Externalities, leakage and technological spillovers:
How much can the OECD coalition do for the climate?

Valentina Bosetti, Enrica De Cian, Emanuele Massetti, and Massimo Tavoni

This draft: June 2010

Abstract

Stable coalitions are generally modestly effective in addressing the environmental externality and frequently only sub-global or partial agreements can be sustained. Very much in line with theoretical results, climate negotiations have reached an *impasse* and only OECD countries appear to agree on a common target, which could give rise to a partial agreement, at least temporary.

The environmental effectiveness of a partial climate coalition depends on the emissions of both coalition members and non-signatories. The optimal reaction of non-signatory countries is driven by two major forces. Free-riding on reduced damage and decreased fossil fuel costs derived by cooperation might lead to an increase in emissions in non-cooperating countries compared to the noncooperative equilibrium. Innovations in carbon-free alternatives, induced by the coalition effort, might spillover to non-signatories and exert a positive effect on emission reductions. The type of reaction of non-signatory countries has a major role in shaping the incentives of signatory countries to remain in the coalition and in defining whether a partial agreement can be, at least temporary, environmentally successful.

Using an game-theoretic calibrated model we analyse the interplay of these competing effects when a partial agreements between OECD countries is formed. We show that when the OECD coalition reduces emissions between 30 and 35% below 2005 levels, the technology effect is sufficiently strong to lead non-signatory countries to reduce their emission below non-cooperative levels. Strengthening the target to be pursued by the OECD coalition, in the range of 40-55% below their 2005 levels, tends to reinforce the leakage effect. In this case non-signatories would erode the coalition environmental efficacy. Results hold if lower damages are considered and if long-term foresight is not the basis of policy maker's decision process.

Key words: Technology Spillovers, climate change, partial cooperation

Address for correspondence:
Enrica De Cian (enrica.decian@feem.it)
Fondazione ENI Enrico Mattei Isola di San Giorgio, 30124
Venice, Italy

1. Introduction

Stable coalitions are generally small and unable to address satisfactorily the environmental problem they are expected to address, especially when dealing with a global externality, such as climate change. This is a well documented result in the literature, in particular within the non-cooperative theory of coalition formation (see among others D’Aspremont *et al.* 1983, D’Aspremont and Gabszewicz 1986, Carraro and Siniscalco 1993, Hoel 1992, Barrett 1992).

On the one hand, the reduction of emissions by the coalition might be insufficient compared to the global discharge of the pollutant. On the other hand, the optimal reaction of non-signatory countries might imply higher emissions compared to the noncooperative case in which no coalition is formed, thus partially offsetting coalition’s effort.

The reaction of non-signatory countries shapes the incentives of signatory countries to remain in and determines the environmental effectiveness of the coalition. A simplified approach often used in the literature assumes that players outside the coalition behave in the least-favourable manner (Maler, 1989). However, this does not guarantee that the choice to is optimal for players which are outside the coalition and members might know that non-signatories do not it find profitable to behave in an extreme fashion. These shortcomings have motivated Chander and Tulkens (1997) to define a type of response in which non-signatory counterparts respond optimally to the equilibrium choice of the coalition. This implies that the solution of the emission game is a Nash equilibrium in which coalition members play their best response to non-members, which individually adopt their best reply strategy. This is also the assumption shared by the experiments presented in the present paper.

What is the reaction of non-signatory becomes more complicated if cooperation can have external effects on non-signatories. In this context, describing the actual response of non-members to a coalition’s strategies implies accounting for different, potentially opposing effects.

Climate change damages are due to global temperature increase, which does not depend on the geographic location of the polluting source. When damage is a function of the total level of emissions, countries have incentive to free ride (Hoel 1991). Each country chooses the level of emissions that equalises marginal benefits and total marginal damages. Emission reduction in one region lowers the damage perceived in all countries, inducing an upward adjustment of the optimal emission strategy in each region. This is named “damage effect”. The resulting incentive to free ride is likely to lead to carbon leakage, an increase in emissions outside the coalition.

Carbon leakage can be due to other effects as well. A first mechanism is the existence of integrated energy markets (Hoel 1991, Hoel 1994, Bohm 1993). Unilateral or partial action would reduce the use of fossil fuels, lowering their prices on the international market. This gives noncooperating countries an incentive to increase demand, with positive effects on emissions. This effect is referred to as “energy market effect”. A second channel of transmission is international trade of energy-intensive goods. A partial climate policy tends to reduce competitiveness of these industries, whose production is reallocated in noncooperating countries. In the literature this effect is known as either “pollution haven hypothesis” or as “terms-of-trade effect”. How do these two channels finally determine the rate of carbon leakage depends on the structure of energy markets, energy supply and international trade elasticities, and substitution possibilities in final production. Burnieaux and Oliveira Martins (2000) performed a sensitivity analysis to each of these factors and concluded that the energy market channel is the most relevant. Several studies estimated the rate of carbon leakage of the Kyoto Protocol using numerical models. They found a very wide range of possible values, going from very low estimates such as 2-6% obtained with the OECD GREEN model, the MIT-EPPA model, or the G-Cubed model (for a review see Burniaux and Oliveira Martins, 2000) to larger estimates such as 40% in Light (2000). Babiker (2005) even found a leakage rate of 130%.

When the transmission of technology between signatory and non-signatory countries is considered. carbon leakage might also have the opposite sign. The virtuous behaviour of coalition’s members might spur the diffusion of cleaner technologies worldwide, lowering emissions in noncooperating countries as well. This is known as “international technology spillovers effect”.

When technological change is endogenous, climate policy has an induced effect on technology innovation and deployment that can mitigate, and in some cases offset, the carbon leakage effect. Golombek and Hoel (2004) studied the effect of international spillovers of abatement technology on leakage, using a static, partial equilibrium model of transboundary pollution with two-country and one-good. In each country a central planner chooses research and development (R&D) expenditures and abatement levels. The costs of the abatement technology depend on both domestic and foreign R&D. In this setting there are cases where a stronger environmental policy in one country might lead to lower emissions also in the other country and thus globally. Results depend on a set of assumptions on country symmetry, the shape of the technology spillovers function, the shape of the damage function, and the level of expenditure on R&D.

Gerlagh and Kuik (2007) developed a formal model of carbon leakage with endogenous energy-saving technical change and international spillovers and derive a reduced-form equation for the rate of carbon leakage. They showed that carbon leakage decreases in the presence of international technology spillovers and that the leakage rate can indeed become negative. Using a CGE model they estimated the rate of carbon leakage of the Kyoto Protocol. Even for moderate levels of technological spillover, carbon leakage can become negative.

Van der Werf and Di Maria (2008), using a stylized model, showed that the presence of directed technical change reduces the rate of carbon leakage. They considered a two country model producing a labour-intensive good and energy. Abatement policies induce a change in prices that stimulates fossil fuel consumption and leads non-abating countries to increase production of energy-intensive goods. At the same time, price changes modify the incentive to innovate, varying the level and the direction of technological change. The paper shows that, even if international technology spillovers are not considered, the induced-technical change effect tends to lower carbon leakage. However, when technical change is directed to develop and deploy zero-carbon alternatives to fossil fuels, there are interactions that may eventually counteract the positive effect of technical change on emissions (Hoel 2009). Whether the zero-carbon option is adopted depends on the relative price of fossil fuels compared to the low-carbon alternative. In turn, this relative price depends on the level of abatement, the resource scarcity, the strength of technology spillovers, and the price elasticity of energy demand.

The existence of numerous channels of interaction linking non-members' reaction to members' effort implies that assessing the environmental effectiveness of partial agreements needs considering all these competing effects. The present paper contributes to this literature by evaluating the consequences of partial cooperation. In particular, it investigates the relative magnitude of the three mechanisms outlined above, the damage effect, the energy market effect, and the technology effect. Because estimating the final outcome of the interplay between these multiple externalities is an empirical question, we use a calibrated, game-theoretic model. The WITCH model is a suitable tool for this purpose because it has a game-theoretic set-up, fossil fuel prices are endogenously influenced by the global use of exhaustible resources, and endogenous technical change accounts for both knowledge and experience international spillovers.

We explore partial cooperation between OECD countries, a coalition that is interesting under several respects. First, in the short-run it is the largest coalition on climate change that is likely to materialise and to share a cap-and-trade scheme. In developing countries' view, it is also the minimum requirement for any larger coalition because countries such as China and India make their effort conditional on that of the industrialised world. Third, it represents the technology frontier and it includes the leading innovators. Therefore, it might be the "right" starting coalition, both in size and composition. It could lead the technological transition towards lower carbon development pathways and it could be the minimum condition to dynamically broaden the number of cooperating countries.

Results indicate that when the OECD coalition reduces emissions between 30 and 35% below 2005 levels, carbon leakage is actually negative. The technology effect is sufficiently strong to counteract the free riding incentive due to reduced damage and energy prices. Comparison of international spillovers of knowledge and technology suggests that the latter effects is more effective at fostering the diffusion of carbon-free alternatives outside the coalition, pointing to the importance of policies that promote technology diffusion. Strengthening the emission reduction effort in the range of 40-55% below 2005 levels actually reduces the overall environmental effectiveness of the coalition because carbon leakage becomes positive and free riding incentives prevail. In this case, non-signatories' behaviour would erode the coalition environmental efficacy.

The remainder of the paper is organised as follows. Section 2 describes the model and the incentive structure of different regions. Section 3 illustrates the interplay of the three different effects in the case of partial cooperation between OECD countries. Different levels of emission reduction by OECD countries are considered and sensitivity analysis to damages and discount rates is also presented. A discussion of results and their policy implications concludes the paper in Section 4.

2. Carbon leakage and international technology spillovers: framing the issue using the WITCH model

WITCH (Bosetti et al. 2006, Bosetti et al 2007, Bosetti et al. 2009) is a dynamic optimal growth model fully integrated with a bottom-up structure of the energy sector. The model has a game-theoretic set-up which makes it possible to capture the noncooperative nature of international relationships. Climate change is the major global externality, but other economic externalities induce free-riding behaviours and strategic interactions.

The WITCH model includes a carbon cycle and climate module that describe the international and intertemporal dimension of GHG emissions. Long-lived greenhouse gases become perfectly mixed with other gases in the world atmosphere. No matter where the initial source of emission is located, GHG emission will eventually affect global mean temperature, and thus climate. Long-lived GHGs remain in the atmosphere from decades to centuries. As a consequence, emissions from any source, anywhere in the world, give rise to a global negative externality that will have impacts all over the world with a geographic distribution that does not depend on polluters location. Climate change impacts can be either positive or negative, depending on regional vulnerability and geographic location. For each region *i*, climate change damage is a reduce-form function of global average temperature increase above pre-industrial levels, which ultimately depends on global emissions (*E*):

$$\begin{aligned} &D_i = d_i(E) \\ &E = e_1 + e_2 + \ldots + e_n \qquad (1) \\ &\frac{\partial d_i(E)}{\partial E} >\leq 0 \end{aligned}$$

Technological advances within the energy sector are endogenous processes driven by innovation and deployment. R&D investments can lead to incremental innovations that advance the performance of exiting technologies, leading for example to improved energy efficiency. They can also result into radical innovations that lead to the introduction and diffusion of brand new, breakthrough technologies.

Both innovation and diffusion are characterised by international spillover. In each country, the process of innovation can be influenced not only by domestic investments in R&D, but also by the domestic and foreign stock of knowledge, an important supply-side determinant of innovation (Schmookler 1966). International knowledge spillovers can be modelled by assuming a simplified relationship between the stock of energy knowledge in each country (H_i) and R&D investments in all model's regions (I):

$$
\begin{aligned}
&H_i = h_i(I) \\
&I = i_1 + i_2 + \ldots + i_n \qquad (3) \\
&\frac{\partial h_i(I)}{\partial I} > 0
\end{aligned}
$$

The effect of foreign knowledge is not automatic, but it depends on absorptive capacity and the distance from the technology frontier, which consist of high income countries (United States, Western Europe, Eastern Europe, Korea-South Africa and Australia, and Canada-Japan-New Zealand).

Once a technology is made available by sufficient R&D investments, the technology is deployed and, over time, it diffuses also outside the group of innovating countries. This is the effect of international experience (or technology) spillovers. What drives the international diffusion is a Learning-By-Doing effect that, over time, reduces the costs of using the technology in all countries. This process makes the technology available to an increasing number of countries that did not have the sufficient inventive capacity to develop those technologies themselves. Indeed, technology adoption does not depend on the level the domestic innovation effort, as in the case of knowledge spillovers. The effect of international technology diffusion characterise not only new, breakthrough technologies, but also options that are already mature but not yet deployed on a vast scale, such as wind and solar power. Whereas breakthrough technologies have not been invented yet and therefore it is reasonable to assume that their costs depends on both innovation and diffusion, technologies such as wind and solar power already exist. In this case, deployment is the main mechanism that drives down costs. To capture both effects, regional investment costs of abatement technologies (C_i)

decline with the global investments in innovation (*I*) and global installed capacity (*CAP)*. For already mature technologies the marginal effect of innovation (*I*) is zero:

$$\begin{aligned}
&C_i = c_i(CAP, I) \\
&CAP = cap_1 + cap_2 + \ldots + cap_n \\
&\frac{\partial c_i(CAP, I)}{\partial CAP} < 0; \frac{\partial c_i(CAP, I)}{\partial I} \leq 0
\end{aligned} \tag{4}$$

Fossil fuel markets are internationally integrated. The regional use of exhaustible resources determines the global demand (*F*) which affects the price of fossil fuels in each region, P_i:

$$\begin{aligned}
&P_i = p_i(F) \\
&F = f_1 + f_2 + \ldots + f_n \\
&\frac{\partial p_i(F)}{\partial F} > 0
\end{aligned} \tag{5}$$

The price increases with global demand to reflect resource scarcity. When a group of countries faces a strong emission constraint, they contract fossil fuel consumption, driving down global demand and consequently international prices. Countries that are outside the coalition, facing a lower price, increase demand, leading to more emissions. The rate of carbon leakage is exactly the ratio of emission increase outside the coalition to emission reduction within the coalition.

It should be mentioned that the WITCH model does not include international trade and international capital flows and therefore it neglects terms-of-trade effects. In the paper we focus on the energy-market channel, which however has been shown to be the most important driver of carbon leakage[1].

In this set-up, the decision of a sub-group of countries to cooperate on climate change affects the strategic behaviour of both members and non-members of the coalition. Non-signatories' emissions might be lower, equal or higher compared to the noncooperative baseline, when no climate agreement is in place.

Reduced emissions by the OECD result in a lower global average temperature increase, with benefits on both members and non-members. Because total damage is lower, non-members increase emissions to bring back the equality between marginal costs and marginal benefits. This is the standard free riding effect that has been formalised, among others, by Tulkens and van Steenberghe (2009). In the standard model, each country *i* minimises abatement costs, $c_i(e_i)$, and climate change

---

[1] Burniaux and Oliveira Martins (2000) analysed the determinants of carbon leakage and they concluded that the non-energy market mechanism and the degree of international capital mobility play only a minor role.

damages, $d_i(E)$. In this case countries interact only through the damage effect and the optimal reaction of country j to an emission reduction in country i is negative[2]:

$$\frac{de_i}{de_j} = \frac{-\frac{\partial^2 d_i(E)}{\partial E^2}}{\frac{\partial^2 c_i(e_i)}{\partial e^2{}_i} + \frac{\partial^2 d_i(E)}{\partial E^2}} < 0 \qquad (6)$$

When the energy market and technology effects are included, what is the optimal reaction to emission reduction in other countries becomes ambiguous. The reaction of each country depends not only on global emissions, but also on the global level of technology, and on the global use of fossil fuels. Therefore, countries minimise the sum of three cost components:

$$c_i(e_i, CAP, I) + d_i(E) + p_i(F) \qquad (7)$$

Denoting the global level knowledge and technology with T, equation (7) can be simplified to:

$$c_i(e_i, T) + d_i(E) + p_i(F) \text{ where } T = CAP + I \qquad (8)$$

Because fossil fuels and emissions are directly related, we can implicitly capture the energy market effect with a cost function that depends on global emissions, $c_i(E,T)$. Equation (8) further simplifies to:

$$c_i(E,T) + d_i(E) \qquad (9)$$

In this setting[3], the reaction function depends on the interplay between the damage effect (DAM), the technology effect (TECH) , and the energy market effect (EMKT):

$$\frac{\partial e_i}{\partial e_j} = DAM + TECH + EMKT = (-) + (+) + (-) > or < 0 \qquad (10)$$

---

[2] This holds under the assumption of convex damage and cost function.

[3] See also Appendix I.

where

$$DAM = -\frac{\frac{\partial^2 d_i(E)}{\partial E^2}}{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i} + \frac{\partial^2 d_i(E)}{\partial E^2}} < 0 \Rightarrow \frac{de_i}{de_j} < 0$$

$$TECH = -\frac{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\left(\frac{dt_i}{de_j} + \frac{dt_j}{de_j}\right)}{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i} + \frac{\partial^2 d_i(E)}{\partial E^2}} > 0 \Rightarrow \frac{de_i}{de_j} > 0$$

$$EMKT = -\frac{\frac{\partial^2 c_i(E,T)}{\partial e_i^{\,2}}}{\frac{\partial^2 c_i(E,T)}{\partial e_i^{\,2}} + \frac{\partial^2 d_i(E)}{\partial E^2}} < 0 \Rightarrow \frac{de_i}{de_j} < 0$$

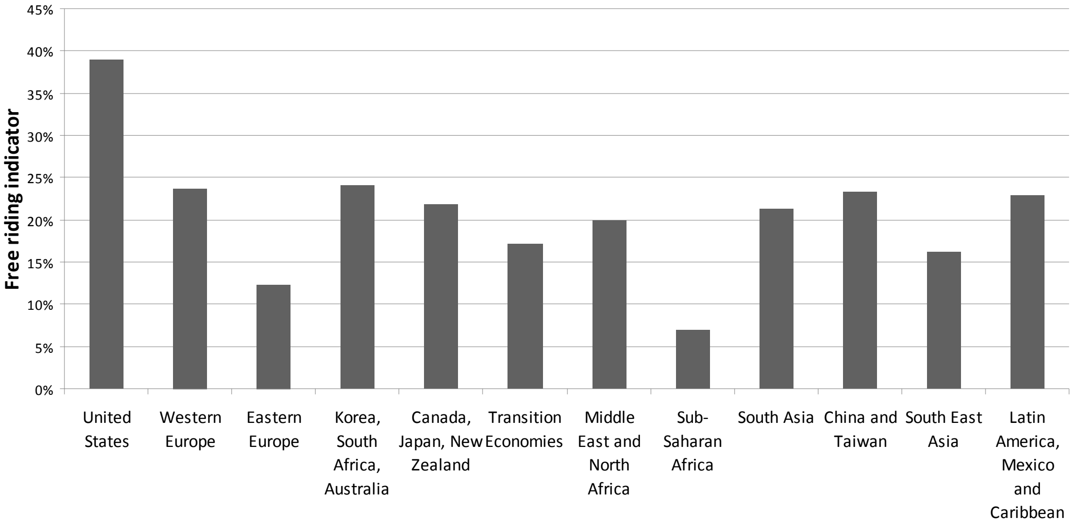
The energy market effect tends to go in the same direction as damage. Non-signatories can enjoy a welfare gain by consuming more resources at a lower price. On the contrary, the technology effect might lead to deployment of low-carbon substitutes also in free-rider regions, lowering their emissions with respect to the noncooperative outcome. However, these two effects are interdependent. If, for example, the low-carbon option is a direct substitute to the use of oil, then the choice between the clean and dirty alternative depends on their relative price (Hoel 2009). On the one hand, lower oil price reduces the attractiveness of low-carbon alternative. On the other hand, innovation and diffusion increase the competitiveness of cleaner technologies.

Which of these three effects prevail is an empirical question that depends on coalition marginal damage and abatement costs. On the other hand, coalition marginal damage and abatement costs depend on the composition of the coalition, on the innovation level, and on the price elasticity of fossil fuels.

As a rule of thumb, coalitions that find it optimal to undertake a thorough decarbonisation of the economy, either because they include many players or because the marginal damage of the coalition is large, lead to a stronger energy market effect. On the contrary, smaller, but less environmentally effective coalitions might see the technology externality prevails. In addition, the size of the technology effect depends crucially on the nature of the decarbonisation pathway followed by the coalition and on the efficiency of the innovation process. If the economy of coalition members is fossil fuel-intensive, cost-effective abatement can be achieved by simply reducing fossil fuel consumption. However, If members are already energy efficient, they cannot rely on substitution but they need to introduce new alternatives and expand the deployment of already mature zero-carbon technologies.

Exploring the free riding incentive already gives some indications on how different regions could react to the damage, energy market, and technology effect. Figure 1 shows the percentage change in cumulated CO2 emissions when either of the listed regions free-rides on the Grand Coalition[4]. The medium free riding incentive is about 20%, with higher and lower values for some regions. On average, free riding incentives are lower in developing countries because of the larger estimated impacts from climate change. Higher free riding incentives prevail in the United States and in Western Europe, where marginal abatement costs are larger, or in those countries which are expected to face low climate change impacts, such as China.

Figure1: Free Riding over Grand Coalition Indicator (Relative Difference of Cumulative CO2 Emissions over the Century with Respect to Nash Solution)



Although a multilateral approach to climate change would be desirable, what is emerging is a sort of *de facto* cooperation between major OECD countries, in a bottom-up manner in which each region pursues a different, although to some degree homogeneous, policy. The EU has already planned the third phase of emission trading, independently of Post-Kyoto agreements, and the US might approve a climate law that foresee a US-cap-and-trade scheme. However, developed countries are concerned with carbon leakage. Indeed, both the EU ETS and the Kerry-Lieberman

---

[4] Here we assume that the abatement of the Grand Coalition is given and it is not optimally adjusted to the new damage that emerges when a region leaves the coalition. In this way, the different free-riding incentive is due soley to different characteristics of each region.

climate bill[5] include specific provisions dealing with the issue of international competitiveness and carbon leakage.

3. Partial cooperation among OECD countries

The current status-quo of international negotiations on climate change suggests that only industrialised countries seem willing to subscribe to important emission reductions. The pledges made right after COP15 held in Copenhagen last December would result in an overall short-term reduction (by Annex I countries) of around 15% compared to 1990 (see among others De Cian and Favero 2010). Developed countries have also stated repeatedly their willingness to keep global warming below the 2 degrees target and, accordingly, to cut their emissions by 2050 between 80 and 90% (see for example the declaration at the G8 meeting in 2009).

At the same time, developed countries are also concerned with the risk of carbon leakage[6] For example, both the U.S. and the EU have proposed unilateral action, but with the possibility to use border measures that protect from potential competitiveness losses. They are aware of the fact that when only a sub-group of countries cooperates on the provision of a public good, the optimal reaction of non-signatories can be detrimental for the environmental effectiveness of the partial agreement. As already mentioned, whether this is the case or not depends, among other things, on the abatement effort of the coalition and on the decarbonisation path it follows.

This section tackles the issue of carbon leakage when OECD countries undertake different degree of mitigation effort. First, we explore the consequences of the abatement path that would be optimal on the basis of cost-benefit considerations. The choice of a policy target using this approach is not without controversies. Cost-benefit analysis implies comparing near-term, certain abatement costs with long-term, uncertain benefits. As a consequence, this criterion is very sensitive to value judgements, such as the economic evaluation of climate change impacts and the choice of the discount rate. The divergence between the results proposed by Nordhaus (2007) and Tol (2002)[7] on the one hand and Stern (2006) on the other hand well clarifies the importance of these assumptions.

Nordhaus (2007), using a high discount rate and conservative estimates of climate change impacts arrive at an optimal temperature increase of around 3.4 °C. Tol (2002) , using mean values climate sensitivity, arrives at 3°C. These studies suggest a gently increasing optimal abatement effort. On the contrary, Stern (2006), by choosing a low discount rate and by assuming large economic impacts, he favours early stringent abatement action.

---

[5] http://kerry.senate.gov/americanpoweract/intro.cfm

[6] See the Kerry-Lieberman proposal in the US and the recent Communication released by the European Union "Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage", COM(2010) 265.

[7] Similar results are shared by Manne and Richels (2004), Mendelsohn et al. (2000) and Pearce (2003).

Our central case considers higher damages and a lower pure rate of time preference compared to what conventionally used in DICE/RICE and WITCH as well. Under the assumption of high damage, the baseline temperate increase (3.4 °C above pre-industrial levels in 2100) leads to a 7% loss of GWP in 2100, whereas the loss would be about half in the case of low damage. The pure rate of time preference is 0.1% declining, instead of 3% declining[8]. We show major results for the case of low damage, high discount rate.

Following their cost-benefit rationale, OECD countries would abide to a 35% emission cut with respect to 2005 emission in 2050. We refer to this scenario as the "OECD base case". We also analyse variations in carbon leakage with the stringency of the emission objective of the coalition. We consider more and less stringent cuts. The support for deeper emission reductions reflects the application of a precautionary approach. Recognising that a temperature increase between 1 and 3 °C above pre-industrial level could already have substantial risk (Hansen, 2005), policy makers have identified the 2 degrees Celsius as a reasonable threshold. Less tighten targets are also considered in order to identify the minimum abatement effort that is required to stimulate further technological change, both inside and outside the coalition.

3.1 Disentangling three different determinants of carbon leakage

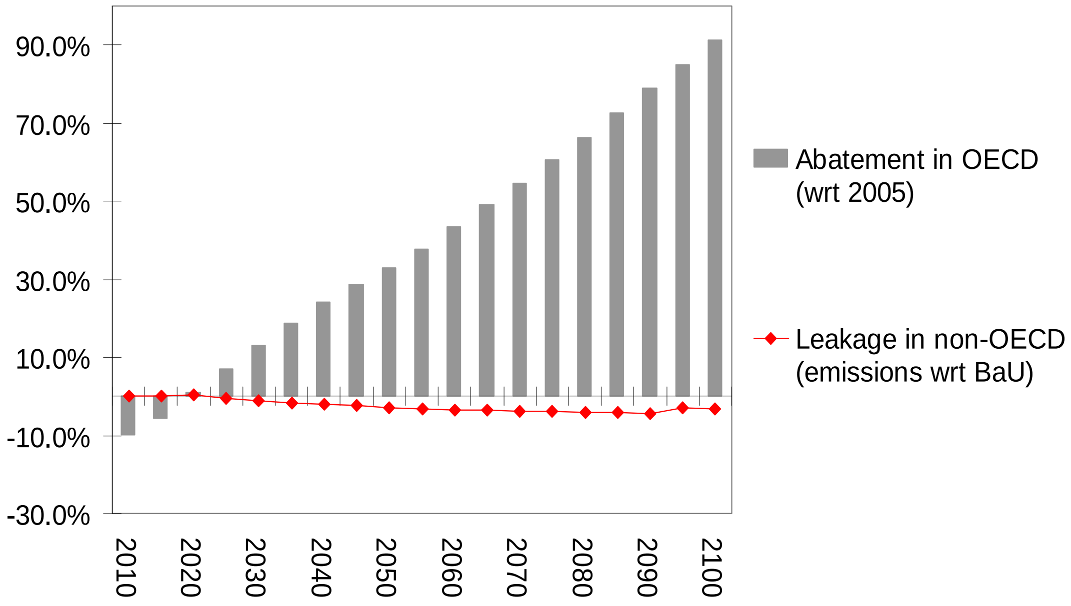
When OECD countries follow the emission path that is optimal on the basis of their abatement costs and climate change damages, the abatement effort is initially moderate and it increases over time. The optimal reaction of non-OECD countries is to slightly reduce their emissions below their baseline levels. Figure 2 shows the optimal abatement effort of the OECD coalition and the optimal reaction of non-OECD countries. Non-OECD emissions would be lower than in the case of no climate agreement at all. Therefore, the optimal abatement effort by the OECD coalition leads to negative leakage.

Even though non-signatories do not have any emission reduction commitment, the increased innovation and deployment induced by the abatement effort taking place within the OECD coalition leads to better technological opportunities also outside the coalition. At the same time, the energy price reduction is not sufficient to induce a rebound effect in non-constrained countries. In addition, the global temperature increase reduction is also quite moderate, from 3.4 to 3.2 °C, and this creates a small incentive to free ride on total damage reduction.

---

[8] We did not adjust the curvature of the utility function and therefore the discount rate is also lower.

Figure 2: Non-OECD energy-related CO2 emissions when reacting to emission reduction in OECD countries (OECD emission reduction: -35% wrt 2005 in 2050)



To disentangle the magnitude and the direction of the technology, energy market, and damage effect we compare the OECD base case with three hypothetical scenarios in which either of the three mechanism is in turned off.

The first of these variations assumes that knowledge and technology investments are completely excludable and kept within the coalition. Non-signatories benefit from the technological improvements that would occur anyway in the Nash, noncooperative baseline, but they do not benefit from the advancements induced by the climate agreement of the OECD countries. We refer to this case as the “ADVANCED TECHNOLOGY as in Nash” case.

The second variation assumes that reduction in fossil fuel consumption induced by the cooperative abatement effort in OECD countries is not reflected in the price of fossil fuels perceived in non-OECD countries, which remains equal to the Nash noncooperative baseline level. We refer to this second case as the “FF Price as in Nash” case.

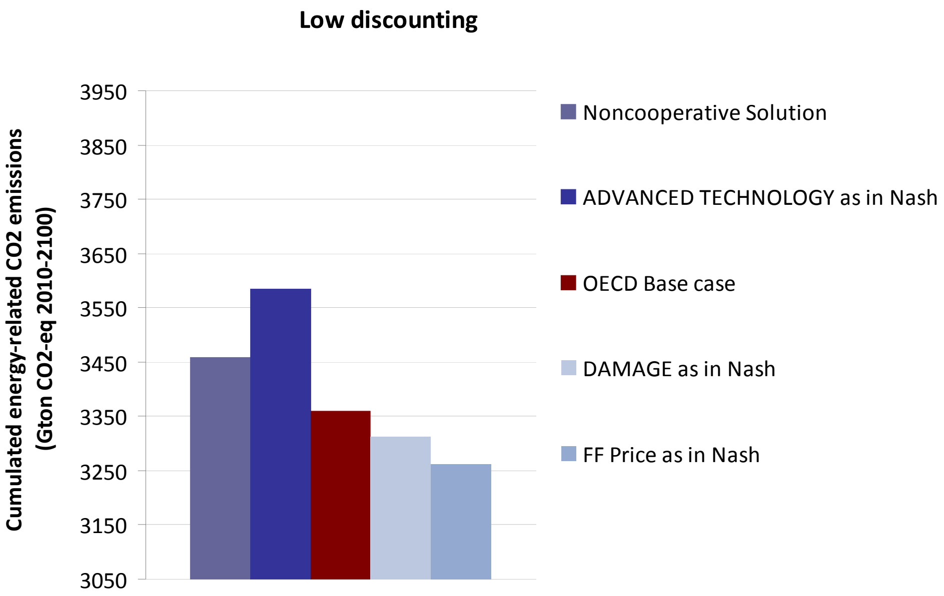
Third, we assume that the temperature increase reduction that follows the mitigation action undertaken in OECD countries can be excludable and that non-OECD countries continue to face a temperature increase as in the Nash noncooperative baseline. We refer to this final case as the “DAMAGE as in Nash” scenario.

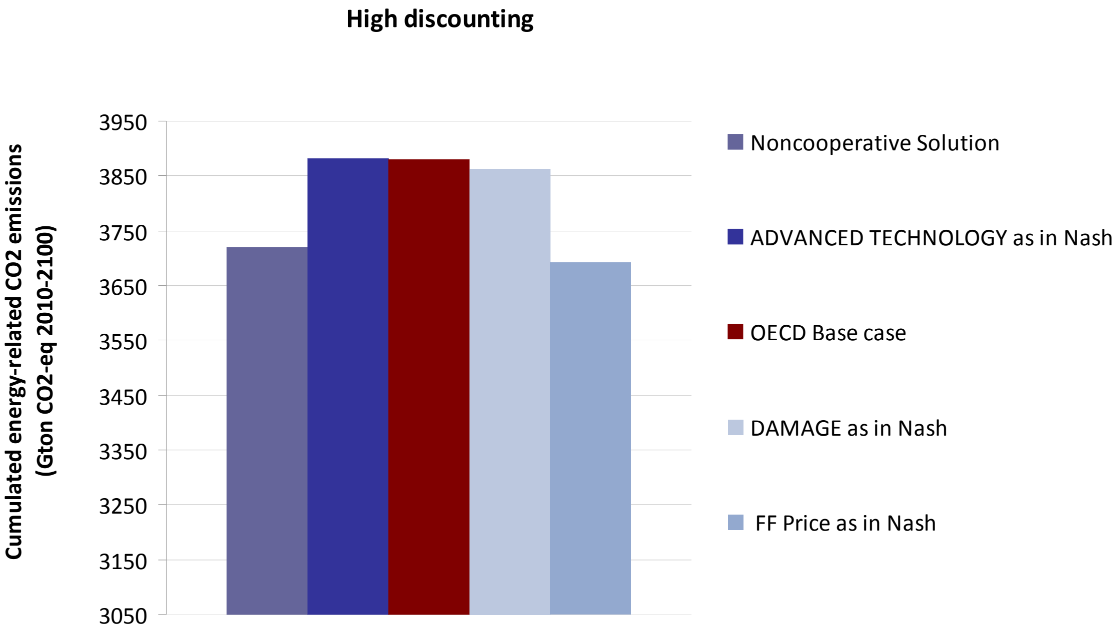
Figure 3 compares the resulting non-OECD emissions in the three scenarios with the noncooperative baseline and the OECD base case, for low and high discounting. The direction of each mechanism holds under different discounting, although the magnitude of each effect differs. High discounting shortens significantly the time horizon of the social planner and all those benefits and damages that occur after 2050 have small influences on cost-benefit considerations. Because damages increase exponentially and technology benefits also take time to materialise, especially the damage and the technology effects become negligible when the PRTP is increased to 3%.

The case with low discounting clearly shows the opposite contribution of the technology effect and, on the other hand, of the energy market and damage effects. Technology spillovers are significant and can prevail, leading to negative carbon leakage, provided the time horizon is sufficiently long. With a high discounting the future benefits of present investments in advanced technologies are not fully perceived and therefore carbon leakage becomes positive. The energy market effect is less sensitive to discounting and indeed it is the main driver behind carbon leakage in this case.

There are at least two reasons that explain why the technology effect can prevail. First, the abatement effort of the OECD coalition is relatively small. Global emissions exceed a path that would stabilise GHG concentrations at 550 CO2-eq by 20% and 140% in 2015 and 2100, respectively. When abatement is not that large, the influence on international prices is also contained. Partial cooperation limited to OECD has an effect on the international price of oil that is half what global cooperation would induce. Abatement effort is not very large because the marginal damage of the coalition is quite small. The largest damages occur in non-OECD countries, whose damage is not internalised by the OECD coalitions. Second, OECD countries are the technology frontier, at least today, and most R&D expenditure occurs there. Therefore, they are a major source of knowledge and technology spillovers.

Figure 3: Cumulated emissions in non-OECD countries when reacting to emission reduction in OECD countries (OECD emission reduction: -35% wrt 2005 in 2050)





3.2 Exploring the technology effect: knowledge diffusion or technology transfers?

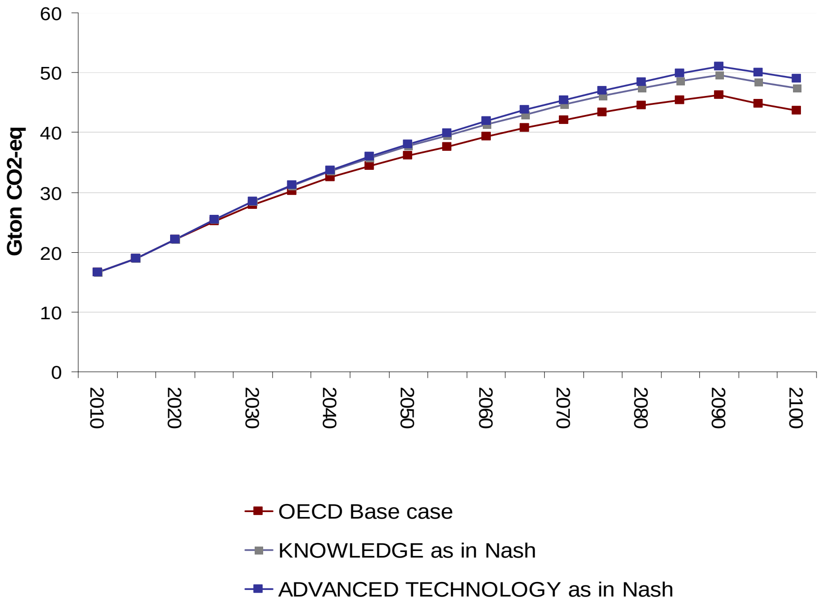
To explore the relative contribution of knowledge spillovers and technology diffusion a fourth variation is considered. We assume that only knowledge investments are completely excludable, whereas the low carbon technologies that are either invented or improved in OECD countries can diffuse outside the coalition by means of technology transfers. This implies that non-signatories benefit from the technological improvements only when they are embedded in new technologies that can be exported or transferred, but they cannot reap the benefits of enhanced knowledge, which remains within the OECD countries. We refer to this case as the “KNOWLEDGE as in Nash” case.

Figure 4 compares this scenario with the OECD base case and the scenario in which both knowledge and technology spillovers are excludable. It indicates that, to foster the adoption of advanced technologies outside the coalition, technology diffusion is more effective than knowledge spillovers.

Knowledge spillovers are less directly effective because they need absorptive capacity to yield some benefits. To lead to visible emission reduction those spillovers need to be embodied into new innovations and new technologies and this is a process that requires a pre-exiting knowledge stock and indigenous inventive capacity. Technology transfers instead are more immediate because they deliver a technology that can be immediately adopted and deployed. Therefore it is less demanding in terms of domestic knowledge capacity (Chandra et al. 2009).

It should be pointed out that we do not consider those barriers that could hinder also technology adoption, such as institutions and governance or access to financial markets. We assume that once technology costs are sufficiently low, all countries can adopt the technology.

Figure 4: Disentangling the contribution of knowledge and technology spillovers. Non-OECD energy-related CO2 emissions when reacting to emission reduction in OECD countries (OECD emission reduction: -35% wrt 2005 in 2050)

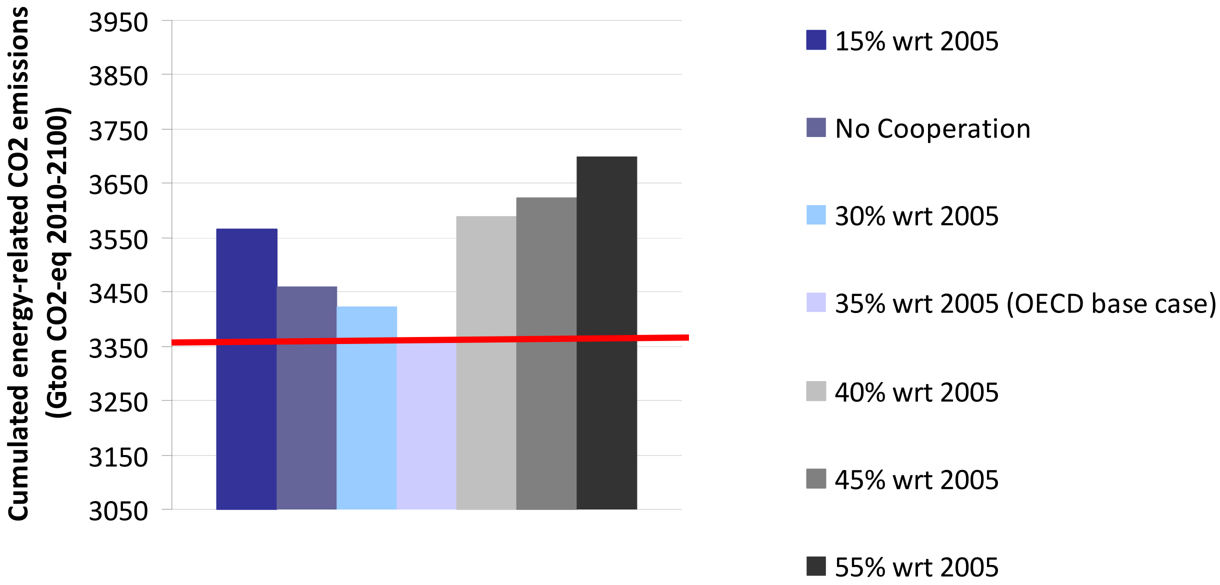


3.3 Sensitivity analysis to different reduction commitments in OECD countries

The previous section showed how, for moderate abatement levels and if agents are sufficiently forward looking, partial cooperation on emission reduction can induce some abatement also outside the coalition because of technological spillovers. What happens when more stringent reductions are considered and the technology effect would compete with stronger free-riding incentives, induced by lower energy prices and lower global damages? What is the minimum abatement effort required in order to stimulate sufficient technological change and diffusion?

To address these questions this section considers the consequences of more and less ambitious emission reduction in OECD countries. Figure 5 shows non-OECD cumulative emissions in reaction to different abatement effort undertaken in the OECD coalition. Compared to the noncooperative case, both milder and stricter commitments would lead to more emissions and thus to positive carbon leakage.

Figure 5: Cumulated emissions in non-OECD countries when reacting to different emission reduction targets in OECD countries

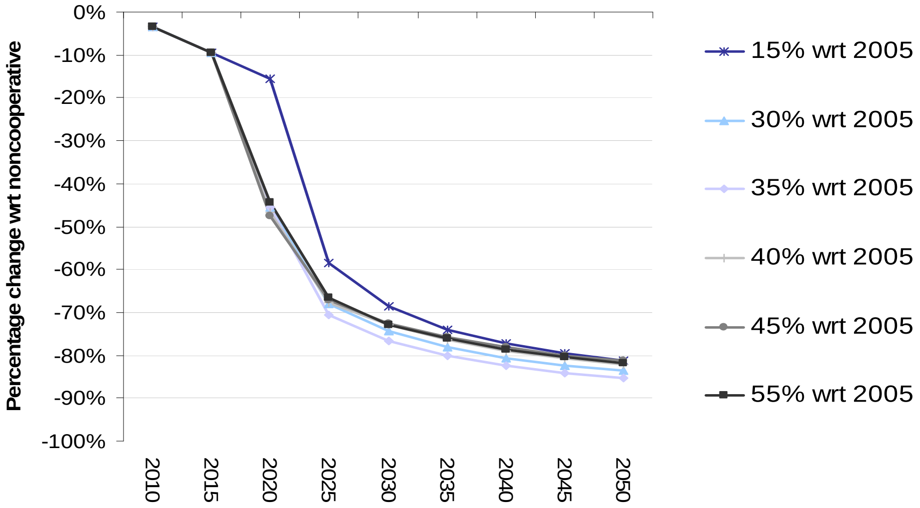


When the objective is too low, there is no need to introduce new and expensive technologies and the minimum abatement effort required is achieved mostly by means of energy efficiency and substitution.

Although more ambitious emission reduction targets continue to exert a positive effect on technology deployment and diffusion, these scenarios are also characterized by a deeper reduction in the use of fossil fuels. As a consequence, non-signatories face a even lower price. A slightly lower relative oil price at the beginning is sufficient to lock-in the energy system to exiting, fossil fuel-based options. Because energy system investments are long-lived, this creates a path dependency that sets non-signatory countries on a path of dirty economic growth. What eventually matters is the price of the incumbent technology not in absolute levels, but relatively to the price of the exiting, dirty alternative.

Figure 6 shows this concept in the case of a breakthrough technology that could replace the use of oil in the final-use sector. Decarbonisation outside power generation is particularly challenging because the mitigation portfolio is not as rich as in the electric sector and therefore marginal abatement costs are higher. The reason why more stringent cases revert the sign of carbon leakage is that, although technology costs remain low, the international price of oil is even lower. For example, the most stringent case (55% wrt 2005) leads to the lowest oil price and this makes more difficult the penetration of the zero carbon substitute. This effect delays the incentive to innovate, especially in non-members. Depending on the relative price, the technology can still become available outside the coalition, but at later stage.

Figure 6: Breakthrough technology price relative to its direct substitute (oil) when OECD undertake different levels of emission reduction



4. Summary and discussion

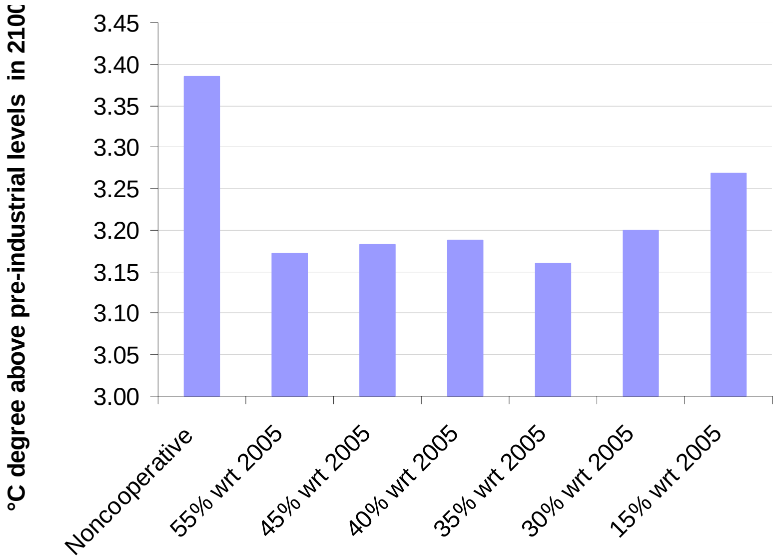
A multilateral approach to climate change, although warranted, has turned out to be slow and inefficient. Rather, what has emerged is a bottom-up architecture in which each region pursues a different, although to some degree homogeneous, policy. The EU has already planned the third phase of emission trading, independently of Post-Kyoto agreements, the US might approve a climate law that foresees a US-cap-and-trade scheme. What is emerging is a sort of *de facto* cooperation between major OECD countries, which several times have agreed on common targets.

However, the global environmental effectiveness of a partial climate coalition crucially depends on the response of non-signatories, which is driven by reduced global damage, lower fossil fuel prices on the international energy markets, and international technology spillovers. On the one hand, free-riding incentives and carbon leakage might induce non-members to increase emissions compared to the noncooperative baseline. On the other hand, innovations and technologies, due to the coalition effort, might spillover to non-signatories and reduce their emissions.

This paper has analysed the interplay of these three effects when a coalition betweeen OECD countries is formed. Results indicate that when the OECD coalition follows an abatement path justified on the basis of cost-benefit considerations, it reduces emissions between 30 and 35% below 2005 levels in 2050. In this case, knowledge spillovers and technology transfers induce emission reduction in non-signatory countries as well. A comparison of the two channel of transmission suggests that technology transfers are more effective at fostering the diffusion of carbon-free alternatives outside the coalition compared to pure spillovers of knowledge .

When the OECD coalition is more ambitious and it cuts emissions in the range of 40-50% below 2005 levels, the overall environmental effectiveness of their effort is actually lower. In this case, carbon leakage becomes negative. The Figure below shows the lower environmental effectiveness of these objectives by comparing the global average temperature increase above pre-industrial levels in 2100 for different scenarios.

Figure 7: Environmental effectiveness of the OECD coalition for different objectives. Global average temperature increase above per-industrial levels.



The policy conclusion that emerges from the present analysis is that near-term partial cooperation between technologically-advanced countries do not need to aim at too ambitious emission reduction targets because this could have negative repercussions that undermine global effectiveness. These countries already perform relatively efficiently in terms of energy and carbon intensity and therefore an intermediate mitigation target would be sufficient to increase innovation and technology deployment beyond baseline levels. The faster the international transmission to non-signatory countries, the lower the risk of carbon leakage.

Given that developing countries keep conditioning their decision to cooperate on the mitigation effort of industrialized countries, the OECD could be the appropriate starting coalition, both in size and composition. It would promote a technological transition towards lower carbon development pathways and it would be the minimum condition to dynamically broaden the number of signatory countries. Carbon leakage might be addressed more effectively by means of policies that promote the international transfer of technologies, rather then by threatening border measures that might actually hinder the diffusion process.

7. References

Babiker MH (2005). "Climate change policy, market structure and carbon leakage", *Journal of International Econonmics*, 65:421–445.

Barrett, S. (1992). "International Environmental Agreements as Games", in R. Pethig, ed., Conflicts and Cooperation in Managing Environmental Resources, Springer-Verlag, Berlin.

Bohm, P. (1993). "Incomplete international cooperation to reduce CO2 emissions: alternative policies," *Journal of Environmental Economics and Management* 24 258-71

Burniaux J, Oliveira-Martins J (2000). "Carbon emission leakages: a general equilibrium view", OECD Economics Department Working Paper 242, OECD Economics Department

Carraro, C. and D. Siniscalco (1993). "Strategies for the International Protection of the Environment", *Journal of Public Economics*, Vol. 52.

Chandra, V., D. Eröcal, PC Padoan, and CA Primo Braga (2009). *Innovation and Growth. Chasing a moving frontier*. OECD, Paris.

Chander, P. and Henry Tulkens (1997). "The Core of an Economy with Multilateral Environmental Externalities." *International Journal of Game Theory* (1997) 26:379-401.

D'Aspremont, C.A. and J.J. Gabszewicz (1986). "On the Stability of Collusion", in G.F. Matthewson and J.E. Stiglitz, eds., *New Developments in the Analysis of Market Structure*, Macmillan, New York.

D'Aspremont, C.A., A. Jaquemin, J.J. Gabszewicz and J. Weymark(1983). "On the Stability of Collusive Price Leadership", *Canadian Journal of Economics*, Vol. 16.

Gerlagh and Kuik (2007). "Carbon Leakage With International Technology Spillovers", FEEM Working Paper No. 33.2007.

Golombek, R. and M. Hoel (2004). "Unilateral emission reductions when there are cross-country technology spillovers," Memorandum 17/2004, Oslo University, Department of Economics

Hansen, J.E., 2005. A slippery slope: how much global warming constitutes ''dangerous anthropogenic interference''? *Climatic Change* 68 (3), 269–279.

Hoel, M. (1991). "Global Environmental Problems: The effect of unilateral action taken by one country", *Journal of Environmental Economics and Management*, 27, 275-85.

Hoel, M. (1992). "International Environment Conventions: the Case of Uniform Reductions of Emissions", *Environmental and Resource Economics*, Vol. 2.

Hoel M. (1994). "Efficient Climate Policy in the Presence of Free Riders," *Journal of Environmental Economics and Management* 27 (3) 259-274.

Hoel, M. and A. de Zeeuw (2009). "Can a Focus on Breakthrough Technologies Improve the Performance of International Environmental Agreements?" NBER Working Paper No. 15043.

Jaffe, Judson and Robert N. Stavins. "Linkage of Tradable Permit Systems in International Climate Policy Architecture." Discussion Paper 08-07, Harvard Project on International Climate Agreements, Belfer Center for Science and International Affairs, Harvard Kennedy School, September 2008.

Light M, Kolstad CD, Rutherford TF (2000) Coal markets, carbon leakage and the KYOTO PROTOCOL. Center for Economic Analysis Working Paper 23, University of Colorado at Boulder

Maler, K.G. (1989). “The Acid Rain Game,” in H. Folmer and E. Ireland, eds., Valuation Methods and Policy Making in Environmental Economics, Elsevier, New York: 188-205.

Manne, A.S., Richels, R.G., 2004. MERGE: An integrated assessment model for global climate change. Stanford University, Stanford, CA, USA.

Mendelsohn, R., Morrison, W., Schlesinger, M.E., Andronova, N.G., 2000. Country specific market impacts of climate change. *Climatic Change* 45 (3–4), 553–569.

Nordhaus, W.D., 2007. The Challenge Of Global Warming: Economic Models and Environmental Policy. Yale University, New Haven, CT, USA.

Pearce, D., 2003. The social cost of carbon and its policy implications. *Oxford Review of Economic Policy* 19 (3), 362–384.

Stern, N., 2006. The economics of climate change, the Stern Review. Cambridge University Press, Cambridge, UK.

Tol, R.S.J., 2002. Welfare specifications and optimal control of climate change: an application of FUND. *Energy Economics* 24 (4), 367–376.

Tulkens, H. and V. van Steenberghe (2009). “Mitigation, Adaptation, Suffering”: In search of the right mix in the face of climate change. CORE, Belgium.

Van der Werf, E. and C. Di Maria (2008). “Carbon leakage revisited: unilateral climate policy with directed technical change”, *Environmental and Resource Economics* 39, 55–74

Appendix I: A framework to describe free-riding incentives: adding the effect of technology effect and international energy markets

In the classic set-up, each region minimises abatement and damage costs:

$$\min_{\{e_i\}} J_i = \mathrm{d_i(E)} + \mathrm{c_i(e_i)}$$

where

d_i is an increasing and strictly convex damage function, *d'>0, d''>0*
c_i is a decreasing and convex function, *c'<0, c''>0*

The Nash equilibrium of the noncooperative game solves the following first order condition:

$$\frac{\partial c_i(e_i)}{\partial e_i} + \frac{\partial d_i(E)}{\partial E}\frac{\partial E}{\partial e_i} = 0$$

In the standard model, when country *i* reduces emissions, total damage is lower and therefore country *j* increases its emissions to bring back the equality between marginal damage and marginal benefit :

$$\frac{de_i}{de_j} = \frac{(-)}{(+)} < 0$$

When technology and energy markets effects are considered, the sign of the best reply function might be reverted. When there are international spillovers, more abatement (that is lower emissions) in country *j* leads to better technology also in country *i* :

$$\downarrow e_j \uparrow t_j \Rightarrow \frac{dt_j}{de_j} < 0; \downarrow e \uparrow t_j - spill => \uparrow t_i \Rightarrow \frac{dt_i}{de_j} < 0 => \left(\frac{dt_i}{de_j} + \frac{dt_j}{de_j}\right) < 0$$

Similarly, lower emissions in country *j* reduces the total use of energy *F*, lowering energy prices and increasing emissions in country *i*:

$$\downarrow e_J \downarrow F \downarrow p_i \uparrow e_i$$

In order to include the technology and energy market effects in the simplest way, we make the following assumptions:

mitigation costs depend on the global level of technology (*T*). We assume and inverse relationship between technology and emissions. This can be interpreted as Learning-By-Doing, as the larger the abatement effort, the lower the emissions and the higher the level of technology. It can also be interpreted as Learning-By-Researching, as more abatement (lower emissions) leads to more innovation. What matters is that the relationship between technology and emissions is inverse; mitigation costs depend on the international price of fossil fuels, which is determined by the global use of energy $F=f_i+f_j$. Without loss of generality, in this context we can assume direct proportionality.

We can thus write the cost-minimisation problem as follows:

$$\min_{\{e_i\}} J_i = \mathrm{d_i(E) + c_i(E,T)}$$

FOC

$$\frac{\partial c_i(E,T)}{\partial e_i} + \frac{\partial d_i(E)}{\partial E}\frac{\partial E}{\partial e_i} = 0$$

Totally differentiating the First Order Condition (FOC) we obtain:

$$\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i} de_i + \frac{\partial^2 d_i(E)}{\partial E^2} de_i + \frac{\partial^2 d_i(E)}{\partial E^2} de_j + \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i} dt_i + \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i} dt_j + \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i} de_j = 0$$

$$\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\frac{de_i}{de_j} + \frac{\partial^2 d_i}{\partial E^2}\frac{de_i}{de_j} + \frac{\partial^2 d_i}{\partial E^2}\frac{de_j}{de_j} + \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\frac{dt_i}{de_j} + \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\frac{dt_j}{de_j} + \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\frac{de_j}{de_j} = 0$$

$$\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\frac{de_i}{de_j} + \frac{\partial^2 d_i}{\partial E^2}\frac{de_i}{de_j} = -\frac{\partial^2 d_i}{\partial E^2} - \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\frac{dt_i}{de_j} - \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\frac{dt_j}{de_j} - \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}$$

$$\frac{de_i}{de_j}\left(\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i} + \frac{\partial^2 d_i}{\partial E^2}\right) = -\frac{\partial^2 d_i}{\partial E^2} - \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\frac{dt_i}{de_j} - \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\frac{dt_j}{de_j} - \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}$$

$$\frac{de_i}{de_j} = \frac{-\frac{\partial^2 d_i(E)}{\partial E^2} - \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\left(\frac{dt_i}{de_j} + \frac{dt_j}{de_j}\right) - \frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}}{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i} + \frac{\partial^2 d_i(E)}{\partial E^2}}$$

$$\frac{de_i}{de_j}=-\frac{\frac{\partial^2 d_i(E)}{\partial E^2}}{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}+\frac{\partial^2 d_i(E)}{\partial E^2}}-\frac{\frac{\partial^2 c_i(E,t_i,t_j)}{\partial e^2{}_i}\left(\frac{dt_i}{de_j}+\frac{dt_j}{de_j}\right)}{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}+\frac{\partial^2 d_i(E)}{\partial E^2}}-\frac{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}}{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}+\frac{\partial^2 d_i(E)}{\partial E^2}}$$

$$DAM=-\frac{\frac{\partial^2 d_i(E)}{\partial E^2}}{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}+\frac{\partial^2 d_i(E)}{\partial E^2}}<0\Rightarrow\frac{de_i}{de_j}<0\ \text{(standard case)}$$

$$TECH=-\frac{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}\left(\frac{dt_i}{de_j}+\frac{dt_j}{de_j}\right)}{\frac{\partial^2 c_i(E,T)}{\partial e^2{}_i}+\frac{\partial^2 d_i(E)}{\partial E^2}}>0\Rightarrow\frac{de_i}{de_j}>0$$

$$EMKT=-\frac{\frac{\partial^2 c_i(E,T)}{\partial e_i^{\,2}}}{\frac{\partial^2 c_i(E,T)}{\partial e_i^{\,2}}+\frac{\partial^2 d_i(E)}{\partial E^2}}<0\Rightarrow\frac{de_i}{de_j}<0$$

$$\frac{\partial e_i}{\partial e_j}=DAM+TECH+EMKT=\frac{(-)}{(+)}-\frac{(-)}{(+)}-\frac{(+)}{(+)}>or<0\Rightarrow\text{empirical question}$$

$$IF\ |TECH|>|EMKT|+|DAM|\Rightarrow\frac{de_i}{de_j}>0$$

Appendix II: The WITCH model

Full details on the WITCH model can be found in Bosetti et al. (2007) and Bosetti et al. (2009). This annex provides a brief summary of the model. It recalls the most distinguishing features related to environmental, economic, and technology externalities, and the game-theoretic set-up.

Brief model description

WITCH is a dynamic optimal growth model ("top-down") with a "bottom-up" representation of the energy sector. It can thus be classified as a hybrid model. The geographical coverage is global and world regions are grouped into twelve macro-regions sharing economic, geographic, and energy similarities. These regions are USA (United States), WEURO (Western Europe), EEURO (Eastern Europe), KOSAU (Korea, South Africa, Australia), CAJANZ (Canada, Japan, New Zealand), TE (Transition Economies), MENA (Middle East and North Africa), SSA (Sub-Saharan Africa), SASIA (South Asia), CHINA (China and Taiwan), EASIA (South East Asia), LACA (Latin America, Mexico and Caribbean).

The WITCH model includes a range of technology options to describe the use of energy and power generation. Different fuels can be used for electricity generation and final consumption: coal, oil, gas, uranium, and biofuels. Electricity can be generated using a series of traditional fossil fuel-based technologies and carbon-free options. Fossil fuel-based technologies include natural gas combined cycle (NGCC), fuel oil and pulverised coal (PC) power plants. Coal-based electricity can also be generated using integrated gasification combined cycle production with carbon capture and sequestration (CCS). Low carbon technologies include hydroelectric and nuclear power, wind turbines and photovoltaic panels (Wind&Solar), and a breakthrough technology. A second backstop option is included in final consumption and it is meant to represent an alternative to oil in transportation such as hydrogen and advanced biofuels. The model features endogenous technical change in the energy sector in the form of both Learning-By-Researching and Learning-By-Doing.

The game-theoretic set-up makes it possible to capture the noncooperative nature of international relationships. Climate change is the major global externality, but other economic externalities induce free-riding behaviours and strategic interactions. The model can produce two different solutions. The cooperative solution is globally optimal because it maximises global social welfare and it internalises environmental and economic externalities. It thus represents a first-best optimum. The decentralised, or noncooperative solution is strategically optimal for each given region (Nash equilibrium), but it does not internalise externalities. It thus represents a second-best optimum. The

Nash equilibrium is computed as an open-loop Nash equilibrium. It is the outcome of a non-cooperative, simultaneous, open membership game with full information.

The remaining of the Appendix describes in detail the environmental, technology, and economic externalities.

The climate externality

Long-lived Greenhouse Gases become perfectly mixed with other gases in the world atmosphere. No matter where the initial source of emission is located, it will affect global GHG concentrations and eventually global mean temperature and climate. For this reason, emissions from any source, anywhere in the world, give rise to a global negative externality. Long-lived GHGs remain in the atmosphere from decades to centuries. Present emissions build up over past emissions and increase the concentrations for very long temporal horizons. The WITCH model includes carbon cycle and climate modules that describe the international and intertemporal dimension of the global externality of GHG emissions.

A climate module describes the physical relationship between GHG emissions, radiative forcing and temperature. Temperature relative to pre-industrial levels increases through augmented radiative forcing of different GHGs. Radiative forcing in turn depends on CO2 and non-CO2 atmospheric concentrations. Stoichiometric coefficients are applied to the use of fossil fuels to derive related CO2 emissions. Among non-CO2 gases, emissions of methane (CH4), Nitrous dioxide (N2O), short-lived fluorinated gases, (SLF, HFCs with lifetimes under 100 years) and long-lived fluorinated (LLF, HFC with long lifetime, PFCs, and SF6) are explicitly modelled. We also distinguish SO2 aerosols, which have a cooling effect on temperature.

A reduced-form damage function, D(n,t), describes a relationship between regional damages and global mean temperature increase above pre-industrial levels, T(t). The quadratic functional form makes it possible to account for both gains and losses:

$$D(n,t) = \theta_{1,n} T(t) + \theta_{2,n} T(t)^2 \tag{A1}$$

Physical impacts can be translated into monetary units by including the damage function into the final production function. Equation (A2) expresses climate change damages as fraction of final output, YGROSS:

$$YNET(n,t) = \frac{YGROSS(n,t)}{\Omega(n,t)} \tag{A2}$$

where

$$\Omega(n,t) = 1 + D(n,t)$$

International knowledge spillovers for energy enhancing R&D

Investments in energy R&D build up a stock of knowledge (HE) that improves overall energy efficiency. The energy knowledge stock augments the quantity of final energy services (ES) that can be provided per unit of physical energy (EN), according to a Constant Elasticity formulation:

$$ES(n,t) = \left[\alpha_H HE(n,t)^{\rho_{ES}} + \alpha_{EN} EN(n,t)^{\rho_{ES}}\right]^{1/\rho_{ES}} \qquad \text{(A3)}$$

Learning processes during knowledge accumulation or deployment of advanced technologies will not be confined within the boundaries of investing countries, but knowledge and expertise are likely to spill, with some lag, worldwide. Therefore, the generation of new ideas is characterised by a innovation possibility frontier that exhibits both intertemporal and international spillovers. At each point in time, new ideas (Z) are produced using a Cobb-Douglas combination between domestic investments (IR&D), the domestic stock of knowledge (HE), and the foreign stock of knowledge (SPILL):

$$Z(n,t) = a\, I_{R\&D}(n,t)^b\, HE(n,t)^c\, SPILL(n,t)^d \qquad \text{(A4)}$$

The contribution of foreign knowledge is not immediate, but it depends on the interaction between two components shown in equation (A5). The first term describes countries' absorptive capacity whereas the second one captures the distance of each region from the technology frontier. The technology frontier is represented by the stock of knowledge in high income countries (USA, WEURO, EEURO, KOSAU, and CAJANZ):

$$SPILL(n,t) \;=\; \frac{HE(n,t)}{\sum_{HI} HE(n,t)}\left(\sum_{HI} HE(n,t) - HE(n,t)\right) \qquad \text{(A5)}$$

The flow of new ideas (Z) adds to the previously cumulated stock and generates the total amount of knowledge available to each country at each point in time:

$$HE(n,t+1) \;=\; Z(n,t) + HE(n,t)(1-\delta_{R\&D}) \qquad \text{(A6)}$$

International experience spillovers for wind and solar

WITCH represents the diffusion of technologies and experience in some niche technologies such as Wind&Solar. The rapid and recent development of wind turbines and photovoltaic panels has led to a reduction in investment costs. A learning curve in wind and solar technologies captures the empirically-observed relationship between declining investments costs and installed capacity, an effect which is known as Learning-By-Doing. Investment costs in new Wind and Solar capital, $SC(n,t)$, decrease with the world installed capacity, $\sum_n K_j(n,t)$:

$$SC_j(n,t+1) = B_j(n) \cdot \sum_n K_j(n,t)^{-\log_2 PR_j} \tag{A7}$$

We assume full technology spillover: investments in additional capacity by virtuous regions drive down investment costs worldwide within a model time period which corresponds to five years. The progress ratio, PR, defines the speed of learning.

International knowledge and experience spillovers in breakthrough technologies

The WITCH model includes two backstop technologies. These are innovative technologies with low or zero carbon emissions that are currently not commercialised and that necessitate dedicated innovation investments to become economically competitive and available in large supplies. For the purpose of modelling, a backstop technology can be seen of as a compact representation of a portfolio of advanced technologies that would become available not before a few decades. The costs of these technologies are modelled with a two-factor learning curve. The unit cost of each backstop technology, $P_{tec,t}$, evolves over time with technology deployment, $CC_{tec,t}$ and the accumulation of a dedicated knowledge stock, $R\&D_{tec,t}$:

$$\frac{P_{tec,T}}{P_{tec,0}} = \left(\frac{R\&D_{tec,T-2}}{R\&D_{tec,0}}\right)^{-c} * \left(\frac{CC_{tec,T}}{CC_{tec,0}}\right)^{-b} \tag{A8}$$

The stock of R&D accumulates with the perpetual rule and with the contribution of international knowledge spillovers, SPILL:

$$R\&D_{tec,T+1} = R\&D_{tec,T}(1-\delta) + IR\&D_{tec,T}{}^{\alpha} \quad SPILL_{tec,T}{}^{\beta} \tag{A9}$$

The two exponents are the Learning-by-Doing index ($-b$) and the Learning-by-Researching index ($-c$) and they define the speed of learning. The learning ratio lr is the rate at which costs decline each time the cumulative capacity doubles, while lrs is the rate at which costs decline at the doubling of the knowledge stock.

We set the initial prices of the backstop technologies at roughly 10 times the 2005 price of commercial equivalents. The cumulative deployment of the technology is initiated at an arbitrarily low value, 1,000twh and 1,000EJ for the electric and non-electric, respectively. Backstop technologies are assumed to be renewable in the sense that the fuel cost component is negligible. The backstop for power generation is assumed to operate at load factors comparable with those of baseload power generation.

Backstops substitute linearly nuclear power in the electric sector, and oil in the non-electric one. Once backstop technologies become competitive, their uptake is not immediate and complete, but rather we assume a transition/adjustment period. These penetration limits capture the inertia in the system, as large deployment of these advanced technologies will require investment and re-organisation in energy infrastructure. At each point in time, the upper limit is equal to 5% of energy produced by other technologies and the backstop itself in the previous period.

International energy markets

The markets of exhaustible resources are assumed to be integrated and they are represented as an international market for each fuel. International prices depend on fossil fuels extraction, which in turn is driven by regional consumption.

The model considers four non renewable fuels: coal, crude oil, natural gas and uranium. Their costs follow a long-term trend that reflects their exhaustibility. Resource prices are calculated endogenously using a reduced-form cost function that allows for non-linearity in both the depletion effect and in the rate of extraction. Assuming competitive markets, the domestic price $P_f\left(n,t\right)$ is equal to the marginal cost and it depends on the cumulative quantity of fossil fuels extracted, Qf (n,t):

$$P_f\left(n,t\right) = \chi_f\left(n\right) + \pi_f\left(n\right)\left[Q_f\left(n,t\right)/\overline{Q}_f\left(n,t\right)\right]^{\psi_f\left(n\right)} \tag{A10}$$

where $\chi_f\left(n\right)$ is a regional markup, $\overline{Q}_f$ is the amount of total resources at time t, and $\pi_f\left(n\right)$ measures the relative importance of the depletion effect. Cumulative extraction depends on the demand for fossil fuels of all 12 regions in the model:

$$Q_f\left(n,t\right) = Q_f\left(n,t-1\right) + \sum_{n=1}^{12} \chi_{f,extr}\left(n,t\right) \tag{A11}$$

Cumulative extraction depends on is the amount of fuel f extracted in region n at time t, $X_{f,extr}\left(n,t\right)$.