thus, the level of investment of the efficient solution is given by

$$x_i^e = \frac{\alpha d}{r}N^2. \tag{23}$$

If we focus on the symmetric solution, the effective investment is

$$y_i^e = x_i^e + X_{-i}^e = Nx_i^e = \frac{\alpha d}{r}N^3, \tag{24}$$

while global effective investment is given by

$$Y^e = N y_i^e = \frac{\alpha d}{r} N^4. \tag{25}$$

Notice that investment increases with marginal damages.

Finally, the level of global emissions is now given by[13]

$$E^e = N\left(\delta - \frac{Nd}{c}\right) - \alpha Y^e = N\left(\delta - \frac{Nd}{c}\right) - \frac{\alpha^2 d}{r} N^4, \tag{26}$$

and the total costs by

$$TC_i^e = \frac{d^2 N^2}{2c} + d\left(N\left(\delta - \frac{Nd}{c}\right) - \frac{\alpha^2 d}{r} N^4\right) + \frac{\alpha^2 d^2}{2r} N^4,$$

where the first term represents abatement costs, the second term the environmental damages and the last term the investment costs. Simplifying this expression total costs of the efficient solution can be written as

$$TC_i^e = dN\delta - \frac{d^2 N^2}{2cr}(r + \alpha^2 c N^2). \tag{27}$$

Next, we compare the efficient outcome with the fully non-cooperative equilibrium. We begin comparing the effective investment using (12) and (24) that yields

$$\begin{aligned} y_i^e - y_i^{nc} &= \frac{\alpha d}{r} N^3 - \frac{\alpha d}{r}\left(1 + \gamma\left(N-1\right)\right)^2 \\ &= \frac{\alpha d}{r}\left(N^3 - \left(1 + \gamma\left(N-1\right)\right)^2\right). \end{aligned}$$

This difference is positive for γ in the interval $[0,1]$ since $(1+\gamma(N-1))^2$ is increasing in γ and its maximum value is N^2 for $\gamma = 1$. Clearly, lower than N^3.

Next, the level of emissions of the fully non-cooperative equilibrium given by (5) is compared with the level of emissions of the efficient solution given by (16)

$$\begin{aligned} E_i^{nc} - E_i^e &= \delta - \frac{d}{c} - \alpha y_i^{nc} - \delta + \frac{Nd}{c} + \alpha y_i^e \\ &= \frac{d}{c}\left(N-1\right) + \alpha\left(y_i^e - y_i^{nc}\right) > 0. \end{aligned}$$

[13] For the efficient solution emissions are also decreasing with respect to marginal damages. Thus, to guarantee an interior solution, marginal damages must be lower than the upper bound defined implicitly by condition $E^e = 0$. Comparing this condition with $E^{nc} = 0$, it is easy to show that the upper bound defined by $E^s = 0$ is lower than the upper bound defined by $E^{nc} = 0$.

Thus, emissions are larger in the fully non-cooperative equilibrium.

Finally, the total costs of the fully non-cooperative equilibrium given by (15) are compared with the total costs of the efficient solution given by (27).

$$TC_i^{nc} - TC_i^{e} = \frac{d^2}{2cr}\left(r\left(N-1\right)^2 + c\alpha^2\left(N^4 - \left(2N-1\right)\left(1+\gamma\left(N-1\right)\right)^2\right)\right). \tag{28}$$

This difference is positive for γ in the interval $[0,1]$ since $(2N-1)(1+\gamma(N-1))^2$ is increasing in γ and its maximum value is $N^2(2N-1)$ for $\gamma = 1$. Clearly, lower than N^4.

The results of comparison are summarized in the following proposition

Proposition 1 *The level of effective investment of the efficient solution is larger than the level of effective investment of the fully non-cooperative equilibrium, while the total costs and emissions are lower.*

Moreover, it is straightforward that the gains coming from cooperation decrease with respect to the degree of spillovers. In other words, the larger the differential technological leakage, the larger the distance between the fully non-cooperative equilibrium and the efficient solution.

5 A R&D Agreement

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

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, i.e. we assume that there is no cooperation as regards the selection of the level of emissions. At the second stage, the R&D investment game, signatory countries coordinate their R&D activities so as to minimize sum of agreement costs taking as given the R&D

investments of non-signatories. As we have just pointed out, the signature of a technology agreement implies that countries share their R&D investments so as to fully internalize the spillover effects, so that 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* 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. As usual the level of participation in the agreement is given by the stability conditions. Under open membership, any country is free to join the agreement if interested. Finally, we assume that the signing of the agreement is binding on signatories. They therefore acquire a commitment to stay and implement the agreement during the second stage of the game so that full compliance is achieved. The game finishes when the emissions subgame is over.

5.1 The Partial Agreement Nash Equilibrium of the Investment Game

In this section, we solve by backward induction stages two and three 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 are given by (8) except that now the global effective investment in R&D is given by

$$\begin{aligned} Y &= \sum_{i=1}^{N-n} y_i^f + \sum_{j=1}^{n} y_j^s = \sum_{i=1}^{N-n} (x_i^f + \gamma(X_{-i}^f + X^s)) + \sum_{j=1}^{n} (X^s + \gamma X^f) \\ &= \sum_{i=1}^{N-n} \left(x_i^f + \gamma \left(\sum_{l=1}^{N-n-1} x_l^f + \sum_{k=1}^{n} x_k^s \right) \right) + \sum_{j=1}^{n} \left(\sum_{k=1}^{n} x_k^s + \gamma \sum_{l=1}^{N-n} x_l^f \right). \end{aligned} \tag{29}$$

As non-signatories do not cooperate at this stage, the analysis of the non-signatories behavior is identical to that performed in the fully non-cooperative equilibrium except that Y is now defined by (29). Thus, for an *interior solution* the level of investment for non-signatories is given again by (11) that is independent of the number of signatories.

For signatories, the choice made by the countries can be represented by the optimization problem (21) except that now N must be substituted by n and Y is defined by (29).

The first-order condition for an *interior solution* is

$$\frac{\partial ATC}{\partial x_j^s} = -nd\alpha\frac{\partial Y}{\partial x_j^s} + rx_j^s = 0,$$

where ATC stands for total cost of the agreement and $\partial Y/\partial x_j^s = n + \gamma(N-n)$, so that the interior solution is defined by the following condition[14]

$$nd\alpha(n + \gamma(N-n)) = rx_j^s.$$

Comparing this condition with condition (22) that characterizes the optimal level of investment for the efficient solution, we can see that signatories internalize the external benefits of abatement but only for the countries that belong to the agreement, nd, instead of Nd as in the efficient solution. Moreover, if there is not full cooperation the decrease in global emissions, $\alpha(n+\gamma(N-n))$, caused by the increase in investment of one signatory is lower than in the efficient solution. Then, the signatories' investment is

$$x_j^s = \frac{\alpha dn}{r}(n + \gamma(N-n), \tag{30}$$

which is increasing with respect to the participation into the agreement. Moreover, if we compare the investment done by each type of country using (11) and (30), the following expression is obtained

$$x_j^s - x_i^f = \frac{\alpha d}{r}\left((1-\gamma)\left(n^2-1\right) + \gamma N(n-1)\right), \tag{31}$$

that is positive for $n \geq 2$ and $\gamma \in (0,1)$. Thus, signatories devote more resources for R&D than non-signatories for any level of participation.

[14] For $n = N$, this expression gives the level of investment corresponding to the efficient solution.

If we focus on the symmetric solution for each type of country, the effective investment of non-signatories is

$$\begin{aligned} y_i^f &= x_i^f + \gamma(X_{-i}^f + X^s) = (1+\gamma(N-n-1))\, x_i^f + \gamma n x_j^s \\ &= \frac{\alpha d}{r}\left((1+\gamma(N-n-1))(1+\gamma(N-1)) + \gamma n^2 (n+\gamma(N-n))\right), \end{aligned} \tag{32}$$

and the effective investment for the signatories

$$\begin{aligned} y_j^s &= X^s + \gamma X^f = n x_j^s + \gamma(N-n) x_i^f \\ &= \frac{\alpha d}{r}\left(n^2 (n+\gamma(N-n)) + \gamma(N-n)(1+\gamma(N-1))\right). \end{aligned} \tag{33}$$

Taking the first derivative of effective investment with respect to the number of signatories the following expressions are obtained

$$\begin{aligned} \frac{\partial y_i^f}{\partial n} &= \frac{\alpha\gamma d}{r}\left((1-\gamma)(3n^2-1) + \gamma N(2n-1)\right), \\ \frac{\partial y_j^s}{\partial n} &= \frac{\alpha d}{r}\left((1-\gamma)(3n^2-\gamma) + \gamma N(2n-\gamma)\right), \end{aligned}$$

that are positive for $n \geq 2$ and $\gamma \in (0,1)$. Thus, the effective investment of both signatories and non-signatories increases with the number of signatories.

Next, we compare the levels of effective investment obtaining that the difference between the signatories' effective investment and the non-signatories' effective investment is

$$y_j^s - y_i^f = (1-\gamma)\frac{\alpha d}{r}\left((1-\gamma)(n^3-1) + \gamma N(n^2-1)\right).$$

This difference is positive for $n \geq 2$ and $\gamma \in (0,1)$. Then, signatories's emissions are lower than non-signatories' emissions since the effective investment of signatories is larger than the effective investment of non-signatories and both signatories' emissions and non-signatories' emissions decrease when the participation increases.[15]

Finally, in order to calculate the total costs, we aggregate the effective investment of the different countries to obtain the global effective investment in R&D:

$$Y = (N-n)\, y_i^f + n y_j^s, \tag{34}$$

[15] Notice that as there is no cooperation for controlling emissions, emissions are given for (5) for both types of countries.

which yields after substituting y_i^f by (32) and y_j^s by (33)

$$Y = \frac{\alpha d}{r} \left((N-n) \left(1 + \gamma \left(N-1\right)\right)^2 + n^2 \left(n + \gamma \left(N-n\right)\right)^2 \right). \tag{35}$$

To evaluate the effect of cooperation on global effective investment, we take the first derivative of Y, given by (34), that yields

$$\frac{\partial Y}{\partial n} = -y_i^f + (N-n)\frac{\partial y_i^f}{\partial n} + y_j^s + n\frac{\partial y_i^f}{\partial n}.$$

This derivative is positive since cooperation increases effective investment both for the signatories and non-signatories and, as we have just showed, the signatories' effective investment is larger than the non-signatories' effective investment. Thus, global effective investment increases with the number of signatories.

Next, global emissions are calculated using global effective investment given by (35), resulting in

$$E = N\bar{\delta} - \alpha Y = N\bar{\delta} - \frac{\alpha^2 d}{r} \left((N-n) \left(1 + \gamma \left(N-1\right)\right)^2 + n^2 \left(n + \gamma \left(N-n\right)\right)^2 \right). \tag{36}$$

It is immediate to conclude that global emissions decrease as the international cooperation increases because global emissions are inversely related with global effective investment.

Now, substituting global effective investment given by (35) and investment given by (11) for non-signatories and by (30) for signatories in (8), the total costs for non-signatories and signatories are obtained

$$\begin{aligned} TC_i^f &= \frac{d^2}{2c} + d\left(N\bar{\delta} - \frac{\alpha^2 d}{r}\left((N-n)(1+\gamma(N-1))^2 + n^2(n+\gamma(N-n))^2 \right) \right) \\ &\quad + \frac{\alpha^2 d^2}{2r}(1+\gamma(N-1))^2, \end{aligned}$$

$$\begin{aligned} TC_j^s &= \frac{d^2}{2c} + d\left(N\bar{\delta} - \frac{\alpha^2 d}{r}\left((N-n)(1+\gamma(N-1))^2 + n^2(n+\gamma(N-n))^2 \right) \right) \\ &\quad + \frac{\alpha^2 d^2}{2r}n^2(n+\gamma(N-n))^2, \end{aligned}$$

where the first term represents abatement costs, the second term the environmental damages and the last term the investment costs. Simplifying theses expressions total cost can be written as

$$TC_i^f = \frac{d^2}{2c} + dN\bar{\delta} - \frac{\alpha^2 d^2}{2r}\left((2(N-n)-1)(1+\gamma(N-1))^2 + 2n^2(n+\gamma(N-n))^2\right), \quad (37)$$

$$TC_j^s = \frac{d^2}{2c} + dN\bar{\delta} - \frac{\alpha^2 d^2}{2r}\left(2(N-n)(1+\gamma(N-1))^2 + n^2(n+\gamma(N-n))^2\right). \quad (38)$$

The comparison of the total costs is immediate because we have established above that signatories invest more resources in R&D. Thus, as the abatement costs and environmental damages are the same, it is the difference in investment that explains the difference in the total costs. The signatories invest more and support a larger cost for controlling pollution. Moreover, there are *positive* externalities for non-signatories stemming from cooperation, i.e. cooperation decreases the total costs of 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.

The effect of cooperation on signatories' total costs is not so obvious since cooperation increases signatories' investment. To evaluate this effect we investigate which is the sign of the first derivative of total costs with respect to the number of signatories

$$\frac{\partial TC_j^s}{\partial n} = -\frac{\alpha^2 d^2}{r}\left(2(1-\gamma)n^3 + 3(1-\gamma)Nn^2 + \gamma^2 N^2 n - (1+\gamma(N-1))^2\right).$$

This derivative is positive for $n \geq 2$ and $\gamma \in (0,1)$. The derivative is increasing with respect to n for $n \geq 0$ and it is easy to check that takes a positive value for $n = 2$, then it will be positive for any level of cooperation equal to or larger than two countries.

Thus, the model presents the usual features of an IEA formation game that are summarized in the following proposition:

Proposition 2 *Signatories invest more and pollute less that non-signatories but signatories' total costs are larger than non-signatories' total costs. Moreover, cooperation is profitable for both signatories and non-signatories.*

5.2 The Nash Equilibrium of the Membership Game

In this section, we use stability conditions to 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.[16]

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

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 decisions. 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 decisions. 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 self-enforcing 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.[17] If N is lower than

[16] We avoid to use the term *self-enforcing* in the definition because as has been pointed out by McEvoy and Stranlund (2009) is a bit misleading. The concept refers to the stability of cooperative agreements, not to enforcing compliance with these agreements once they are signed. Nevertheless, we use this term in the rest of the paper but clearly understanding that it refers to the stability of the agreement not to the compliance of the agreement.

[17] 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

$\tilde{n}$, 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 there exists a self-enforcing technology agreement. The result is

Proposition 3 *The participation in an IEA increases as the coalition information exchange increases although the membership upper bound is of six countries regardless of the number of countries involved in the environmental problem.*

Proof. In order to prove this result, we write the auxiliary function $\Omega(n)$ using the expressions of the total costs (37) and (38)

$$\begin{aligned}\Omega(n) &= \frac{\alpha^2 d^2}{2r}\left((2(N-n+1)-1)(1+\gamma(N-1))^2 + 2(n-1)^2(n-1+\gamma(N-n+1))^2\right.\\ &\quad \left. -2(N-n)(1+\gamma(N-1))^2 - n^2(n+\gamma(N-n))^2\right),\end{aligned}$$

that after some manipulations can be written as

$$\begin{aligned}\Omega(n) &= \frac{\alpha^2 d^2}{2r}\left((1-\gamma)(n^3-8n^2+10n-4)(n+\gamma(N-n))\right.\\ &\quad \left. +\gamma N(n^2-4n+2)(n+\gamma(N-n)) + \ 2(n-1)^2(1-\gamma)^2 + (1+\gamma(N-1))^2\right).\end{aligned}$$

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 positive for all n. Thus, no agreement consisting of seven or more signatories is going to satisfy the internal stability condition. Next, we study the stability of a bilateral agreement. For $n = 2$, the difference in costs is

$$\Omega(2) = -\frac{\alpha^2 d^2}{2r}\left(\left(N^2 - 10N + 13\right)\gamma^2 + (10N - 26)\gamma + 13\right),$$

which is negative for $N \geq 9$. Thus, the internal stability condition is satisfied for any value of $\gamma \in (0, 1)$. In order to evaluate the external stability condition, we need to look at the sign of $\Omega(3)$:

$$\Omega(3) = \frac{2\alpha^2 d^2}{r}\left((5N-12)\gamma^2 - (5N-24)\gamma - 12\right).$$

as an equality.

This expression is negative for γ in the interval $(0,1)$ and $N \geq 9$.[18] Thus, as the external stability condition requires that $\Omega(3)$ be positive, a bilateral agreement cannot be stable. For an agreement with three countries, the internal stability condition is fulfilled for all γ because $\Omega(3)$ is negative as we have just seen. On the other hand, the external stability condition requires that

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

be positive. Doing $\Omega(4) = 0$, we obtain a critical value for γ in the interval $(0,1)$ defined by the positive root of this equation

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

such that if γ is larger than or equal to $\bar{\gamma}(N;4)$, the external stability condition is satisfied. Then, an agreement consisting of three countries is stable provided that γ is larger than or equal to $\bar{\gamma}(N;4)$. For an agreement with four countries, the internal stability condition is fulfilled if γ is lower than $\bar{\gamma}(N;4)$ because then $\Omega(4)$ is negative. Moreover, the external stability condition requires that

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

be positive. Doing now $\Omega(5) = 0$, we obtain a critical value for γ in the interval $(0,1)$ defined by the positive root of this equation

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

such that if γ is larger than or equal to $\bar{\gamma}(N;5)$, the external stability condition for an agreement consisting of four countries is satisfied. Then, the agreement is stable provided that $\bar{\gamma}(N;5)$ is lower than $\bar{\gamma}(N;4)$. It is not complicated to show that this is the case and therefore we can conclude that an agreement consisting of four countries is stable in the interval $[\bar{\gamma}(N;5), \bar{\gamma}(N;4)]$. For an agreement consisting of five countries the internal

[18] We do not investigate the stability of an IEA for $N \leq 8$ because the focus of the paper is on global environmental problems that involve a great number of countries.

stability condition is satisfied for all γ lower than or equal to $\bar{\gamma}(N;5)$ because then $\Omega(5)$ is negative. However, the external stability condition requires that

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

be positive. Doing $\Omega(6) = 0$, we obtain a critical value for γ in the interval $(0,1)$ defined by the positive root of this equation

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

such that if γ is larger than or equal to $\bar{\gamma}(N;6)$, the external stability condition for an agreement consisting of five countries is fulfilled. Then, as $\bar{\gamma}(N;6)$ is lower than $\bar{\gamma}(N;5)$ we can conclude that an agreement consisting of five countries is stable in the interval $[\bar{\gamma}(N;5), \bar{\gamma}(N;6)]$. Finally, an agreement consisting of six countries can be stable if γ is lower than or equal to $\bar{\gamma}(N;6)$ because the external stability condition is satisfied for all γ. Remember that $\Omega(n)$ is positive for all $n \geq 7$ regardless of the value of γ. ■

In order to illustrate this result, 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 $\gamma \in (0, 0.05]$ and 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 I shows the solution of the investment game for different values of participation. 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's investment and that this difference is increasing 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.

$\Rightarrow$ TABLE I $\Leftarrow$

In Table II 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, what explains the increment in participation is that the reduction in the spillover effects soften the variations in investments caused by the exit of one country from the agreement. Except for $n = \{9, 10\}$, when one country leaves the agreement the reduction in investment that it achieves 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 effects on global emissions. Except for $n = \{8, 9, 10\}$, when one country leaves the agreement the increase in global emissions that the exist causes when $\gamma = 0.025$ is lower than when $\gamma = 0.025$. Thus, when spillover effects are lower the incentive to act as a non-signatory is augmented because the increment in environmental damages is in this case smaller. But for an interior solution, marginal damages are low and the first incentive dominates the second yielding a larger level of participation. Thus, although the increase in environmental damages is lower when spillover effects are lower, the decrease in investment costs is also lower and the net effect, because of the low marginal damages, is that the exit from the agreement becomes unprofitable for a larger number of signatories.

$\Rightarrow$ TABLE II $\Leftarrow$

6 An International Research Joint Venture

In the previous section we have studied a technology agreement for which signatories select cooperatively their level of R&D investment and also pool their R&D efforts so as to fully internalize spillover effects creating a differential technological leakage with respect to non-signatories. Nevertheless, this type of agreement does not promote a big participation: regardless of the size of the differential technological leakage, membership cannot be larger than six countries. In this section, we want to isolate the effect of information exchange to have a clear idea of what is the responsibility of the cooperation in selecting R&D investments on the failure of participation studying an agreement that only obliges signatories to share information.

6.1 The Partial Agreement Nash Equilibrium of the Investment Game

As signatories do not cooperate at this stage, the analysis of the signatories behavior is identical to that performed in the fully non-cooperative equilibrium except that global effective investment is defined by (29) which implies that $\partial Y/\partial x_j^s = n + \gamma(N-n)$. Then the condition that characterizes the signatories' optimal investment in an international research joint venture (IRJV) is

$$d\alpha(n + \gamma(N-n)) = rx_j^s.$$

Comparing this condition with condition (10) that defines the optimal level of investment for the fully non-cooperative equilibrium, we can see that the difference is only in the effect that investment of signatories has on global emissions that in the previous condition is $\alpha(n + \gamma(N-n))$, an effect larger than in the fully non-cooperative equilibrium. Then, the signatories' investment is

$$x_j^s = \frac{\alpha d}{r}(n + \gamma(N-n)), \tag{39}$$

which is increasing with respect to the participation into the agreement. Moreover, if we compare the investment done by each type of country using (11) and (39), the following expression is obtained

$$x_j^s - x_i^f = \frac{\alpha d}{r}(1-\gamma)(n-1),$$

that is positive for $n \geq 2$ and $\gamma \in (0,1)$. Thus, signatories devote more resources for R&D than non-signatories for any level the participation and the difference increases with the differential technological leakage or coalition information exchange given by $1-\gamma$ and the membership. However, signatories' investment in an IRJV is lower than in a R&D agreement because each signatory does not take into account the external marginal revenue that its investment causes in the rest of signatories.

From this point the analysis of the investment game equilibrium follows step by step the analysis developed in Section 5.1 and leads to same type of results. For this reason, we omit it and summarize the results in the expressions of total costs that are used for the stability analysis

$$TC_i^f = \frac{d^2}{2c} + dN\bar{\delta} - \frac{\alpha^2 d^2}{2r}\left((2(N-n)-1)(1+\gamma(N-1))^2 + 2n(n+\gamma(N-n))^2\right), \quad (40)$$

$$TC_j^s = \frac{d^2}{2c} + dN\bar{\delta} - \frac{\alpha^2 d^2}{2r}\left(2(N-n)(1+\gamma(N-1))^2 + (2n-1)(n+\gamma(N-n))^2\right). \quad (41)$$

6.2 The Nash Equilibrium of the Membership Game

In this section, the stability analysis is performed to find out whether there exists a self-enforcing IRJV. The result of the research is

Proposition 4 *The grand coalition is the unique IRJV regardless of the level of coalition information exchange and the number of countries involved in the environmental problem.*

Proof. In order to prove this result, we write the auxiliary function $\Omega(n)$ using the expressions of the total costs given by (40) and (41)

$$\begin{aligned}\Omega(n) \;=\; & \frac{\alpha^2 d^2}{2r}\left((2(N-n+1)-1)(1+\gamma(N-1))^2 + 2(n-1)(n-1+\gamma(N-n+1))^2\right. \\ & \left. -2(N-n)(1+\gamma(N-1))^2 - (2n-1)(n+\gamma(N-n))^2\right),\end{aligned}$$

that after some manipulations yields

$$\Omega(n) = -\frac{\alpha^2 d^2}{2r}(1-\gamma)(n-1)((1-\gamma)(5n-1)+6\gamma N).$$

Thus $\Omega(n)$ is negative for all $n \geq 2$ and $\gamma \in (0,1)$. This implies that all the agreement satisfy the internal stability condition but, on the other hand, as it is explained in Section 5.2 this also means that all the agreements does not satisfy the external stability condition. Then the only stable IRJV consists of all countries because only the grand coalition is stable if the internal stability condition is fulfilled. ■

This result establishes that is only necessary a low degree of asymmetry in terms of information exchange to do stable the grand coalition. The stability appears in an IRJV basically because the signatories investment levels are closer to the fully non-cooperative equilibrium than in the R&D agreement which implies that the reduction in investment costs of an exit from the agreement do not compensate the increase in environmental damages. To better understand this argument we have recalculated the numerical example of Table II for an IRJV. The results appear in Table III.

$\Rightarrow$ TABLE III $\Leftarrow$

Comparing both tables it can be seen that for both types of agreements, the exit from the grand coalition implies an important reduction in investment for the country in percentage terms. Almost 99% in a R&D agreement and 88% in an IRJV but this difference in eleven percentage points, that in absolute values are 1.976 for an R&D agreement and 0.176 for an IRJV, is enough to do unprofitable the exit. Notice, that this occurs even for a small increase in global emissions. An exit from one country from the grand coalition increases global emissions in less than 1% for an IRJV and in more than 8% for a R&D agreement. However, an IRJV is stable with full participation and a R&D agreement is unstable. An exit increases the costs in one case and decreases them in the other case. Thus, what is explaining the stability of the grand coalition for an IRJV is the small effect that the reduction of investment has in investment costs and this occurs because the level of investment for signatories is closer to the fully non-cooperative equilibrium than when the countries coordinate its levels of investment. Thus, from this conclusion is inferred that the low participation in a R&D agreement as that studied in the previous section is explained by the free-rider incentives that appears in the provision of the global effective investment, a global public good. If countries coordinate their R&D investment to take into account their external positive effects, the difference in investment levels with respect to the fully non-cooperative equilibrium creates the incentive to act as a free-rider of the agreement that appears in the standard models of IEA formation.[19]

[19] Remember that the non-signatories' investment is independent of the number of signatories and equal to the investment corresponding to the fully non-cooperative equilibrium.

6.3 The effectiveness of an IRJV

Participation is a necessary condition for the successful of an IEA but it is not a sufficient condition. The successful of an IEA must be assessed in terms of the reduction in costs achieved by the agreement. As the "ideal" aim of an IEA should be to implement the efficient solution, the maximum reduction in costs that could be achieved by an agreement is given by (28), the difference in total costs between the fully non-cooperative equilibrium and the efficient solution. Then, the effectiveness of an IRJV can be evaluated as the percentage of this difference that is achieved by the agreement. Thus, the first step to get this evaluation is to calculate the reduction in total costs implemented by the agreement. Using (15) and (41) the difference in total costs can be written as

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

as expected the gains coming from cooperation increase with the differential technological leakage and the marginal damages.

Using this expression, the effectiveness of the agreement can be calculated dividing by (28) that yields

$$\begin{aligned} & \frac{TC_i^{nc} - TC_i^s(n=N)}{TC_i^{nc} - TC_i^e} \\ = \; & \frac{\alpha^2 c(2N-1)(N^2 - (1+\gamma(N-1))^2)}{r(N-1)^2 + \alpha^2 c(N^4 - (2N-1)(1+\gamma(N-1))^2)}. \end{aligned}$$

Then, the effectiveness can be measured using an index β implicitly defined as follows

$$\frac{TC_i^{nc} - TC_i^s(n=N)}{TC_i^{nc} - TC_i^e} - \frac{1}{\beta} = 0, \quad \text{with } \beta \geq 1 \tag{42}$$

so that the effectiveness is maximum if $\beta = 1$.

Developing this difference the following expression is obtained

$$\frac{\alpha^2 c(\beta(2N-1)N^2 - N^4 - (\beta-1)(2N-1)(1+\gamma(N-1))^2) - r(N-1)^2}{\beta(r(N-1)^2 + \alpha^2 c(N^4 - (2N-1)(1+\gamma(N-1))^2)}.$$

Thus, as the denominator is positive, a necessary condition to obtain a ratio equal to zero is $\beta(2N-1)N^2 - N^4 > 0$ that yields a threshold value for β equal to $N^2/(2N-1)$ that allows to conclude that

Proposition 5 *The effectiveness of an IRJV decreases with the number of countries involved in the environmental problem regardless of the marginal damages level and the coalition information exchange.*

The larger N, the larger β and the lower the gains coming from cooperation. For instance, with $N = 10$, the difference (42) can be zero only for values of β larger than 5.2 which means that the agreement can only achieve a reduction in total costs lower than 19% of the maximum reduction in total costs that could be reached through cooperation regardless of the level of marginal damages and the differential technological leakage. In fact, in the numerical example studied in this section the grand coalition only achieves 18,7% of the total gains coming from cooperation. For $N = 100$, the threshold value for β is 50.25 and the reduction in costs that the grand coalition can implement is lower than 2%. Thus, sharing information between signatories does the grand coalition stable but at the cost of a low effectiveness.

7 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 coalition information exchange decreases 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 (imperfect) public good practically eliminates the positive effects of the differential technological leakage on participation. On the other hand, we find that the grand coalition is stable if the countries sign an international research joint venture that only obliges signatories to share information but in this case the effectiveness of the agreement is very low. Summarizing, our analysis does not give reasons to think that technology agreements as those studied in this paper could be a good alternative to international cooperation in emission abatement.

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 what means that the focus has been on mitigation. However, the model admits corner solutions or in other words, it admits the possibility of GHG emissions being completely eliminated, that is, fossil fuels could be completely eliminated adopting a breakthrough technology. In our model emissions can become zero if a certain level of investment is reached. In this way, we would have a complete view of the possibilities that a R&D agreement has to promote more participation in 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 think of some kind of probabilistic model that implies that the investment in R&D can fail in bringing a cleaner technology.

References

[1] Amir, Rabah (2000). "Modelling Imperfectly Appropriable R&D via Spillovers." *International Journal of Industrial Organization*, 18, 1013-1032.

[2] Barrett, Scott (2006). "Climate Treaties and "Breakthrough" Technologies." *American Economic Review*, 96, 22-25.

[3] Barrett, Scott (2009). "The Coming Global Climate-Technology Revolution." *Journal of Economic Perspectives*, 23, 53-75.

[4] Battaglini, Marco and Bård Harstad (2012). "Participation and Duration of Environmental Agreements." *NBER Working Paper 18585.*

[5] Buchner, Barbara and Carlo Carraro (2004). "Economic and Environmental Effectiveness of a Technology-Based Climate Protocol." *Climate Policy*, 4, 229-248.

[6] Carraro, Carlo and Domenico Siniscalco (1997). "R&D Cooperation and the Stability of International Environmental Agreements." In *International Environmental Negotiations: Strategic Policy Issues,* edited by Carlo Carraro. Edward Elgar Publishing.

[7] Chander, Parkash and Henry Tulkens (1995). "A Core-Theoretic Solution for the Design of Cooperative Agreements on Transfrontier Pollution." *International Tax and Public Finance*, 2, 279-294.

[8] d'Aspremont, Claude and Alexis Jacquemin (1988). "Cooperative and Noncooperative R&D in Duopoly with Spillovers." *American Economic Review,* 78, 1133-1137.

[9] d'Aspremont, Claude and Alexis Jacquemin (1990). "Cooperative and Noncooperative R&D in Duopoly with Spillovers: Erratum" *American Economic Review,* 80, 641-642.

[10] d'Aspremont, C.A., Jacqemin, J., Gadszeweiz, J., and Weymark, J.A.(1983). "On the Stability of Collusive Price Leadership." *Canadian Journal of Economics,* 16, 17- 25.

[11] de Coninck, Heleen, Carolyn Fischer, Richard G. Newell and Takahiro Ueno (2008). "International Technology-Oriented Agreements to Address Climate Change." *Energy Policy*, 36, 335-356.

[12] Golombek, Rolf and Michael Hoel (2005). "Climate Policy under Technology Spillovers." *Environmental and Resource Economics*, 31, 201-227.

[13] Harstad, Bård (2012). "Climate Contracts: A Game of Emissions, Investments, Negotiations, and Renegotiations." *Review of Economic Studies*, 79, 1527-1557.

[14] Heal, Geoffrey and Nori Tarui (2010). "Investment and Emission Control under Technology and Pollution Externalities." *Resource and Energy Economics*, 32, 1-14.

[15] Hoel, Michael and Aart de Zeeuw (2010). "Can a Focus on Breakthrough Technologies Improve the Performance of International Environmental Agreements?" *Environmental and Resource Economics*, 47, 395-406.

[16] Hong, Fuhai and Larry Karp (2012). "International Environmental Agreements with Mixed Strategies and Investment." *Journal of Public Economics*, 96, 685-697.

[17] Hübler, Michael and Michael Finus (2013). "Is the Risk of North-South Technology Transfer Failure an Obstacle to a Cooperative Climate Change Agreement?" *International Environmental Agreements: Politics, Law and Economics,* forthcoming. DOI 10.1007/s10784-013-9208-3.

[18] Kamien, Morton I., Eitan Muller and Israel Zang (1992). "Research Joint Ventures and R&D Cartels." *American Economic Review*, 82, 1293-1306.

[19] Kemfert, Claudia (2004). "Climate Coalitions and International Trade: Assessment of Cooperation Incentives by Issue Linkage." *Energy Policy*, 32, 455-465.

[20] Lessmann, Kai and Ottmar Edenhofer (2011). "Research Cooperation and International Standards in a Model of Coalition Stability." *Resource and Energy Economics*, 33, 36-54.

[21] McEvoy, David M. and John K. Stranlund (2009). "Self-Enforcing International Environmental Agreements with Costly Monitoring for Compliance." *Environmental and Resource Economics*, 42, 491-508.

[22] Nagashima, Miyuki and Rob Dellink (2008). "Technology Spillovers and Stability of International Climate Coalitions." *International Environmental Agreements: Politics, Law and Economics,* 8, 343-365.

[23] Nagashima, Miyuki, Hans-Peter Weikard, Kelly de Bruin and Rob Dellink (2011). "International Climate Agreements under Induced Technological Change." *Metroeconomica*, 62, 612-634.

[24] Ruis, Arjan and Aart de Zeeuw (2010). "International Cooperation to Combat Climate Change." *Public Finance and Management*, 10, 379-404.

[25] Strand, Jon (2007). "Technology Treaties and Fossil-Fuels Extraction." *Energy Journal*, 28, 129-141.

[26] Urpelainen, Johannes (2010). "Enforcing International Environmental Cooperation: Technological Standards Can Help." *Review of International Organizations*, 5, 475-496.

[27] Urpelainen, Johannes (2012). "The Strategic Design of Technology Funds for Climate Cooperation: Generating Joint Gains." *Environmental Science & Policy*, 15, 92-105.

[28] Xepapadeas, A. (1995). "Induced Technical Change and International Agreements under Greenhouse Warming." *Resource and Energy Economics*, 17, 1-23.

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

α=1, δ=100, c=0.75, d=0.01, r=0.5, N=10

Table I. Numerical example 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	0.024		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

α=1, δ=100, c=0.75, d=0.01, r=0.5, N=10

Table II. Numerical example with $\gamma = 0.025$

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	0.044	0.031	0.093	999.44	9.9946	9.9948
3	0.024	0.063	0.033	0.195	999. 06	9.9908	9.9916
4	0.024	0.083	0.036	0.337	998.31	9.9833	9.9848
5	0.024	0.102	0.040	0.515	997.09	9.9711	9.9736
6	0.024	0.122	0.045	0.734	995.28	9.9530	9.9566
7	0.024	0.141	0.050	0.992	992.77	9.9279	9.9327
8	0.024	0.161	0.057	1.289	989.44	9.8946	9.9009
9	0.024	0.180	0.065	1.625	985.18	9.8520	9.8599
▶ 10		0.200		2.000	979.87		9.8087

α=1, δ=100, c=0.75, d=0.01, r=0.5, N=10

TABLE III. Numerical example with $\gamma = 0.025$.

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:
http://www.feem.it/getpage.aspx?id=73&sez=Publications&padre=20&tab=1
http://papers.ssrn.com/sol3/JELJOUR_Results.cfm?form_name=journalbrowse&journal_id=266659
http://ideas.repec.org/s/fem/femwpa.html
http://www.econis.eu/LNG=EN/FAM?PPN=505954494
http://ageconsearch.umn.edu/handle/35978
http://www.bepress.com/feem/

NOTE DI LAVORO PUBLISHED IN 2014

CCSD	1.2014	Erin Baker, Valentina Bosetti, Karen E. Jenni and Elena Claire Ricci: Facing the Experts: Survey Mode and Expert Elicitation
ERM	2.2014	Simone Tagliapietra: Turkey as a Regional Natural Gas Hub: Myth or Reality? An Analysis of the Regional Gas Market Outlook, beyond the Mainstream Rhetoric
ERM	3.2014	Eva Schmid and Brigitte Knopf: Quantifying the Long-Term Economic Benefits of European Electricity System Integration
CCSD	4.2014	Gabriele Standardi, Francesco Bosello and Fabio Eboli: A Sub-national CGE Model for Italy
CCSD	5.2014	Kai Lessmann, Ulrike Kornek, Valentina Bosetti, Rob Dellink, Johannes Emmerling, Johan Eyckmans, Miyuki Nagashima, Hans-Peter Weikard and Zili Yang: The Stability and Effectiveness of Climate Coalitions: A Comparative Analysis of Multiple Integrated Assessment Models
CCSD	6.2014	Sergio Currarini, Carmen Marchiori and Alessandro Tavoni: Network Economics and the Environment: Insights and Perspectives
CCSD	7.2014	Matthew Ranson and Robert N. Stavins: Linkage of Greenhouse Gas Emissions Trading Systems: Learning from Experience
CCSD	8.2013	Efthymia Kyriakopoulou and Anastasios Xepapadeas: Spatial Policies and Land Use Patterns: Optimal and Market Allocations
CCSD	9.2013	Can Wang, Jie Lin, Wenjia Cai and ZhongXiang Zhang: Policies and Practices of Low Carbon City Development in China
ES	10.2014	Nicola Genovese and Maria Grazia La Spada: Trust as a Key Variable of Sustainable Development and Public Happiness: A Historical and Theoretical Example Regarding the Creation of Money
ERM	11.2014	Ujjayant Chakravorty, Martino Pelli and Beyza Ural Marchand: Does the Quality of Electricity Matter? Evidence from Rural India
ES	12.2014	Roberto Antonietti: From Outsourcing to Productivity, Passing Through Training: Microeconometric Evidence from Italy
CCSD	13.2014	Jussi Lintunen and Jussi Uusivuori: On The Economics of Forest Carbon: Renewable and Carbon Neutral But Not Emission Free
CCSD	14.2014	Brigitte Knopf, Bjørn Bakken, Samuel Carrara, Amit Kanudia, Ilkka Keppo, Tiina Koljonen, Silvana Mima, Eva Schmid and Detlef van Vuuren: Transforming the European Energy System: Member States' Prospects Within the EU Framework
CCSD	15.2014	Brigitte Knopf, Yen-Heng Henry Chen, Enrica De Cian, Hannah Förster, Amit Kanudia, Ioanna Karkatsouli, Ilkka Keppo, Tiina Koljonen, Katja Schumacher and Detlef van Vuuren: Beyond 2020 - Strategies and Costs for Transforming the European Energy System
CCSD	16.2014	Anna Alberini, Markus Bareit and Massimo Filippini: Does the Swiss Car Market Reward Fuel Efficient Cars? Evidence from Hedonic Pricing Regressions, a Regression Discontinuity Design, and Matching
ES	17.2014	Cristina Bernini and Maria Francesca Cracolici: Is Participation in Tourism Market an Opportunity for Everyone? Some Evidence from Italy
ERM	18.2014	Wei Jin and ZhongXiang Zhang: Explaining the Slow Pace of Energy Technological Innovation: Why Market Conditions Matter?
CCSD	19.2014	Salvador Barrios and J. Nicolás Ibañez: Time is of the Essence: Adaptation of Tourism Demand to Climate Change in Europe
CCSD	20.2014	Salvador Barrios and J. Nicolás Ibañez Rivas: Climate Amenities and Adaptation to Climate Change: A Hedonic-Travel Cost Approach for Europe
ERM	21.2014	Andrea Bastianin, Marzio Galeotti and Matteo Manera: Forecasting the Oil-gasoline Price Relationship: Should We Care about the Rockets and the Feathers?
ES	22.2014	Marco Di Cintio and Emanuele Grassi: Wage Incentive Profiles in Dual Labor Markets
CCSD	23.2014	Luca Di Corato and Sebastian Hess: Farmland Investments in Africa: What's the Deal?
CCSD	24.2014	Olivier Beaumais, Anne Briand, Katrin Millock and Céline Nauges: What are Households Willing to Pay for Better Tap Water Quality? A Cross-Country Valuation Study
CCSD	25.2014	Gabriele Standardi, Federico Perali and Luca Pieroni: World Tariff Liberalization in Agriculture: An Assessment Following a Global CGE Trade Model for EU15 Regions
ERM	26.2014	Marie-Laure Nauleau: Free-Riding in Tax Credits For Home Insulation in France: An Econometric Assessment Using Panel Data

CCSD	27.2014	Hannah Förster, Katja Schumacher, Enrica De Cian, Michael Hübler, Ilkka Keppo, Silvana Mima and Ronald D. Sands: European Energy Efficiency and Decarbonization Strategies Beyond 2030 – A Sectoral Multi-model Decomposition
CCSD	28.2014	Katherine Calvin, Shonali Pachauri, Enrica De Cian and Ioanna Mouratiadou: The Effect of African Growth on Future Global Energy, Emissions, and Regional Development
CCSD	29.2014	Aleh Cherp, Jessica Jewell, Vadim Vinichenko, Nico Bauer and Enrica De Cian: Global Energy Security under Different Climate Policies, GDP Growth Rates and Fossil Resource Availabilities
CCSD	30.2014	Enrica De Cian, Ilkka Keppo, Johannes Bollen, Samuel Carrara, Hannah Förster, Michael Hübler, Amit Kanudia, Sergey Paltsev, Ronald Sands and Katja Schumacher: European-Led Climate Policy Versus Global Mitigation Action. Implications on Trade, Technology, and Energy
ERM	31.2014	Simone Tagliapietra: Iran after the (Potential) Nuclear Deal: What's Next for the Country's Natural Gas Market?
CCSD	32.2014	Mads Greaker, Michael Hoel and Knut Einar Rosendahl: Does a Renewable Fuel Standard for Biofuels Reduce Climate Costs?
CCSD	33.2014	Edilio Valentini and Paolo Vitale: Optimal Climate Policy for a Pessimistic Social Planner
ES	34.2014	Cristina Cattaneo: Which Factors Explain the Rising Ethnic Heterogeneity in Italy? An Empirical Analysis at Province Level
CCSD	35.2014	Yasunori Ouchida and Daisaku Goto: Environmental Research Joint Ventures and Time-Consistent Emission Tax
CCSD	36.2014	Jaime de Melo and Mariana Vijil: Barriers to Trade in Environmental Goods and Environmental Services: How Important Are They? How Much Progress at Reducing Them?
CCSD	37.2014	Ryo Horii and Masako Ikefuji: Environment and Growth
CCSD	38.2014	Francesco Bosello, Lorenza Campagnolo, Fabio Eboli and Ramiro Parrado: Energy from Waste: Generation Potential and Mitigation Opportunity
ERM	39.2014	Lion Hirth, Falko Ueckerdt and Ottmar Edenhofer: Why Wind Is Not Coal: On the Economics of Electricity
CCSD	40.2014	Wei Jin and ZhongXiang Zhang: On the Mechanism of International Technology Diffusion for Energy Productivity Growth
CCSD	41.2014	Abeer El-Sayed and Santiago J. Rubio: Sharing R&D Investments in Cleaner Technologies to Mitigate Climate Change